# TRANSACTIONS

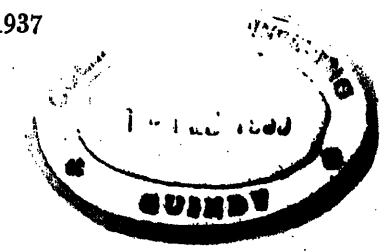
OF THE

# AMERICAN INSTITUTE

OF

# ELECTRICAL ENGINEERS

JANUARY TO DECEMBER 1937



## VOLUME 56

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# Preface

This, the fifty-sixth volume of the TRANSACTIONS of the American Institute of Electrical Engineers, includes the entire text content of the 12 monthly issues of ELECTRICAL ENGINEERING published during 1937 and a 28-page supplement, immediately preceding the index, which contains two papers not published in ELECTRICAL ENGINEERING.

Fourth in the series of annual volumes initiated under the Institute's unified publication plan, which became effective January 1, 1934, this is the last to be published under that plan. Certain changes in publication policy, approved by the Institute's board of directors October 28, 1937, will become effective January 1, 1938, and consequently will be reflected in the 1938 TRANSACTIONS; these changes in publication policy are outlined on page 1409 of this volume.

Discussions of technical papers, printed in ELECTRICAL ENGINEERING from month to month as they became available, are thoroughly correlated in the comprehensive multientry annual reference index which begins on page 1537 of this volume, immediately following the 28-page supplement. A reference to any of the several subject entries for any technical paper will lead directly to any discussion on that paper that may have been published during 1937. It is of importance to note: first, that, of 1936 papers, this volume contains all discussions published after December 1936; second, that, likewise, the discussions of many of the later 1937 papers will appear in the 1938 TRANSACTIONS.

# Errata

1. Page 60, figure 2*a*, capacitance between surfaces of shell should be indicated as $C'$.

2. Page 65, figure 14, first solid line from bottom should indicate power; second solid line from bottom should indicate power factor.

3. Page 97, figure 11, reproduction correct on page 204.

4. Page 168, first column, lines 16–18 should read: The relation between voltage breakdown $(V/V_0)$ and oil gap spacings $(d/d_0)$ for these curves is closely expressed by $\log (V/V_0) = 0.5 \log (d/d_0)$.

5. Page 170, first column, lines 16–18 should read: The relation between voltage strength $(V/V_0)$ and thickness $(d/d_0)$ over the greater range of the 2 curves for fullerboard is expressed by $\log (V/V_0) = 0.6$ to $0.7 \log (d/d_0)$.

6. Page 334, nomenclature should give $\mathcal{P} = 3.192 \frac{A}{\delta}$.

7. Page 557, table I, should give the following values for 13.8-kv lines:

| Line | Length Line | No. Gaps | No. Structures | Structures With Gaps |
|---|---|---|---|---|
| 13,862<br>13,863 | 0.62 | 90 Ph.<br>8 Gr. | 28 | 15 |
| 13,887<br>13,888 | 3.38 | 426 Ph.<br>71 Gr. | 150 | 71 |
| 13,860<br>13,861 | 3.46 | 240 Ph.<br>40 Gr. | 161 | 40 |

8. Page 615, equations 10 should read:

$$P(s) = V_k(s) \qquad I^k(s) = \hat{V}_\alpha(s) * \hat{I}_\alpha(s)$$

9. Page 622, figure 4, equations in subcaption should read:

$$I_q = \frac{E_q s_2}{\sqrt{r_q^2 + x_q^2 s_2^2}}$$

and

$$I_q = \frac{E_q}{\sqrt{(r_q^2/s_2^2) + x_q^2}}$$

10. Page 1004, equation 1 should read:

$$E_s = E_r \cosh px + I_r Z_0 \sinh px$$

11. Page 1005, equation 5 should read:

$$Z_s = Z_0 \left( \frac{\alpha x}{\cos^2 \beta x} + j \tan \beta x \right) = Z_0 \tan \beta x \left( \frac{Rx}{Z_0 \sin 2\beta x} + j\, 1.0 \right)$$

12. Page 1006, equation 8 should read:

$$R' = \frac{84\sqrt{f}\, 10^{-9}}{r\sqrt{1 - \left(\frac{2r}{D}\right)^2}} = \frac{0.01455}{\sqrt{\lambda}\, r \sqrt{1 - \left(\frac{2r}{D}\right)^2}}$$

13. Page 1009, fourth line following equation 40, $z_0$ should be $Z_0$.

Electrical Engineering

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JANUARY 1937

for January 1937—

A Million-Cycle Telephone System
Abrasion—A Factor in Electrical Brush W...
Lightning Protection for Transmission L...
Inductive Co-ordination
Two-Reaction Theory of Synchrono...
Proposed Transformer Standards
Sealed-Off Ignitrons for Weldi...
Contributions to Synchronous-...
Synchronous Machine Wi...
Electrical Characteristics ...
Short-Time Spark-Ov...
A Single-Element ...
Ultrahigh-Speed ...
Pole Flexibili...
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## We Present

# Easy-Reading Page

...eve readers of eye-...int fatigue and dis-... ELECTRICAL ENGINEERING ...some of the indirect ...search by noted illumina-...authorities in the field of ...a hopeful step toward a ...sy-reading page." This issue ...paper of an improved quality, ...oned scientifically to provide the ...for an effective non-glare easy-... Typography, too, has been ...ed in the interests of reader-comfort. ...the ink, which after all makes a periodical out of otherwise blank paper, has been specially compounded to contribute toward the desired results, and in all probability will be improved still further in the future.

Concerning this change, Maurice Holland (A'23, M'30) director, division of engineering and industrial research, National Research Council, has written the following statement:

"I have been advised on good authority that 70 per cent of our current knowledge comes to us through the medium of the printed page. Therefore, especially in view of the recent notable advances in the science and art of electrical illumination, it would seem that we have not carried through to the ultimate conclusion, so far as the reader is concerned.

"Particularly as exemplified in the 'better light, better sight' campaign, much scientific and technical effort has been focused with pronounced success on such modern illuminants as the 'IES lamps.' But all this has had to do with the *source* of the light. Therefore, it seems not only timely, but highly important that thoughtful attention should be given to the question of effective *utilization* of light, particularly with reference to the printed page.

"The advance samples of the January 1937 issue of ELECTRICAL ENGINEERING that I have seen represent the nearest to a scientifically developed easy-reading page that so far has been produced through the media of the graphic arts. It is a definite contribution. It is a definite challenge. An easy-reading page involves not only the paper on which it is printed, but, to be most effective, should represent the co-operative effort of printers, ink manufacturers, type designers, and other elements of the graphic arts."

Frankly an experiment, this step represents ELECTRICAL ENGINEERING's effort to serve its readers in the most effective manner possible. Comments are invited.



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Page 1 circuit lation $(V/$ lines $d/d_0)$ the 2 rv phe- ar high = 0.6 t.7 le

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| No. Structu | Structures With Gaps |
|---|---|
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**Transformers.** Transformers are discuss in 2 papers in this issue. The first outli certain proposed changes in the AI transformer standards (*pages 32–6*). T second paper presents the results of a se of dielectric tests on transformer oil a solid insulation (*pages 164–71*).

**Impulse Generator Charts.** Comparison the voltage waves of impulse generators commercial testing on the basis of the c stants of the generator circuit as well wave shape is suggested in a paper in issue; charts for selecting circuit conste are included (*pages 183–8*).

**Directional Relay.** A relay of the p phase directional type having only a si element has been developed by the us multiple poles. Reducing the numbe elements has reduced the size and weig the relay, and has resulted in low in and high speed (*pages 77–80*).

**Sealed-Off Ignitrons.** Ignitrons offe means of control for resistance weldin their ability to supply very large cur for fractions of a cycle. Principles of d and manufacturing technique for both d metal tubes of the sealed-off typ ussed in this issue (*pages 37–40*).

**er of Gaps.** Spark-over of s ps, insulators, bushings, and very short time lags has d some data obtained fo 4 microseconds, on blished (*pages 67–76*)

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# Electrical Engineering

Published Monthly by
American Institute of Electrical Engineers
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VOLUME 56, NO. 1 ▼ ▼ ▼ JANUARY 1937


## We Present

# The Easy-Reading Page

IN AN EFFORT to relieve readers of eye-strain, with its attendant fatigue and discomfort, or worse, ELECTRICAL ENGINEERING introduces with this issue some of the indirect results of extensive research by noted illumination and research authorities in the field of "effective seeing"—a hopeful step toward a much-needed "easy-reading page." This issue is printed on new paper of an improved quality, blended and toned scientifically to provide the foundation for an effective non-glare easy-reading page. Typography, too, has been modified in the interests of reader-comfort. Even the ink, which after all makes a periodical out of otherwise blank paper, has been specially compounded to contribute toward the desired results, and in all probability will be improved still further in the future.

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# A Million-Cycle Telephone System

ABOUT 2 years ago a new wide-band system for multichannel telephone transmission over coaxial cables was described in an AIEE paper.[1] An experimental system has now been installed between New York and Philadelphia. The various tests and trials which are planned for this system have not been carried far enough to justify a formal AIEE technical paper for presentation and discussion. Meanwhile, the considerable interest that has been aroused in the system has led to this brief statement of its principal features and its general technical performance as so far measured, which has been prepared by M. E. Strieby (M'22) carrier transmission research engineer of the Bell Telephone Laboratories, Inc., New York, N. Y.

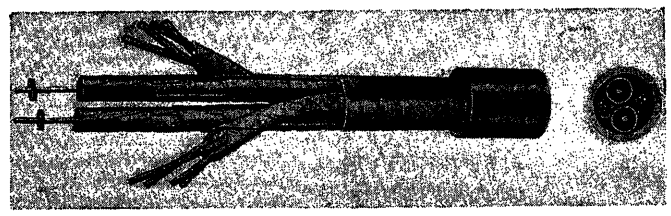


Fig. 1. View showing structure of coaxial cable

The coaxial cable itself has been installed between the long-distance telephone buildings in New York and Philadelphia, a distance of 94.5 miles. It has been equipped with repeaters, at intervals of about 10 miles, capable of handling a frequency band of about 1,000,000 cycles.

This million-cycle system is designed to handle 240 simultaneous 2-way telephone conversations. Only a part of the terminal apparatus has been installed, sufficient in this case to enable adequate tests to be made of the performance of the entire system. A general view of the New York terminal is shown in figure 2. Some preliminary test conversations have been held over the system both in its normal arrangement for providing New York-Philadelphia circuits, and with certain special arrangements whereby the circuit was looped back and forth many times to provide an approximate equivalent of a very long cable circuit. The performance has been up to expectations, and no important technical difficulties have arisen to cast doubt upon the future usefulness of such systems. Much work remains to be done, however, before coaxial systems suitable for general commercial service can be produced.

## The Coaxial Cable

Figure 1 shows a photograph of the particular cable used in this installation. It contains 2 coaxial units, each having a 0.265-inch inside diameter, together with 4 pairs of 19-gauge paper-insulated wires, the whole enclosed in a lead sheath having a $^{7}/_{8}$-inch outside diameter. The central conductor of the coaxial units is a 13-gauge copper wire insulated with hard-rubber disks at intervals of $^{3}/_{4}$ inch. The outer conductor is made up of 9 overlapping copper tapes which form a tube 0.02 inch thick; this is held together with a double wrapping of iron tape.

The transmission losses of this coaxial conductor at various frequencies are shown in figure 5. This attenuation is about 4 per cent higher than is calculated for a solid copper tube of the same dimensions and material. Another matter of importance is the shielding obtained from

1. Systems for Wide Band Transmission Over Coaxial Lines, by L. Espenschied and M. E. Strieby, Electrical Engineering (AIEE Transactions), volume 53, 1934, pages 1371–80.

Fig. 2. The New York terminal of the coaxial system

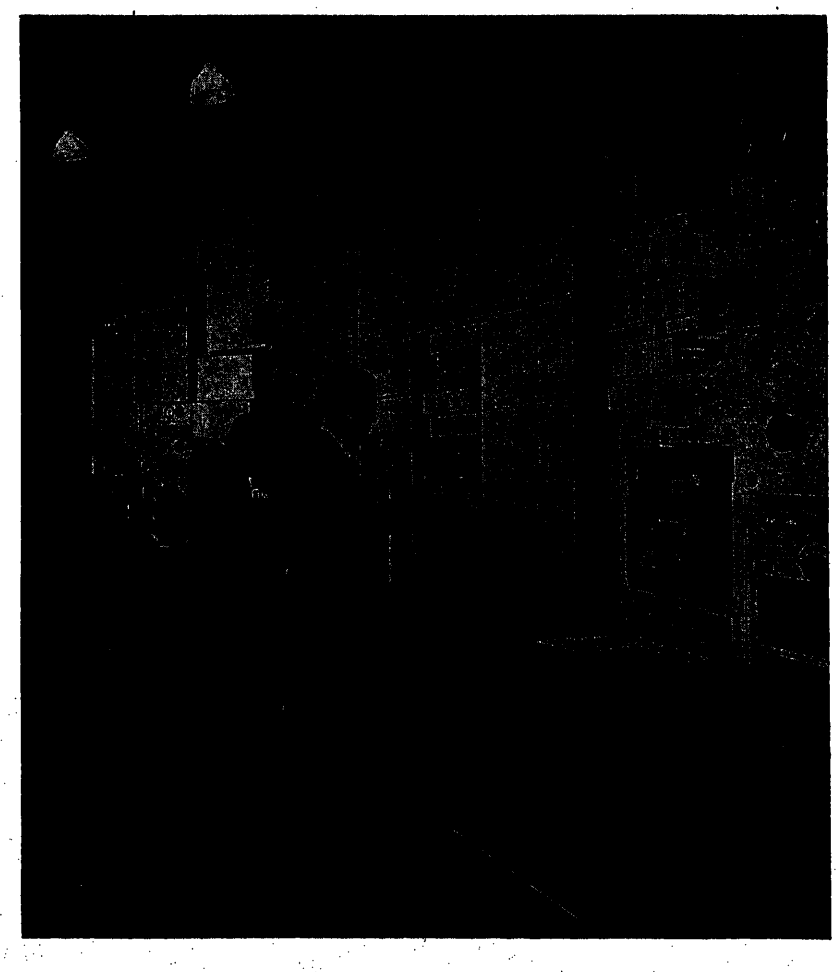
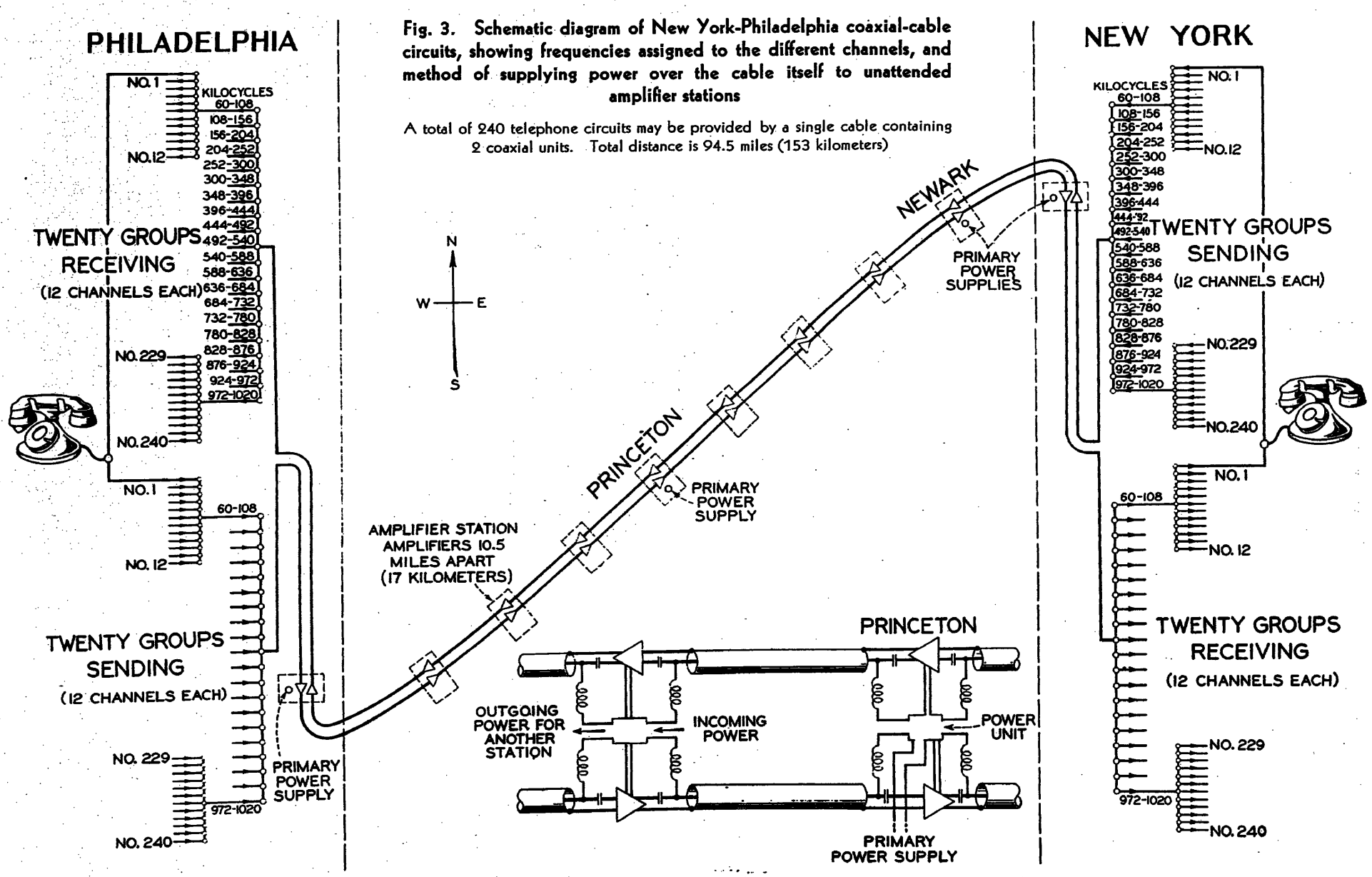


**Fig. 3. Schematic diagram of New York-Philadelphia coaxial-cable circuits, showing frequencies assigned to the different channels, and method of supplying power over the cable itself to unattended amplifier stations**

A total of 240 telephone circuits may be provided by a single cable containing 2 coaxial units. Total distance is 94.5 miles (153 kilometers)



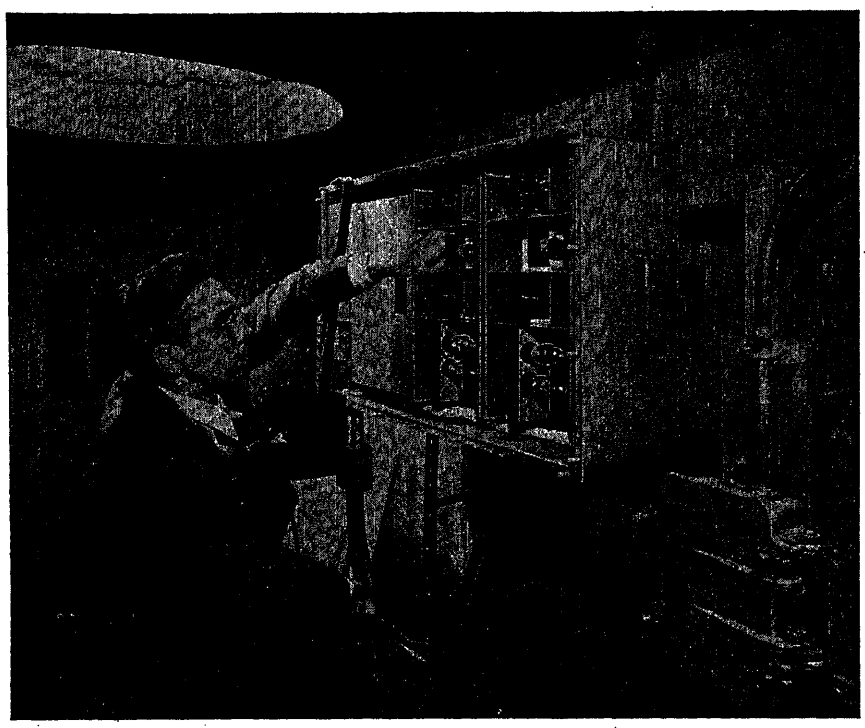


Fig. 4. Million-cycle repeater mounted in a manhole

one conductor to the other or to outside interference. Inasmuch as the most severe requirement is that of cross talk from one coaxial unit to another, this has been used as a criterion of design. Figure 6 shows the average meas-

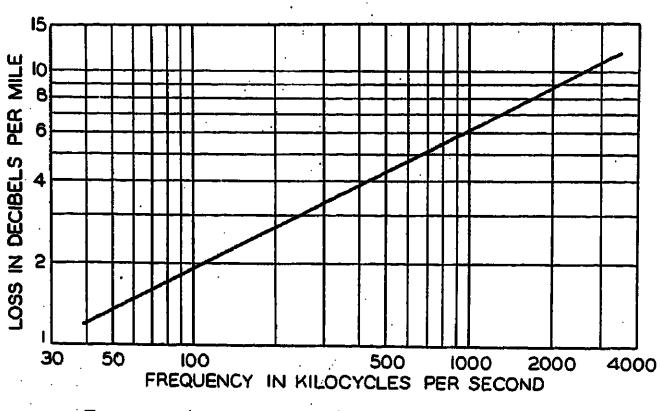



Fig. 5. Attenuation of the coaxial conductor

ured high-frequency cross talk in this particular cable on a 10-mile length without repeaters, both near-end and far-end.

## Repeaters

The amplifiers used in this system were designed for about a 10-mile spacing and a frequency range of 60 to 1,024 kilocycles. A total of 10 complete 2-way repeaters has been provided, including those at the terminals. Two of the intermediate repeaters are at existing repeater stations along the route, the other 6 being at unattended locations along the line. Four of these are in existing manholes, while the other 2 were placed above ground for a test of such operation. Figure 4 shows a manhole repeater with the cover removed for routine replacement of vacuum tubes. Figure 8 shows one of the installations above ground.

The measured gain of a typical repeater is shown by the points on the curve of figure 7. The curve itself is the line loss that the repeater is designed to compensate. Three stages of pentodes are used with negative feedback around the last 2 stages. Attenuation changes due to temperature of the line are compensated automatically by a pilot channel device which has been installed at every second or third repeater. The regulating mechanism uses 4 small tubes and is added to the normal repeater when desired. The amplifiers shown in figure 8 are regulating. As the cable is underground, the temperature changes are very slow and but meager data on the accuracy of compensation are yet available.

## Terminals

The New York and Philadelphia terminals of the cable have each been equipped to handle 36 2-way telephone conversations. As may be remembered, the scheme

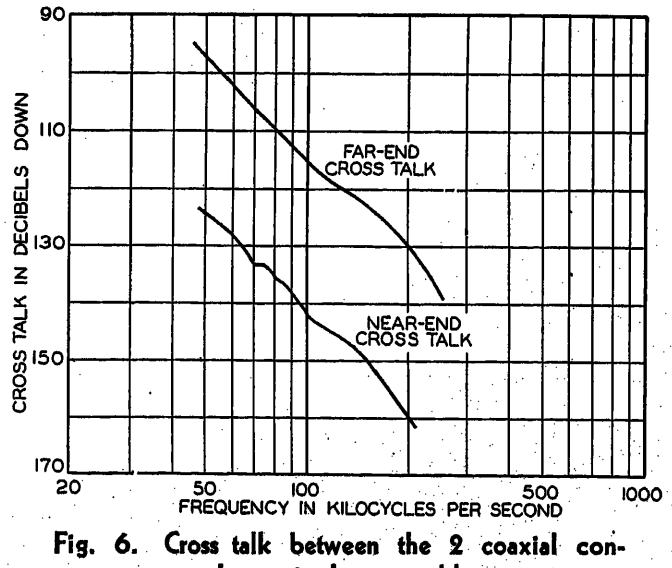



Fig. 6. Cross talk between the 2 coaxial conductors in the new cable

employed involves 2 steps of modulation, the first of which is used to set up a 12-channel group in the frequency range from 60 to 108 kilocycles. Three such groups have been provided in this installation. In order

to transmit at the higher frequencies, a second step of modulation is used in which an entire 12-channel group is moved to the desired frequency location by a "group" modulator. Six such group modulators have been provided at various frequencies throughout the range, including both the top and bottom. Patching facilities have been provided so that any 12-channel group may be transmitted over any one of the high frequency paths. A typical frequency characteristic of one of the channels is shown in figure 9. It may be observed that relatively high quality has been obtained, due largely to the use of crystal filters, even though the channels are spaced throughout the frequency range at 4,000-cycle intervals.

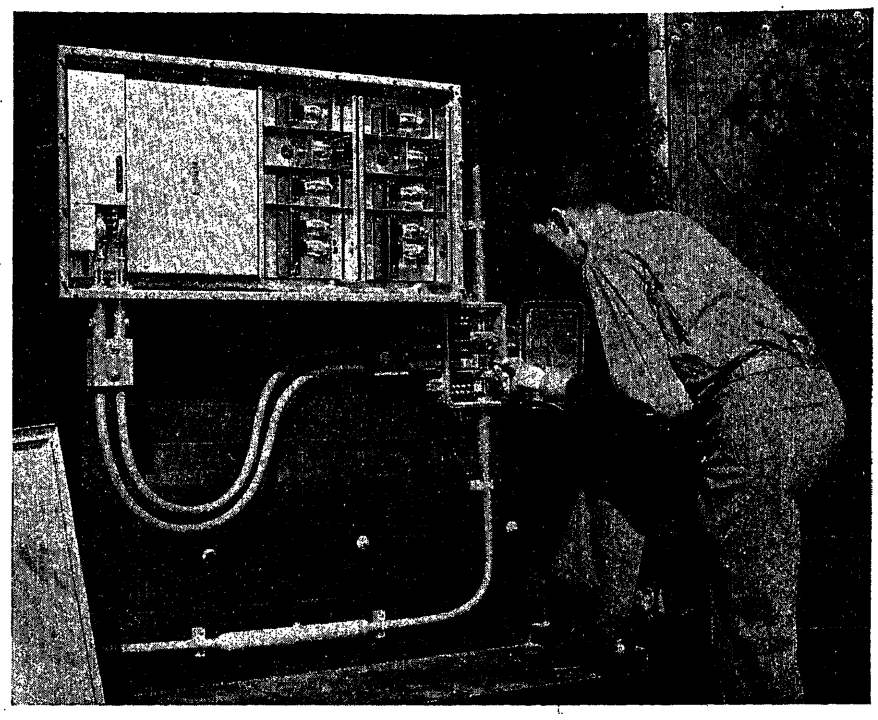


**Fig. 8. Installation of coaxial repeater above ground**

## Preliminary Tests

As already noted, various long circuits have been built up by looping back and forth through the coaxial system. One setup over which conversations were successfully carried out consisted of 5 voice-frequency links in tandem, each link being 760 miles long, giving a total circuit length of 3,800 miles. This setup included, in each direction, 70 stages of modulation and the equivalent of 400 line amplifiers, the transmission passing 20 times through each one of the 20 one-way line amplifiers constituting the 10 2-way repeaters.

This demonstrated that the complete assemblage of

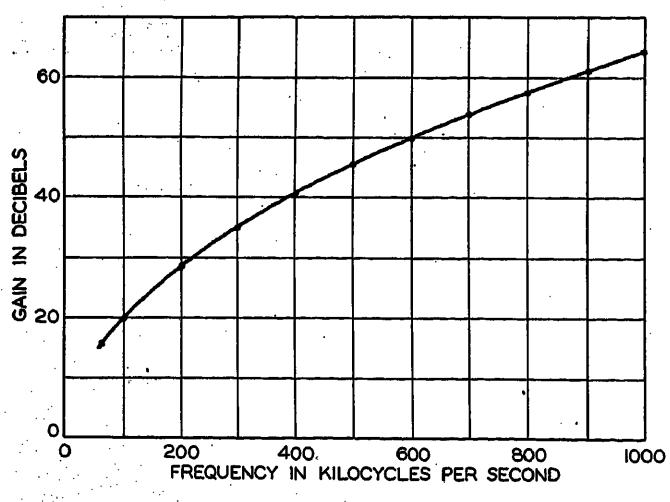



**Fig. 7. Gain-frequency characteristic of coaxial repeater**

parts, including filters which divide the frequency range into the required bands, modulators which produce the necessary frequency transformations, and amplifiers which counteract the line attenuation, introduced very little distortion. Many problems require further consideration, however, before these systems will be ready for design and production for general use. The final systems must have such refinement that they are suitable

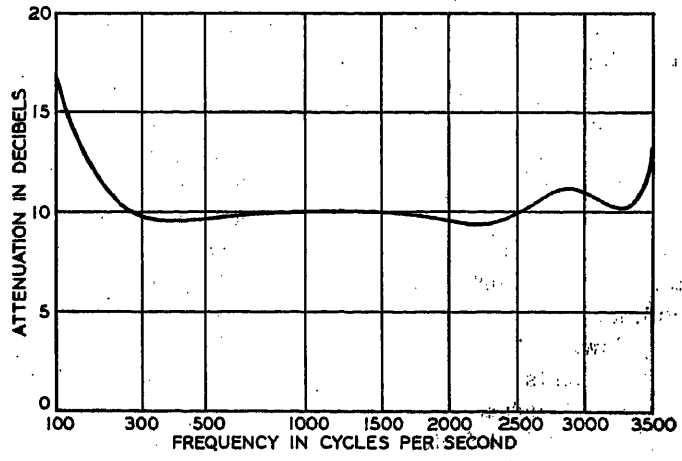



**Fig. 9. Frequency characteristic of a typical speech channel**

for transcontinental distances; the tremendous amplifications needed for such distances must have very precisely designed regulation systems, particularly where aerial construction is involved; noise and cross talk must not accumulate over the long distances; the repeaters must have such stability and reliability that continuity of service will be assured with hundreds of repeaters operating in series and each repeater handling several hundred different communications.

# Abrasion—A Factor in Electrical Brush Wear

By V. P. HESSLER
ASSOCIATE AIEE

**An investigation of the effect of abrasion upon electrical brush wear is reported in this paper. Tests of the rate of wear of anode and cathode brushes, and of brushes carrying current and those that did not, show that abrasion is an important factor in electrical brush wear.**

A BRIEF résumé of the literature on electrical brush wear was reported by the author in a previous paper.[1] A more complete review of this literature has also been reported by the author in another publication.[2] In the interest of brevity, these publications will be assumed to be available to the reader. The investigations reported in this paper represent an extension of the previous work, all of which has been carried on under the auspices of the Iowa Engineering Experiment Station. In the previous investigations the brushes were operated with the anode and cathode brushes (throughout this paper the brush at which the conventional current flow is from the brush to the ring is called the anode brush) on separate paths, for the purpose of obtaining fundamental information concerning the wear of brushes at different polarities. These experiments have been extended to include the condition of brushes tracking and brushes trailing. That is, with brushes tracking, the anode and cathode brushes are both operated on the same path; with brushes trailing, a brush not carrying current is operated on the same path with a current-carrying brush.

The situation of brushes tracking on a drawn copper ring duplicates the arrangement of a d-c commutator rather closely; however, the more important reason for making such a test was to ascertain the effect of the ring surface upon anode and cathode brush wear. The previous investigations indicated a very pronounced polarity effect, but there was nothing in the data to indicate whether the difference in the rates of wear of the anode and cathode brushes was caused by a ring-surface condition, a brush-surface condition, or by the direction of current flow.

The results of the tests with the brushes not tracking and with brushes tracking indicated that abrasion might be an important factor in electrical brush wear; consequently a series of tests was run with brushes trailing, with the hope of evaluating the magnitude of this factor in brush wear. It was assumed that if a brush carrying current were operated on the same ring simultaneously with a brush not carrying current, both might lose material at the same rate as a result of abrasion, while the current-carrying brush would lose additional material as a result of the current flow. This assumption proved to be substantially correct.

## Apparatus Used in the Tests

All of the tests were made upon drawn electrolytic-copper rings. The rings were rolled from strip copper, brazed on the inside of the hoop and pressed upon cast aluminum disks. The rings were turned true and finished with the shaft rotating in its own bearings, so it was possible to maintain the ring eccentricity below 0.0005 inch.

The brush holders were of the radial type. The dimensions of the brushes were 1/2 by 1/2 by 2 inches. It was realized that a brush of these dimensions in a radial brush holder might be subject to chatter, but it caused no apparent difficulty. The brushes were fitted very closely, and the rings were always rotated in the same direction. Double surfaces were observed on the brush faces only during the running-in period. The brush holders were mounted 90 degrees apart on vertical and horizontal diameters. The rings were always rotated in the direction from the lower brush to the upper brush, because the author thought that less of the material abraded from the preceding brush would be carried under the following brush with such an arrangement.

Some of the physical characteristics of the brush materials are given in table I. The tests ordinarily were conducted on 4 rings simultaneously. The 4 pairs of brushes were connected in series and the group connected to an 80-volt d-c generator through a variable resistor. By dropping a large part of the circuit voltage in the variable resistor and operating the generator under conditions corresponding to a point high on its saturation curve it was possible to maintain a constant circulating current through the brushes.

**Table I—Physical Constants of Brush Materials**

| Brush Grade | Resistivity, Ohm-Inches | Hardness (Scleroscope) | Transverse Strength, Pounds Per Square Inch | Normal Current Density, Amperes Per Square Inch | Type of Material |
|---|---|---|---|---|---|
| *A* | 0.0020 | 65 | 3,600 | 55 | Electrographitic lampblack |
| *B* | 0.00225 | 54 | 2,960 | 60 | Electrographitic lampblack |
| *C* | 0.00106 | 40 | 3,500 | 45 | Carbon graphite |
| *D* | 0.00142 | 40 | 3,500 | 45 | Carbon graphite |
| *E* | 0.0000064 | 20 | 4,900 | 115 | Metal graphite |
| *F* | 0.000010 | 16 | 4,000 | 100 | Metal graphite |
| *G* | 0.00000242 | 5 | 9,700 | 150 | Heavy metal graphite |
| *H* | 0.0014 | 76 | | 65 | Electrographitic |
| *I* | 0.0013 | 60 | | 65 | Electrographitic |

A paper recommended for publication by the AIEE committee on electrical machinery. Manuscript submitted September 28, 1936; released for publication November 27, 1936.

V. P. HESSLER is assistant professor of electrical engineering at Iowa State College, Ames. The author wishes to express his appreciation to the National Carbon Company and the Morganite Brush Company for furnishing the brushes which were used in the tests.

1. For all numbered references see list at end of paper.

The temperature and humidity were maintained constant throughout the tests by means of automatically controlled air-conditioning equipment. The atmosphere was kept as nearly dust free as possible by means of a specially designed dust collector, but no attempt was made to make quantitative measurements of the dust condition.

The rate of wear was determined by measuring the length of the brushes at the beginning and again at the end of a run by means of a micrometer with an electrical contact arrangement. The rate of wear is represented by the ratio of the change in length during the run to the duration of the run. The unit "inches per 100,000 hours" was chosen simply for ease of calculation and presentation of the data. A rate of wear of 11.4 inches per 100,000 hours is equivalent to a life of one year per inch.

The data on contact drop were obtained by means of an auxiliary copper-leaf brush, which was lowered to the ring whenever readings were desired. Each test brush was equipped with a potential lead to eliminate errors caused by the shunt voltage drop, and the contact voltage drop was corrected for the voltage drop through the brush material.

A more complete description of the apparatus is included in a previous paper on brush wear.[1] The same apparatus, except for a few minor changes in brush-holder mountings, was used in these tests.

## Test Procedure

The brushes always were sanded carefully and run for several hours with a nominal current before any readings were taken. The rings were sanded at the beginning of each series of tests and then not cleaned again until the beginning of the next series of tests. The temperature and the relative humidity were held constant at 45 degrees centigrade and 50 per cent, respectively, throughout the

**Fig. 1. Curves showing rate of wear and contact voltage drop with brushes tracking**

Ambient temperature—45 degrees centigrade
Relative humidity—50 per cent
Ring material—Copper
Brush material—Electrographitic lampblack, designated as material *A* in table I
Ring speed—3,500 feet per minute
Brush pressure—3 pounds per square inch

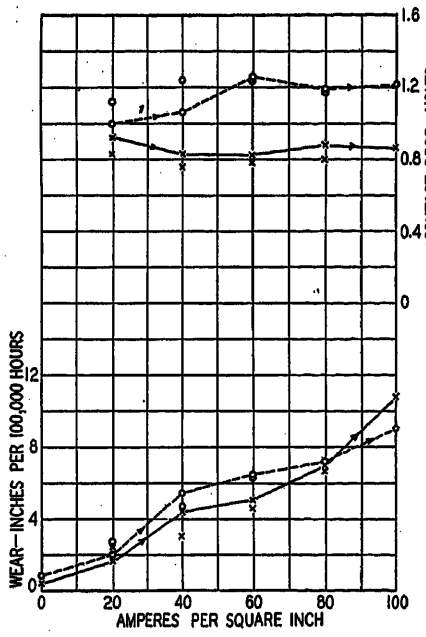



**Fig. 2. Curves showing rate of wear and contact voltage drop with brushes tracking**

Test conditions identical with those of figure 1, except that the brush material was of the grade designated *B* in table I

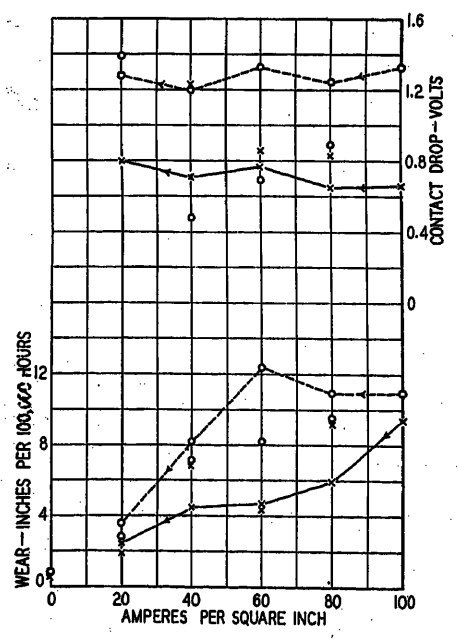



**Fig. 3. Curves showing rate of wear and contact voltage drop with brushes tracking**

Test conditions identical with those of figure 1, except that the brush material was of the grade designated *C* in table I

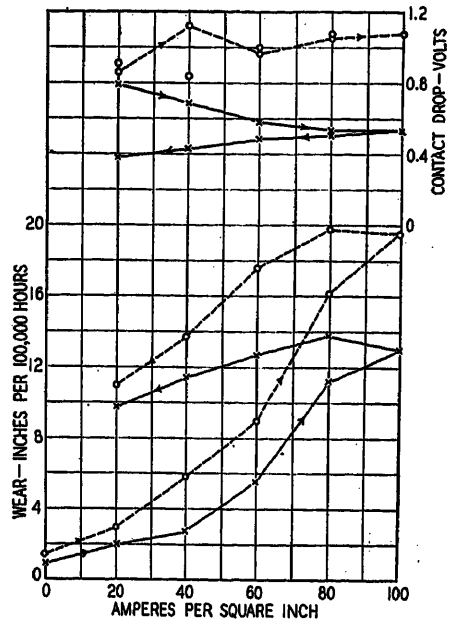
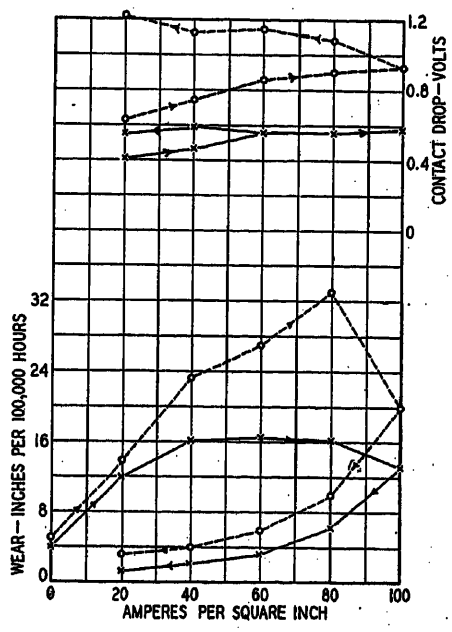



**Fig. 4. Curves showing rate of wear and contact voltage drop with brushes tracking**

Test conditions identical with those of figure 1, except that the brush material was of the grade designated *D* in table I



tests. Ring speed was 3,500 feet per minute and brush pressure 3 pounds per square inch. The curves of contact voltage drop represent the average of several readings taken at intervals throughout the period of operation at a given current density. The equipment was run approximately 24 hours to obtain the data for each point on the wear curves.

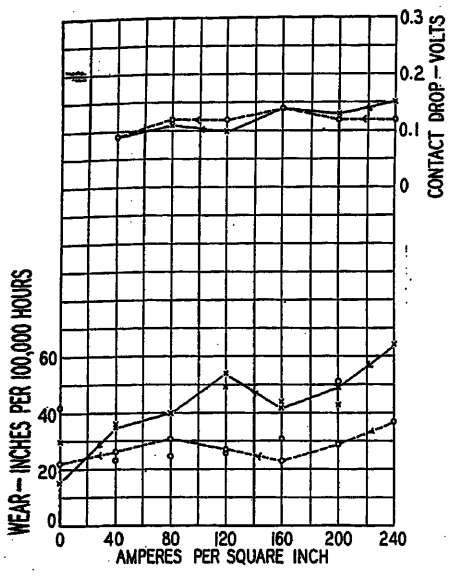



**Fig. 5. Curves showing rate of wear and contact voltage drop with brushes tracking**

Test conditions identical with those of figure 1, except that the brush material was of the grade designated *E* in table I

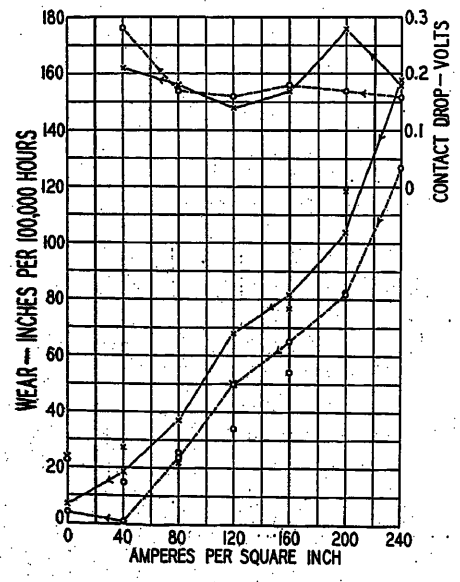



**Fig. 6. Curves showing rate of wear and contact voltage drop with brushes tracking**

Test conditions identical with those of figure 1, except that the brush material was of the grade designated *F* in table I

The experiments with brushes tracking simply consisted of arranging 2 brushes on the same path of a given ring and obtaining wear and contact voltage drop data. The arrangement was somewhat more involved in the case of brushes trailing, for which 4 brushes were mounted on each ring in such a manner that a pair of brushes operated on each of 2 ring paths. The electrical circuit was arranged to carry current through one brush of each pair, to reverse the current through the first 2 brushes, or to connect to the other 2 brushes on a given ring. This arrangement made it possible to observe whether the results obtained were peculiar to a given brush and holder or could be duplicated on other brushes. Also it gave some idea of the time required for changes in film formation to take place. The sequence of readings represents approximately 24-hour periods of operation. In all trailing tests, except for figures 12 and 13, identical brushes were used in all 4 positions on the ring. The tests for figures 13 and 14 were conducted with one metallic brush and one nonmetallic brush on each path, for the purpose of studying whether the higher rate of wear of metallic brushes results from a more abrasive ring path or from the mechanical structure of the metallic brush.

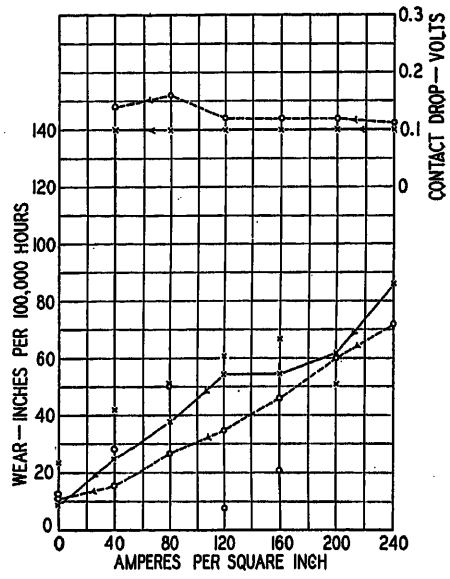



**Fig. 7. Curves showing rate of wear and contact voltage drop with brushes tracking**

Test conditions identical with those of figure 1, except that the brush material was of the grade designated *G* in table I

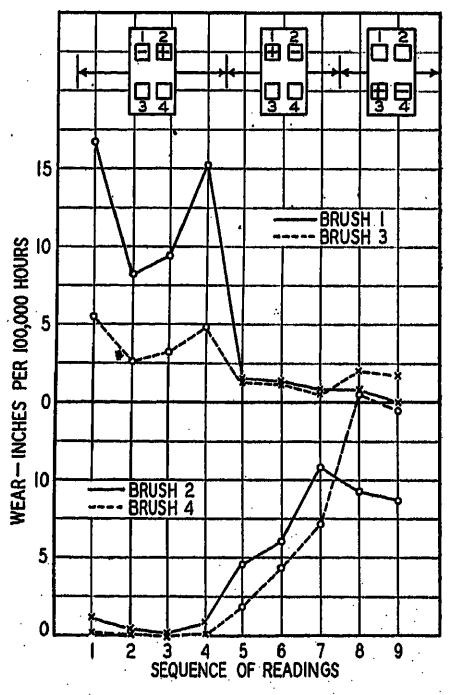



**Fig. 8. Curves showing rate of wear with brushes trailing**

Ambient temperature—45 degrees centigrade
Relative humidity—50 per cent
Ring material—Copper
Brush material—Electrographitic lampblack, designated as material *H* in table I
Ring speed—3,500 feet per minute
Brush pressure—3 pounds per square inch
x—Anode brush
o—Cathode brush

## Results of Tests

All of the test results are given in the form of curves in figures 1 to 13. The arrows on the curves of figures 1 to

7 indicate the sequence in which the tests were made. For example, in figure 3, tests were started at zero current; the current was increased to 100 amperes per square inch and reduced to 20 amperes per square inch by 20-ampere increments. For most cases only the descending or ascending curves are shown. The experimental points not connected by curves represent the other values.

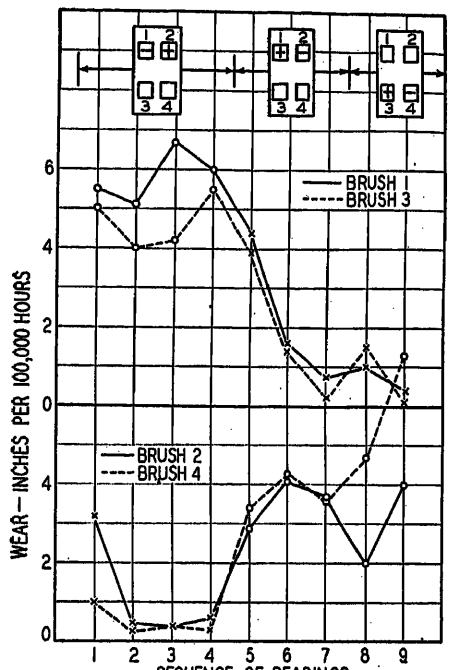



**Fig. 9. Curves showing rate of wear with brushes trailing**

Test conditions identical with those of figure 8, except that the brush material was of the grade designated *I* in table I

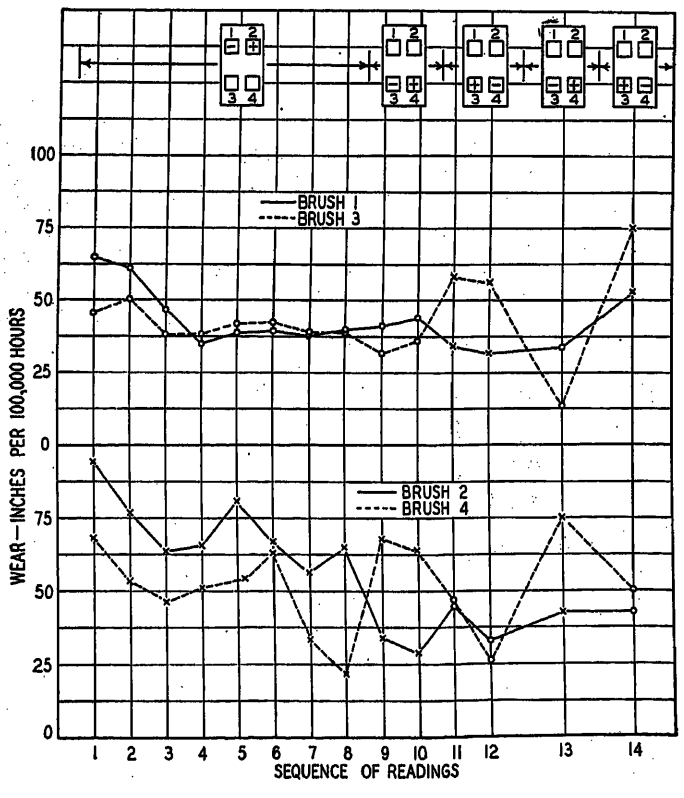



**Fig. 10. Curves showing rate of wear with brushes trailing**

Test conditions identical with those of figure 8, except that the brush material was of the grade designated *E* in table I

Figures 1 to 7 represent the results of the tests with brushes tracking

The results for various brush materials with brushes trailing are given in figures 8 to 13. The boxes at the top of each figure represent the electrical connection and mechanical arrangement of the 4 brushes on a ring. The minus sign indicates the cathode brush and the plus sign the anode brush. For example, the left box in figure 8 indicates that brushes 1 and 3 are operating on the same

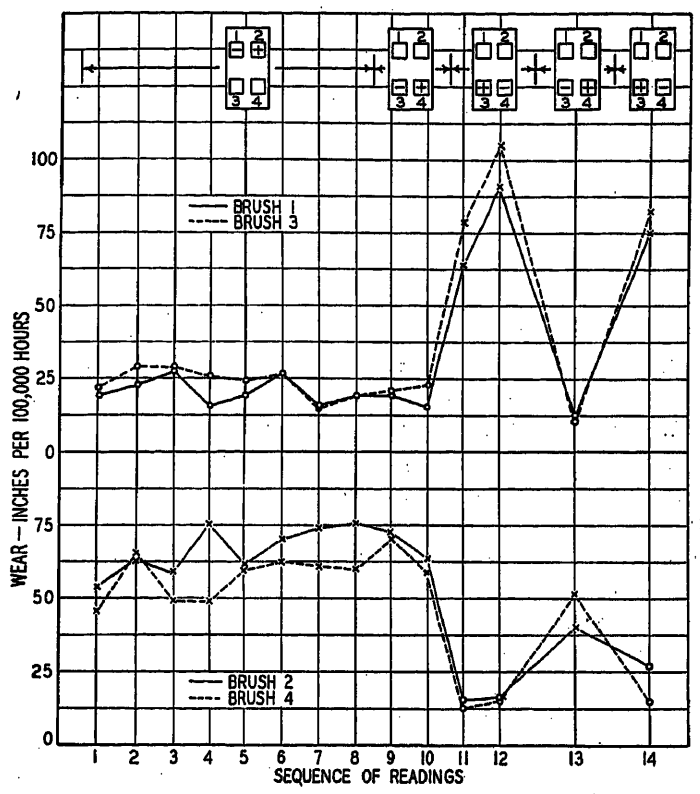



**Fig. 11. Curves showing rate of wear with brushes trailing**

Test conditions identical with those of figure 8, except that the brush material was of the grade designated *F* in table I

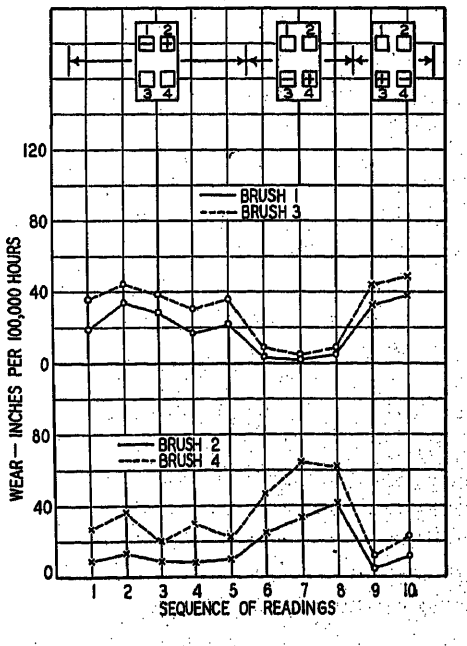



**Fig. 12. Curves showing rate of wear with brushes trailing**

Test conditions identical with those of figure 8, except that brushes 1 and 2 were of grade *I* and brushes 3 and 4 were of grade *F*

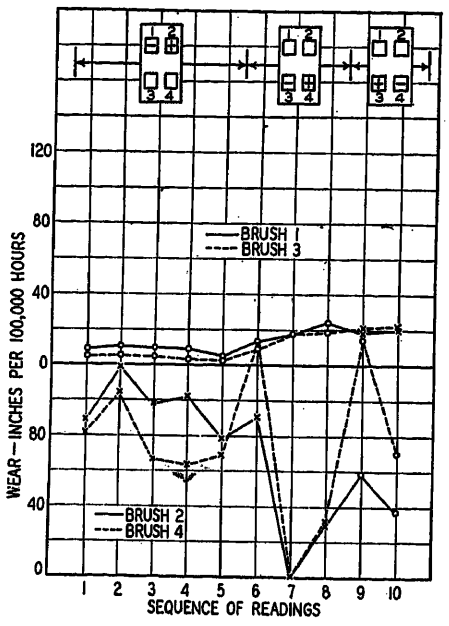



**Fig. 13. Curves showing rate of wear with brushes trailing**

Test conditions identical with those of figure 8, except that brushes 1 and 2 were of grade *F* and brushes 3 and 4 were of grade *I*

path, with brush 1 as the cathode-current-carrying brush, and brushes 2 and 4 are operating on the other path of the same ring with 2 as the anode brush. Readings 1, 2, 3, and 4 were obtained with this arrangement. For readings 5, 6, and 7 the polarity of the current-carrying brushes was reversed. For readings 8 and 9 the current was shifted to the other 2 brushes. As stated previously, the same grade of brush was used in all 4 positions in the tests of figures 8 to 11. The tests of figures 12 and 13 were conducted with one metallic and one nonmetallic brush on each path.

## Interpretation of Results

Even the most casual comparison of figures 1 to 7 with the curves of the previous paper[1] indicates that there is a fundamental difference between operating brushes tracking and not tracking. With brushes of both polarities operating on the same path practically all of the difference in wear which was previously observed disappears. This seems to indicate that the more rapid wear of the carbon or graphite cathode brush was caused by a ring-surface condition set up as a result of current flow. Photomicrographs of ring surfaces show this supposition to be correct. Figure 14*a* and 14*b* show characteristic ring paths as produced by graphite anode and cathode brushes, respectively. The anode-brush path was very smooth, whereas the cathode-brush path was so rough that the peaks and valleys could not be brought into focus simultaneously.

The reader may note that the arrows are reversed on the wear curves of figures 3 and 4. These curves were obtained simultaneously on separate rings mounted upon the same shaft; therefore, any explanation would have to be made in terms of the ring or brush materials. No difference in operation has been observed between the various drawn copper rings used in the tests. Previous tests have shown that the rate of wear of certain brush grades decreases as the brushes are "run in" whereas others increase during the running-in period. In each case the ring may present a satisfactory uniformly polished appearance. No doubt, the same phenomenon has occurred in figures 3 and 4.

The results presented in figures 8 to 13 show definitely that brush wear is largely abrasion resulting from a ring-surface condition set up by current flow. In general, the trailing brush wears at almost the same rate as the current carrying brush. The sequence of readings from 4 to 7 in figure 9 indicates that a surface condition affecting the rate of wear is being established. If the wear were purely electrical, the reversal would take place in a much shorter period.

It is interesting to note that in several instances in figures 10 and 11 the trailing metallic brush wears more rapidly than the current-carrying brush. The sequence of readings from 10 to 14 in figure 11 shows in a very striking manner the polarity effect on metallic brushes.

Figures 12 and 13 show that even for widely dissimilar materials the wear of the trailing brush is governed by the nature and polarity of the current-carrying brush. The decrease in wear from reading 6 to 7 in figure 13 was caused by cleaning the ring.

After showing that brush wear is largely abrasion it was thought that it might be reduced by burnishing or polishing the ring continuously. This was attempted with a cotton tape, which reduced brush wear by about 60 per cent in the first tests. However, it was not possible to obtain these results consistently. An attempt to obtain better results with the aid of certain fine abrasives resulted in tremendously increased rates of brush wear.

The foregoing results suggest using metallic and nonmetallic brushes on the same path to reduce brush wear, but no commercial machine seems to be adaptable to such an arrangement. The metallic brush would not commutate a high-voltage machine and the nonmetallic brush would not have the current-carrying capacity for a low-voltage machine.

An interesting study of brush wear in hydrogen and in air was made by Baker and Hewitt[3] in which they found that brush wear in air was many times that in hydrogen. It would be very instructive to repeat these tests with a trailing brush on each path to ascertain the effect of abrasion in these tests.

(*Concluded on page 16*)

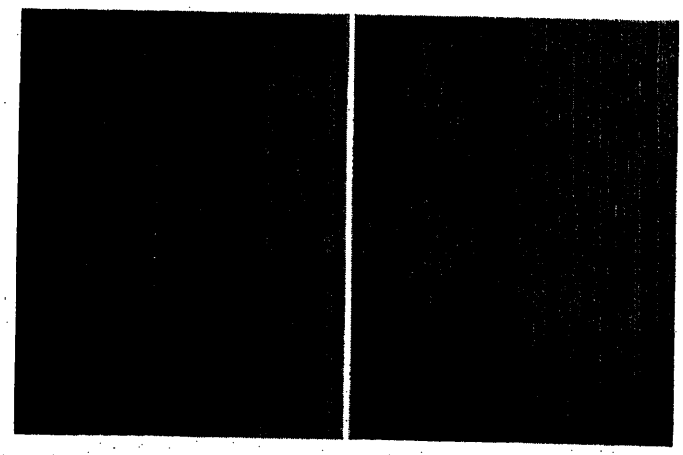


**Fig. 14. Photomicrographs of ring surfaces**

Left—Path of anode brush. Right—Path of cathode brush

# Lightning Protection for Transmission Lines

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**To meet the need for lightning protection on low-voltage transmission lines at moderate cost, and particularly for wood-pole lines, a design is presented in this paper that has high insulation strength and uses, in place of a ground wire, a shielding phase conductor with a lightning protector tube. Lightning currents are drained to ground with a minimum number of tubes of low current rating.**

THE RESULTS of many years of lightning-research work have been applied to steel-tower transmission lines with great improvements in operating results. In general, there has been less accomplished in improving wood-pole line design. The records of the company with which the writers are associated show lightning outages on unprotected wood-pole lines to be 48 per 100 miles of line per year as compared to a rate of 5 for steel-tower lines with 2 ground wires. Such relatively poor performance shows the need for improved protection.

Early investigators attempted to prevent line outages by increasing insulation. Measurements of stroke currents indicate that some outages can be prevented by over-insulation but that obtaining reliable operation by the use of high insulation is costly and impractical.

The most widely used form of protection consists of ground wires to intercept all direct strokes. These are very effective when properly installed with adequate clearances and low-impedance ground connections. In many cases, however, the cost of the extra wire and of enlarging the structures for increased clearances and heavier loading cannot be economically justified. Particularly in the case of wood construction, low-resistance grounds may be difficult and expensive to obtain. In addition, unless special precautions are taken, the ground lead will render useless a portion of the normal wood insulation. The use of additional wires and larger structures naturally increases construction and maintenance costs.

A recent and increasingly popular protection scheme consists in the installation of lightning protector tubes[1,2] to drain surge currents from the phase wires and extinguish the resulting power arc. It is customary to install a tube for each phase on protected structures. Where ground resistances are low, strokes to one wire will cause phase-to-ground faults. Where more than one wire is struck or where ground resistances are high, the tubes will have to interrupt phase-to-phase short-circuit currents. On power systems using neutral resistors or reactors, co-ordination may be difficult since present tubes are effective only within a limited range of short-circuit currents. A given tube will not interrupt currents below its rating and will fail because of excessive internal pressures on currents in excess of its rating. In general, tubes are effective, although a large number are required to secure protection on lines with short span lengths and high ground resistances.

## Summary

Without departing radically from present practices with wood-pole lines, a design is proposed for improved lightning performance. Use is made of wood insulation and a shielding conductor with lightning-protector tubes. Computation methods are shown so that the recommendations may be adapted to local conditions. It may be concluded that:

1. It is possible on low-voltage transmission lines to secure at moderate cost a large reduction in lightning outages.
2. It is possible to secure the advantages of a ground wire without the cost of the additional wires and heavier structures.
3. Protection may be secured by the use of low-rating lightning-protector tubes on one phase of a 3-phase circuit.
4. A method of protection is presented which may be used on higher voltage lines with economies resulting from the elimination of ground wires.
5. With the assumptions used and by using a standard pole top the proposed design shows an estimated reduction in lightning outages of approximately 75 per cent.

## Proposed System of Protection

The proposed design is an attempt to secure at moderate cost a line combining the advantages of the 3 present protection methods as follows:

1. One phase of each circuit is made a shielding conductor by locating it so that the remaining phases will be shielded from direct strokes.
2. Lightning currents are drained from the shielding conductor by means of a lightning-protector tube.
3. The remaining phases are isolated from the shielding conductor and tube ground circuit by insulation sufficient to prevent phase-to-phase faults. This allows the use on each structure of a single tube designed to withstand only phase-to-ground currents which, in general, are much less than phase-to-phase currents.

## Construction Features

Figure 1 shows the described features incorporated in a single-circuit wood-pole top. The location of

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1. For all numbered references see list at end of paper.

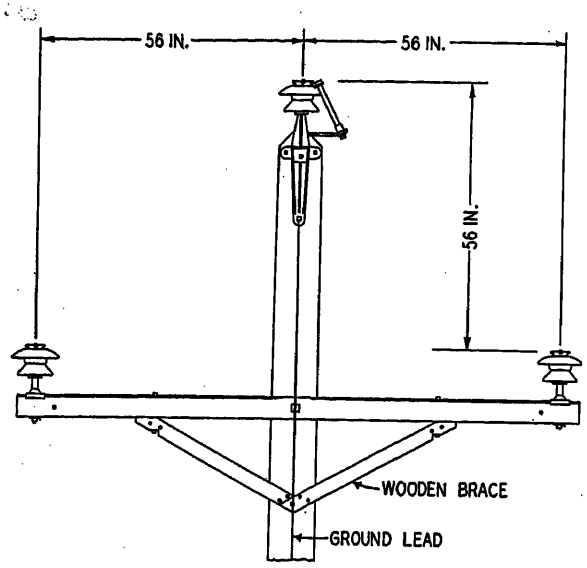



**Fig. 1 (left). Single - circuit pole showing shielding conductor and lightning protector tubes**

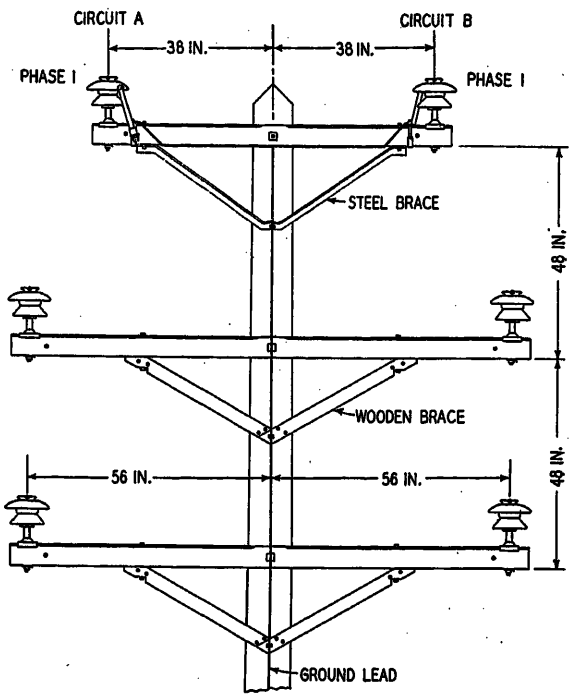



**Fig. 2 (right). Double - circuit pole showing shielding conductor and lightning protector tubes**

the shielding conductor with reference to the other phase wires may be determined by use of the conventional shielding angle[3] or by assuming a cloud height and considering the distances to the line conductors.[4] For a structure of the size shown the shielding-angle method was used as giving the more conservative results.

To prevent flashovers between the tube ground lead and the lower phase wires without excessively close tube spacings requires the use of insulation having high impulse strength. In the design shown this is obtained by the use of wooden crossarm braces. The breakdown strength for the combination shown is 645 kv at 4 microseconds. Insulation values for other desired forms of construction may be obtained from an earlier paper.[5] For most practical designs only the breakdown strength of the insulators and wood need be considered since it is lower than that of the direct path through air.

The tube is placed as shown so as to drain lightning currents from the shielding conductor to ground. The mounting arrangement must be such that the breakdown of the tube and associated gap is at all times less than that of the insulator and the wood between the insulator pin and tube mounting.

The single-circuit pole top may be expanded to provide for an additional circuit as shown in figure 2. The same clearances are maintained and tubes are installed on the 2 top shielding conductors. It is important that the same phase of each circuit be on the top arm so that, in the event of a stroke involving the top 2 conductors, the tubes will not be required to interrupt phase-to-phase currents.

## Distance Between Protected Poles

The expected number of outages and the magnitude of lightning strokes to a line[6] in a territory with an isokeraunic level of 30 are shown in figure 3. While this curve is for a steel-tower line with 2 ground wires, it may be used without serious error for a wood-pole line. This curve is used to find the line performance for an equivalent lightning level. For example, a design for strokes up to 4,000 kv gives an expected

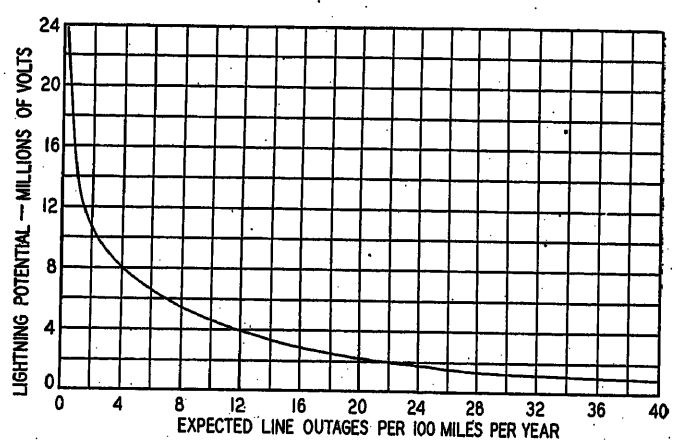



**Fig. 3. Expectancy curve of lightning outages**

outage rate of 12 per 100 miles per year as compared with a rate of 48 for an unprotected line, a reduction in outages of 75 per cent.

Assuming a surge impedance of 200 ohms for the lighting channel and 4,000 kv as the stroke potential, the stroke current is 20,000 amperes. Since the ground current theoretically may reach double this value, it is necessary to use a tube heavy enough to withstand 40,000 amperes surge current.

A computation of the voltages appearing on the shielding conductor for a stroke to a protected pole involves the use of a rate of voltage rise in the stroke. A rate of 1,000 kv per microsecond is believed to be a value which should give conservative results. Neglecting the length of the ground lead, the initial voltage on the shielding conductor $E_L$ at the struck pole is

$$E_L = E_{\text{stroke}} \times \frac{2Y_0}{Y_0 + 2Y_1 + Y_2} = E_s b_0$$

where

$Y_0$ = surge admittance of stroke
$Y_1$ = surge admittance of shielding conductor

$Y_2$ = surge admittance of ground
$a$ is used for reflection factors
$b$ is used for refraction factors

Sufficiently accurate results are secured by considering only the reflections from the first 2 protected poles on each side of the struck pole. The reflection factor at the struck pole is

$$a_1 = \left(1 - \frac{2Y_1}{Y_0 + 2Y_1 + Y_2}\right)$$

The reflection factors at the first and second protected poles away are

$$a_2 = a_3 = \left(1 - \frac{2Y_1}{2Y_1 + Y_2}\right)$$

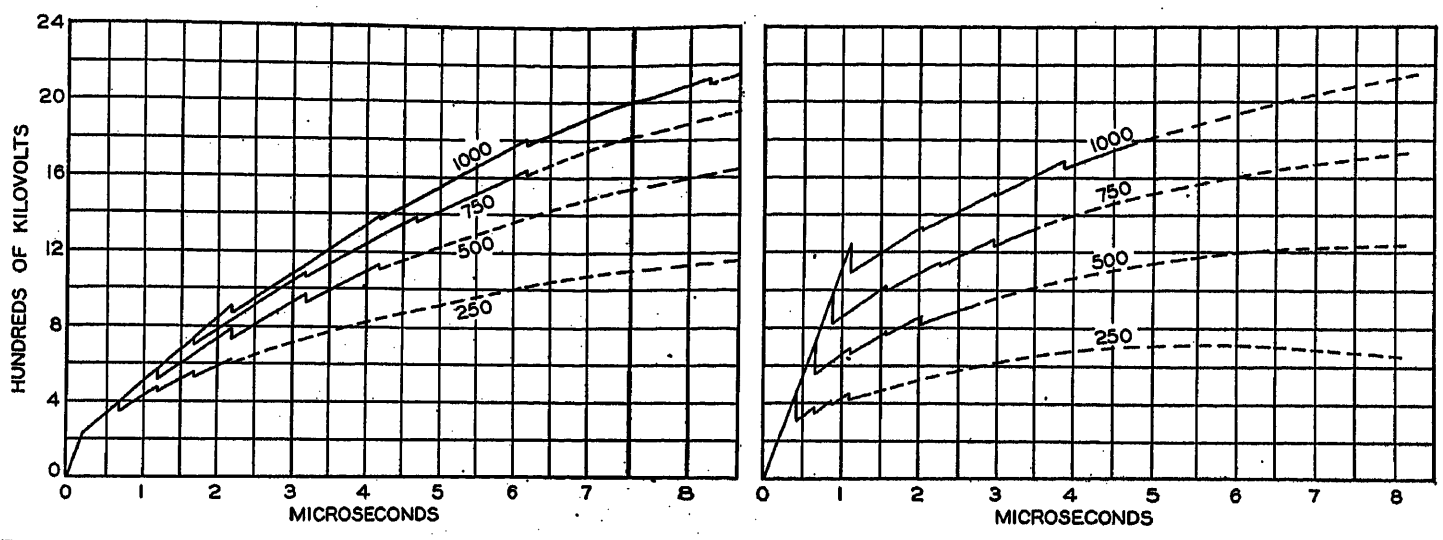
Similarly the refraction factors are

$$b_1 = \frac{2Y_1}{Y_0 + 2Y_1 + Y_2} \qquad b_2 = b_3 = \frac{2Y_1}{2Y_1 + Y_2}$$

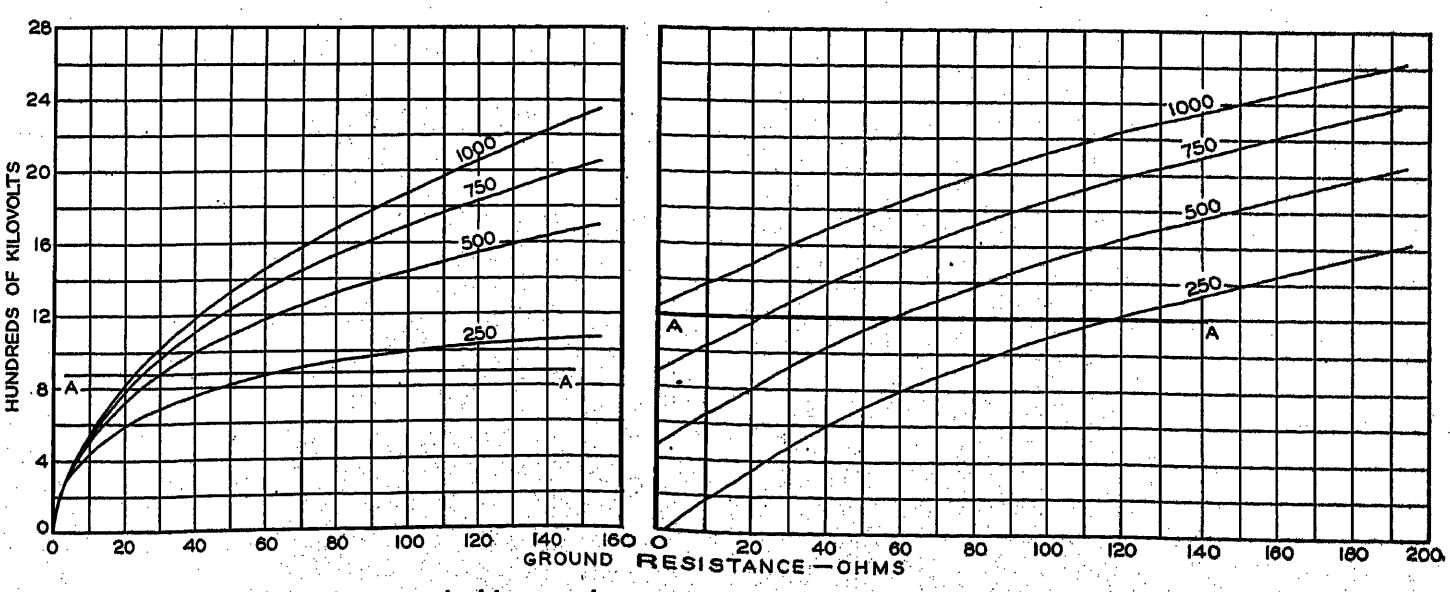
The reduction factors at the struck pole for successive reflections found by using the lattice method[4] are:

| Reflection | Reduction Factors |
|---|---|
| First | $A = -a_2b_1$ |
| Second | $B = a_2b_1(a_2b_1 - b_2^2 - a_1a_2)$ |
| Third | $C = a_2^2b_1(b_1b_2^2 + b_2^3 - 3a_1b_2^2 - a_2b_2^3 - a_2b_1^2 - a_1^2a_2)$ |
| Fourth | $D = a_2^2b_1(b_1b_2^4 + 4a_1a_2b_1b_2^2 + a_2^2b_1b_2 + a_2^2b_1b_2^2 + a_2b_1^3 + a_1^2a_2^2b_1 + a_1a_2b_2^2 - 2a_2b_1^2b_2^2 - a_1b_2^4 - 3a_1^2a_2b_2^2 - 2a_1a_2^2b_2^2 - a_2^3b_2^3 - a_2b_1b_2^2 - a_1a_2^2b_1^2 - a_1^3a_2^2)$ |

Where the rate of voltage rise $de/dt$ in the stroke equals 1,000 kv per microsecond, $d/1{,}000$ may be used for elapsed time in microseconds after the initial contact of the stroke with the shielding conductor where $d$ is the distance between protected poles (con-




**Figs. 4 and 5. Curves for voltage on shielding conductor for stroke to protected pole (left) and to unprotected pole (right)**
Ground resistance, 50 ohms; rate of voltage rise in stroke, 1,000 kv per microsecond; numbers on curves are distances between poles in feet




**Figs. 6 and 7. Curves for voltage on shielding conductor with stroke of 20,000 amperes to protected pole (left) and to unprotected pole (right) for various ground resistances**
Voltage required for flashover of unprotected pole shown by $AA$; numbers on curves are distances between poles in feet

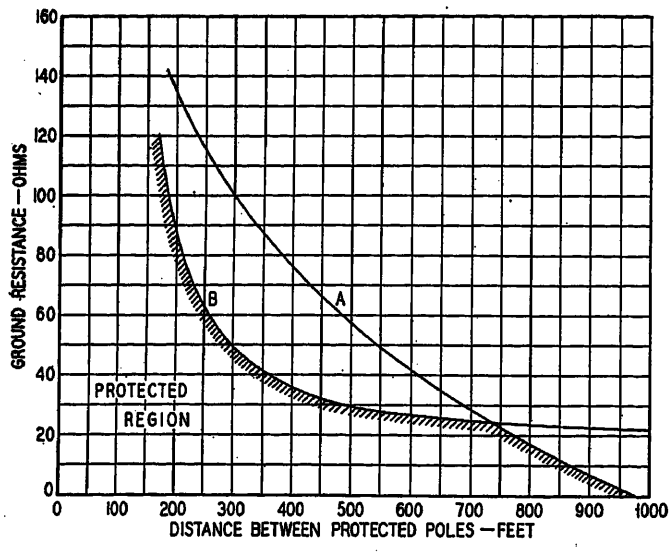



**Fig. 8. Curves showing relation between ground resistance and spacing of protector tubes**

*A*—Limit of protected region, unprotected pole
*B*—Limit of protected region, protected pole

sidering equal spacing) in feet. The voltage at the struck pole is:

$$E_L = \frac{d}{1{,}000} \times \frac{de}{dt} \times b_0$$

At time $t = 2d/1{,}000$

$$E_{2d} = 2E_L$$
$$E_{4d} = 4E_L - 4E_LA$$
$$E_{6d} = 6E_L - 8E_LA - 4E_LB$$
$$E_{8d} = 8E_L - 12E_LA - 8E_LB - 4E_LC$$
$$E_{10d} = 10E_L - 16E_LA - 12E_LB - 8E_LC - 4E_LD$$

With values obtained as shown, figure 4 was plotted for ground resistances of 50 ohms, giving the voltages at the struck pole as a function of time for various spacings of tubes. Curves for other values of ground resistance were calculated in a similar manner. In computing the curves the fact was considered that the voltage at the struck pole must rise to an appreciable value before tube breakdown occurs. This explains the small irregularities in the curves. For all practical purposes, after several reflections the effect of this factor is negligible.

A similar procedure was followed to obtain the voltages on an unprotected pole with a stroke to the shielding conductor at this point. These values are shown in figure 5.

With the assumed rate of voltage rise and a stroke potential of 4,000 kv, the maximum voltage is reached in 4 microseconds. Using values at this time from figures 4 and 5 for ground resistances of 50 ohms and from similar curves for other ground resistances, figures 6 and 7 were plotted to show the voltages appearing on the struck pole for strokes to the protected and unprotected poles. In order to determine the correct ground resistances and tube spacings for the proposed design, the impulse breakdown values of the insulation between the lower phase wires and the ground lead or ground are shown as straight lines on the curves. These values were increased by 30 per cent to allow for coupling between the shielding conductor and other phase wires. The intersections of the straight lines and the curves are plotted in figure 8 to show the maximum ground resistance for safe protection with given tube spacings. Local conditions will dictate whether it is more economical to use closely spaced tubes or to take steps to lower ground resistances.

It is realized that there may be some disagreement in regard to the assumptions made for these calculations but the values chosen are considered sufficiently conservative and accurate to give a co-ordinated installation. Future investigations will probably yield more accurate data but these should affect the figures for expected line performance rather than the fundamental design.

At the present time several 26-kv lines are being rebuilt incorporating the features of this proposed design. It is expected that these lines will be in operation during the coming lightning season so that some field experience will be obtained within a year.

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# Abrasion—A Factor in Electrical Brush Wear

(*Continued from page 12*)

## Conclusions and Results

The principal findings are as follows:

1. The wear of brushes on concentric rings is largely abrasion resulting from a ring condition established by the current flow.

2. The abrasive ring condition is caused by the cathode brush for carbon or graphite brush materials, but is caused by the anode brush in the case of metallic brush materials.

3. The abrasive action of the anode metallic brush path is much more pronounced than that of the cathode carbon or graphite brush path.

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# Inductive Co-ordination of Common-Neutral Power-Distribution Systems and Telephone Circuits

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**Early installations of 3-phase 4-wire power distribution systems of the multigrounded or common-neutral type in some cases created noise problems involving neighboring telephone circuits. Operating experience, studies of specific situations and comprehensive co-operative research over a period of years have developed means of largely avoiding difficulties of this character. The relative importance of various features of the power and telephone systems which have been found to affect the noise-induction problems involved is discussed here, and the general co-operative procedures most helpful in conversions to, or extensions of, these types of power distribution systems, are outlined.**

PRIOR to about 1915, delta-connected 2,300-volt 3-phase primary circuits were used extensively for the distribution of electric current. While some distribution networks throughout the country still operate in this manner, the marked increase in load densities, starting about 1915, often made the retention of the 2,300-volt delta system impracticable. In a few instances the development of the particular network was at a point where it was feasible to change from the 2,300-volt delta to a 4,600-volt delta arrangement, but in other cases the existing equipment represented too great an investment for a complete change of this character.

From studies of various methods of caring for the augmented load densities, it was found that the existing equipment could largely be saved and the capacity of the distributing networks substantially increased by converting them to a 2,300/4,000-volt star-connected 4-wire primary system. By about 1925 this system had extended to most of the larger cities and most power companies had found it economical to use in at least some parts of their territories.

In using the 2,300-volt equipment on the 4,000-volt 4-wire system it was necessary to stabilize the neutral conductor in some way. Most of the 4-wire systems had the neutral conductor grounded at the substation only, although sometimes low-voltage lightning arresters were placed on it at various points in the distribution network to aid in its stabilization in case of a break in it. In some instances, at the time of the installation of the 4-wire system, the primary neutral was connected at various points in the network to driven ground rods thus resulting in a multigrounded neutral system. In at least one instance the neutral conductor was not solidly grounded even at the substation, it being connected to ground through lightning arresters.

The experiences of the power companies with the multigrounded neutral were generally favorable. It was found to be more reliable and to embrace some simplifications over other distribution methods. While the early multigrounded neutral arrangements were obtained by making connections to ground along the primary neutral conductor and interconnecting it, at service transformers, to well-grounded secondary neutrals, a further simplification in the arrangement was readily apparent.

It will be noted in figure 1 that this interconnection of the primary and secondary neutrals resulted in 2 grounded neutrals on the pole line in all sections where the secondary neutral existed. In extending the multigrounded neutral arrangement or in reconstructing existing portions of the network, these 2 neutrals were combined into a single well-grounded conductor continuous in all portions of a feeder area and often continuous in all parts of a substation area or of several contiguous substation areas. This arrangement, called the "common-neutral," which was first extensively applied in Minneapolis, Minn., by S. B. Hood, resulted in certain savings in equipment and relief of congested pole heads and in a neutral network most effectively grounded since all secondary neutral grounds were thus made available, in addition to any driven grounds along the pole line.

The operation of this system in Minneapolis showed many advantages in the protection of secondary networks from the effects of voltage rises under abnormal conditions. In addition, a paper presented in 1925 by Mr. Hood[1] pointed out that over a period of 3 years the rate of transformer failure was reduced to $^{8}/_{10}$ of 1 per cent per annum. This excellent performance in transformers arose undoubtedly from the fact that with the "common-neutral" or interconnected neutral arrangements the lightning arresters are connected directly around the transformers. Later studies showed that the connection of the lightning arresters directly between the primary conductors and secondary neutral provides a degree of protection which cannot readily be obtained in any other way.[2–7]

In urban areas, the multigrounded or common-neutral method of distribution introduced, in some instances, noise induction in nearby telephone circuits. In view

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The authors wish to acknowledge their indebtedness to their many co-workers who aided in carrying on the various investigations on which this paper is based.

1. For all numbered references see list at end of paper.

of this fact an extensive co-operative investigation was undertaken by project committee No. 6 of the Joint Subcommittee on Development and Research of the National Electric Light Association and Bell Telephone System to determine the factors involved in the co-ordination of

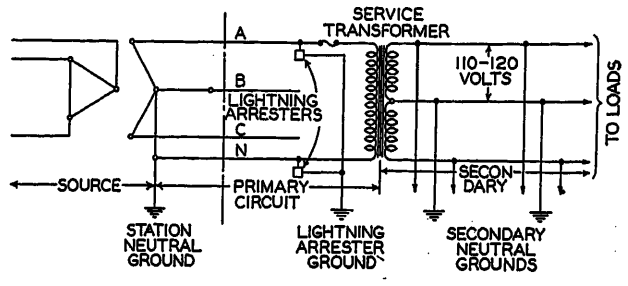



**Fig. 1A. Simplified feeder operating with primary neutral grounded at source only**

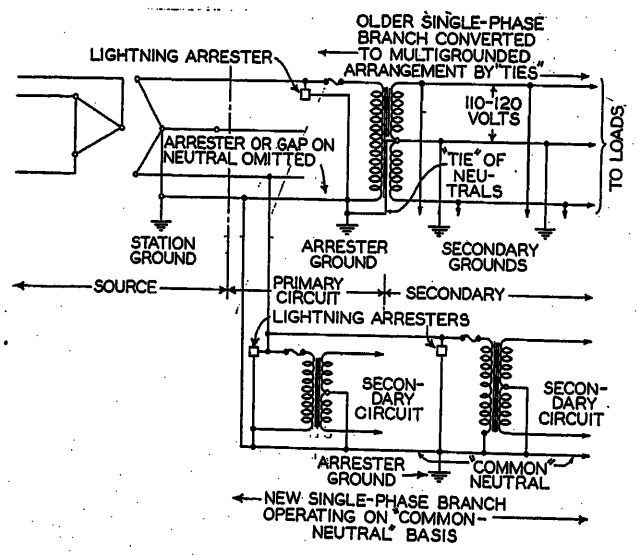



**Fig. 1B. Simplified feeder operating with multiple grounds on primary neutral—older part of feeder having ties between primary and secondary and new extensions being of common-neutral arrangement**

local power distribution systems and telephone systems. A study was carried out in Minneapolis during the years 1924–26 having as its primary objective the determination of the factors involved where the telephone distribution was largely in aerial cable. The investigation was continued in Elmira, N. Y., in 1926–29 to embrace the factors introduced when the exchange telephone plant was of open-wire construction.[8] Supplementing these detailed technical studies, an investigation of certain economic features of various arrangements of power and telephone distributing methods and of their practical application under varying conditions was carried out in California in 1928–29. As a result of these investigations the various factors involved in the co-ordination of multigrounded or common-neutral power systems and telephone distribution systems were determined and certain practices developed for the co-ordination of these systems under various conditions in urban areas.[9]

The purpose of this paper is that of briefly outlining a few of the more important features of power and telephone circuits affecting noise co-ordination. Following such a review there is presented a list of measures which

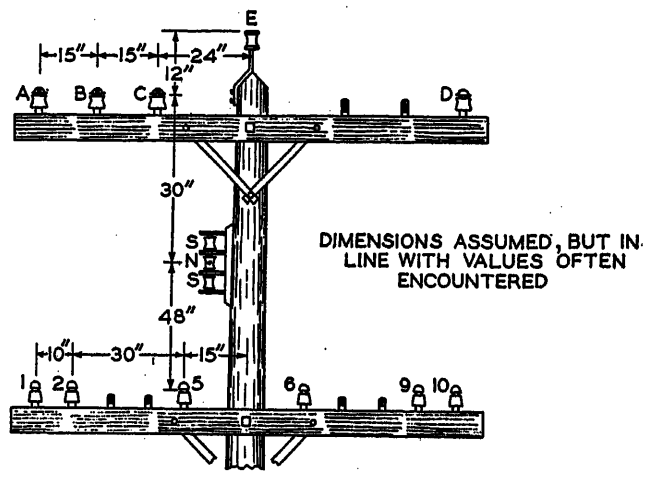



**Fig. 2. Effect of relative positions on joint-use pole of power and telephone conductors on coefficients of induction for voltages and currents**

Direct Metallic Circuit Induction In Untransposed Telephone Circuits

Magnetic Induction at 1,000 Cycles
Volts Metallic per Ampere of Power-Circuit Current per 1,000 Feet of Exposure

| Type of Power Circuit | Induction Component | Power Conductors* | Pair 1–2 | Pair 5–6 | Pair 9–10 | Avg |
|---|---|---|---|---|---|---|
| Single phase | Residual | A & N | 0.021 | 0.043 | 0.0044 | 0.022 |
| | | C & N | 0.0044 | 0.018 | 0.0053 | 0.0092 |
| | | E & N | 0.0002 | 0.023 | 0.0013 | 0.0082 |
| 2 phase wires and neutral | Residual | A, C, & N | 0.013 | 0.031 | 0.005 | 0.016 |
| | | A, D, & N | 0.008 | 0.018 | 0.009 | 0.012 |
| 3 phase | Residual | A, B, C, & N | 0.012 | 0.033 | 0.005 | 0.017 |
| | | A, C, D, & N | 0.007 | 0.01 | 0.004 | 0.007 |
| 2 phase wires and neutral | Balanced | A, C, & N | 0.017 | 0.026 | 0.0009 | 0.015 |
| | | A, D, & N | 0.026 | 0.13 | 0.026 | 0.061 |
| 3 phase | Balanced | A, B, C, & N | 0.015 | 0.023 | 0.012 | 0.017 |
| | | A, C, D, & N | 0.023 | 0.123 | 0.026 | 0.057 |

* In each case, conductor "N" is a multigrounded neutral, the other wires being phase conductors. Assumed 50 per cent of the residual current in the neutral and 50 per cent in the ground.

Electric Induction
Volts per Kilovolt Vm/Kv

| Type of Power Circuit | Induction Component | Power Conductors* | Pair 1–2 | Pair 5–6 | Pair 9–10 | Avg |
|---|---|---|---|---|---|---|
| Single phase | Residual | A & N | 7 | 19 | 3 | 9.7 |
| | | C & N | 2 | 7.3 | 2.3 | 3.9 |
| | | E & N | 0.4 | 9 | 0.2 | 3.2 |
| 2 phase wires and neutral | Residual | A, C, & N | 5 | 13 | 2.6 | 6.9— |
| | | A, D, & N | 2 | 7 | 2 | 3.7 |
| 3 phase | Residual | A, B, C, & N | 2.8 | 10 | 2 | 5.0 |
| | | A, C, D, & N | 1.4 | 2.2 | 0.7 | 1.4 |
| 2 phase wires and neutral | Balanced | A, C, & N | 3 | 7 | 0.4 | 3.5 |
| | | A, D, & N | 6 | 30 | 5 | 13.7 |
| 3 phase | Balanced | A, B, C, & N | 2.7 | 5.8 | 0.4 | 3.0 |
| | | A, C, D, & N | 5.6 | 27 | 5.4 | 12.7 |

* Wires S and S assumed continuous through exposure and grounded.

extended experience has shown will, where given proper consideration by both parties, enable multigrounded or common-neutral power circuits and telephone circuits to live harmoniously. No attempt is made, however, to reiterate the extensive technical information obtained

Table I*—Average Current and Voltage Wave Shapes of 2,300/4,000-Volt 3-Phase 4-Wire Distribution Circuits

| Frequency in Cycles per Second | Order of Harmonic | Phase-to-Neutral Voltage at Bus | Current in Industrial Feeder (in Amperes) | | | | Current in Residential Feeder (in Amperes) | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | Light Load | | Heavy Load | | Light Load | | Heavy Load | |
| | | | Phase | Residual | Phase | Residual | Phase | Residual | Phase | Residual |
| 60 | | 2380 | 65 | | 130 | | 53 | | 99 | |
| 180 | *3* | *16* | *1.1* | *2.6* | *1.1* | *2.9* | *1.8* | *5.2* | *1.9* | *6.0* |
| 300 | 5 | 21 | 1.0 | 0.15 | 1.3 | 0.16 | 0.43 | 0.21 | 0.75 | 0.29 |
| 420 | 7 | 6.4 | 0.3 | 0.03 | 0.3 | 0.05 | 0.13 | 0.06 | 0.17 | 0.08 |
| 540 | *9* | *1.7* | *0.04* | *0.08* | *0.04* | *0.13* | *0.04* | *0.09* | *0.04* | *0.09* |
| 660 | 11 | 1.9 | 0.07 | 0.01 | 0.09 | 0.01 | 0.04 | 0.01 | 0.06 | 0.02 |
| 780 | 13 | 1.8 | 0.08 | 0.01 | 0.05 | 0.01 | 0.02 | 0.01 | 0.04 | 0.01 |
| 900 | *15* | *0.42* | *0.01* | *0.01* | *0.01* | *0.03* | *0.01* | *0.01* | *0.01* | *0.01* |
| 1,020 | 17 | 0.90 | 0.03 | 0.01 | 0.07 | 0.01 | 0.02 | 0.01 | 0.03 | 0.01 |
| 1,140 | 19 | 0.87 | 0.02 | | 0.04 | | 0.01 | 0.01 | 0.02 | 0.01 |
| 1,260 | *21* | *0.16* | | | *0.01* | | | | *0.01* | *0.01* |
| 1,380 | 23 | 1.4 | 0.05 | | 0.06 | | 0.01 | | 0.03 | 0.01 |
| 1,500 | 25 | 2.1 | 0.06 | 0.01 | 0.09 | 0.01 | 0.01 | 0.01 | 0.03 | 0.01 |
| 1,620 | *27* | *0.79* | | *0.01* | *0.01* | *0.02* | | | *0.01* | *0.01* |
| 1,740 | 29 | 1.5 | 0.02 | | 0.03 | 0.01 | 0.01 | | 0.02 | 0.01 |
| 1,860 | 31 | 1.4 | 0.01 | | 0.02 | | | | 0.01 | |
| TIF** | | 9.7 | 11.2 | | 8.9 | | 6.6 | | 5.8 | |
| Kv. T or I. T. | | 23.2 | 733 | 193 | 1,160 | 330 | 346 | 238 | 571 | 283 |

Note: Values for triple harmonics are in *italic* type.
* Tables 31 and 32, pages 235–6 of volume II of Engineering Reports of Joint Subcommittee on Development and Research.
** New weighting—see Engineering Report No. 33 of Joint Subcommittee on Development and Research.

from the investigations outlined above as these are adequately covered in the references cited.

## Recent Trends

During the past few years there has been extensive conversion from other types of urban power distribution to the multigrounded or common-neutral system of primary distribution. Where there exists a 3-phase 3-wire delta circuit the system is converted by making the secondary neutral network continuous, reinforcing it where necessary, and making the required changes in transformer connections. Where there is a 3-phase 4-wire unigrounded primary system the conversion is, as previously mentioned, made by interconnecting the primary and the secondary neutral at each load transformer, generally removing the primary neutral only at the time of major rebuilding. In either case extensions are usually made using a single neutral in the secondary position.

In the urban areas most of the multigrounded or common-neutral systems are of the 2,300/4,000-volt class, although there are a few instances where 4,600-volt systems have been converted. At the present time there is being constructed a 6,900/12,000-volt common-neutral distribution system at Wichita, Kan.

The distinct trend in power distribution practice has been, in no small measure, influenced by the improved over-all protection features readily obtained by the multigrounded neutral arrangement as well as by certain equipment savings. The recent emphasis placed on the electrification of rural areas and the distinct need for maximum service continuity on rural power circuits have increased the interest in the use of the multigrounded or common-neutral method of distribution in rural areas. The rural systems are generally of the 7,600/13,200-volt class, although 4,600/8,000-volt circuits have been used to some extent.

The factors affecting inductive co-ordination involved in the use of the common-neutral method of distribution in rural areas, are somewhat different from those encountered in urban areas. This is largely due to the lower load densities, the greater lengths of circuits, higher operating voltages and to the somewhat different types of equipment employed in rural telephone distribution. These factors were investigated by the Joint Subcommittee on Development and Research during the summers of 1935 and 1936 and the more important considerations determined.[10]

## Factors Influencing Inductive Co-ordination

In any problem of inductive co-ordination it is convenient to subdivide the factors influencing co-ordination into those relating to the inductive influence of the power circuit, the inductive susceptiveness of the telephone circuit and the inductive coupling between the 2 types of circuits. As far as urban distribution circuits are concerned the load current unbalance of the power circuit is usually the controlling influence factor. For rural distribution circuits the unbalanced charging currents are generally more important than the unbalanced load currents. Likewise, in an exchange telephone circuit the admittance and impedance unbalances of the 2 sides of the circuit are usually the controlling factors in its inductive susceptiveness. As far as coupling between the power and telephone circuits is concerned this is largely controlled by their relative positions and the lengths of the exposure. For urban areas their relative positions are largely fixed by the normal arrangement of conductors and cables on jointly used poles. In rural areas power and telephone circuits are generally at roadway separation although some joint use exists. In urban areas considerable control can often be exercised over the coupling by planning the routes of the main feeds of the 2 services so as to avoid long sections of close exposure. In rural areas

where there are no paralleling routes close together it is generally necessary for both services to use the same roads and therefore the opportunity to control the coupling by the co-operative planning of routes is much reduced. Certain quantitative indications of the extent to which this measure of co-ordination is applicable in the 2 types of areas are shown in the illustrative examples in the appendix.

## Power Circuits

Power systems operate, for the most part, at frequencies of 60 cycles and below. Telephone circuits, on the other hand, depend mainly upon frequencies above about 200 cycles for the transmission of speech. Ordinarily, therefore, the effects of induction from the fundamental-frequency currents and voltages in neighboring power lines are negligible as far as telephone-circuit noise is concerned. It is quite generally recognized, however, that it is impracticable commercially to build rotating machinery and transformers which are entirely free from harmonics. There are, therefore, harmonics present on all operating power systems, and it is the harmonic-frequency components induced into telephone circuits from these power-system harmonics that are of major importance from the noise standpoint.[11]

In any distribution circuit the harmonic currents present will fall within the following classes: load currents, transformer-exciting currents, and line-charging currents. With a uni-grounded neutral the load currents and the transformer-exciting currents are practically entirely confined to the wires of the circuit. Where the neutral is multigrounded, the vector sum of the currents in the phase conductors (residual current) will divide between the neutral conductor and the paralleling earth path as determined by the relative impedances of these 2 paths. While there is some variation in the division of the return current between the neutral and ground paths, for most practical purposes this division may be assumed to be about half in each path at all the frequencies of interest.

As pointed out above, in the case of a line operating with uni-grounded neutral, the earth-return components of the load and transformer-exciting currents are ordinarily negligibly small. However, this is not true of the line-charging current which is chiefly a function of the magnitude and frequency of the impressed voltage, the circuit length, and, at nontriple harmonic frequencies, of the balance of the admittances to ground of the various phase conductors. While multigrounding the neutral ordinarily increases the earth-return components of the load and transformer-exciting currents, it has been found, due to the parallel path provided by the neutral wire, on an average to decrease slightly the amount of charging current in the earth.

In an urban distribution system where the load density is relatively high, the load currents and transformer-exciting currents are relatively large and the line-charging currents are usually negligible. In such a system multigrounding the neutral results in an increase in the current returning through the earth and a consequent increase in the inductive influence of the power distribution system.

In rural areas, however, where the load density is low and the load currents and transformer-exciting currents are relatively small, the line-charging currents become significant. In general, under such conditions the multigrounding of the neutral does not increase the magnitude of the ground-return current at frequencies of interest from the noise-induction viewpoint. Under certain conditions the magnitude of this ground-return current may actually be substantially decreased by the multigrounding of the neutral. This effect is more marked for the higher-voltage circuits.

The harmonics present in a distribution circuit may be divided into: (1) triple harmonics, that is, the third harmonic and odd multiples of it; and (2) nontriple harmonics that is, the odd harmonics, starting with and including the fifth, which are not multiples of 3. The triple harmonics in a 3-phase system are in phase in the 3 line conductors so that their residual value (vector sum) is the arithmetic sum of their magnitudes in the 3 phase wires. The nontriple harmonics are spaced, in time phase, the same as the 60-cycle fundamental, and the magnitude of the residual current (vector sum) for these harmonics is usually much less than their arithmetic sum. If these harmonics were perfectly balanced the residual current for these frequencies would be zero. In exposures involving 3-phase sections of line the balance of the nontriple harmonics between phases is influenced by the degree of balance of the loads and single-phase branches, and therefore has an important effect in reducing the over-all influence of the power system. In exposures involving single-phase extensions, or extensions consisting only of 2 phase wires and a neutral wire, this advantage of the balancing of the nontriple harmonics is, of course, not obtainable.

The extent to which induction from the nontriple harmonic voltages and currents in power-distribution circuits can be controlled by power-circuit transpositions is ordinarily very limited. Usually, due to the large number of exposure discontinuities arising from changes in the power or telephone circuits, the power-circuit transpositions are quite ineffective. This is particularly true in cases where the induction from the ground-return current is controlling. In specific cases where considerable wave-shape distortion exists and the induction from the balanced voltages and currents may therefore be relatively im-

**Table II*—Relative Importance of Circuit Unbalances**

| | 500 Cycles | | | 1,000 Cycles | | |
|---|---|---|---|---|---|---|
| | Contribution From: | | | Contribution From: | | |
| Type of Service | Station | Cable | Office | Station | Cable | Office |
| Individual (bridged ringers) | Negligible | 3 | 3 | Negligible | 20 | 20 |
| Party-line (grounded 8-*A* ringers) | 100 | 3 | 3 | 100 | 20 | 20 |

* See page 72 of volume I of Engineering Reports of Joint Sub-Committee on Development and Research.

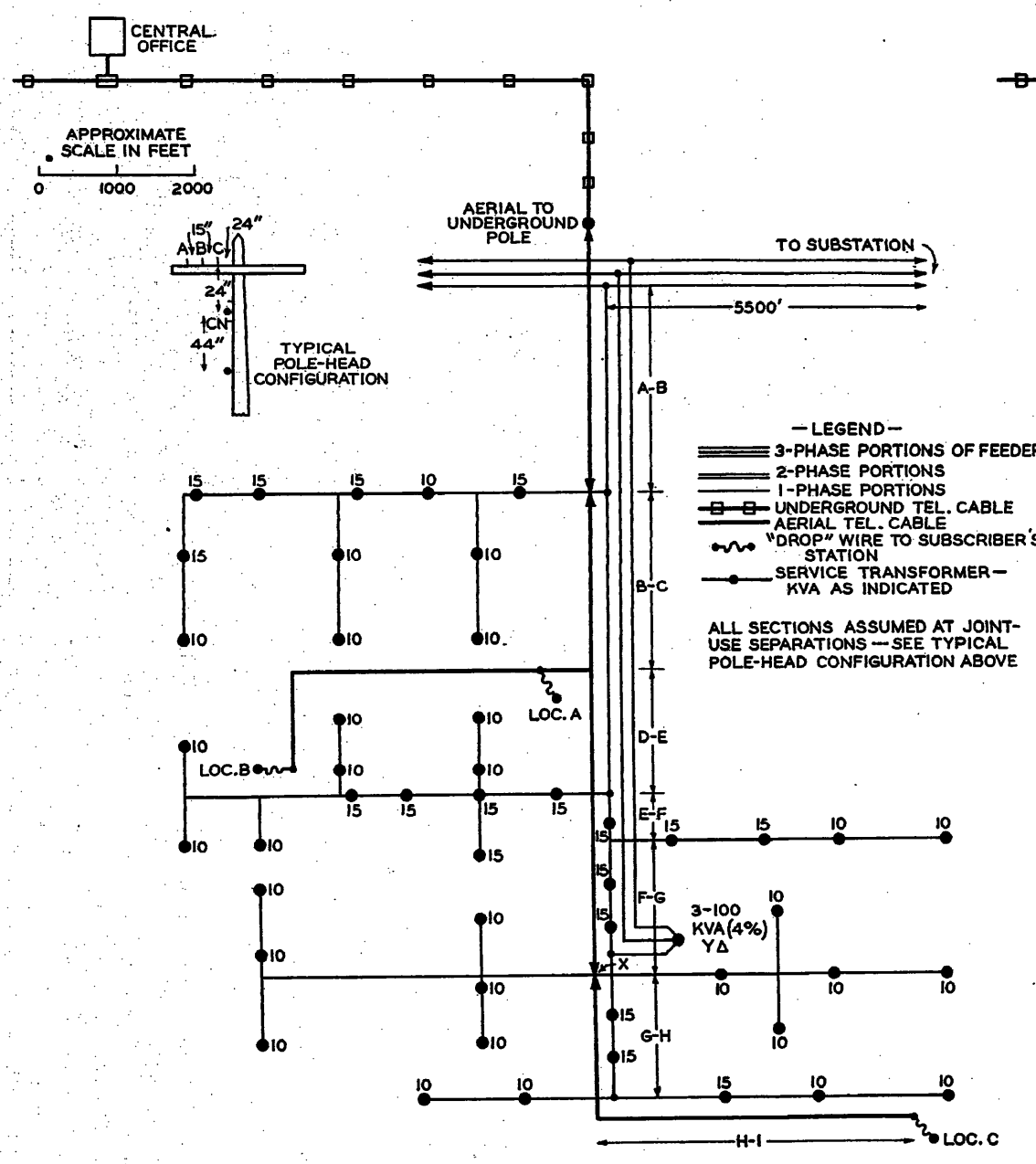



Fig. 3. Example of possible arrangement of feeder layout in an urban area where long aerial telephone cable is exposed to a heavily loaded single-phase feeder

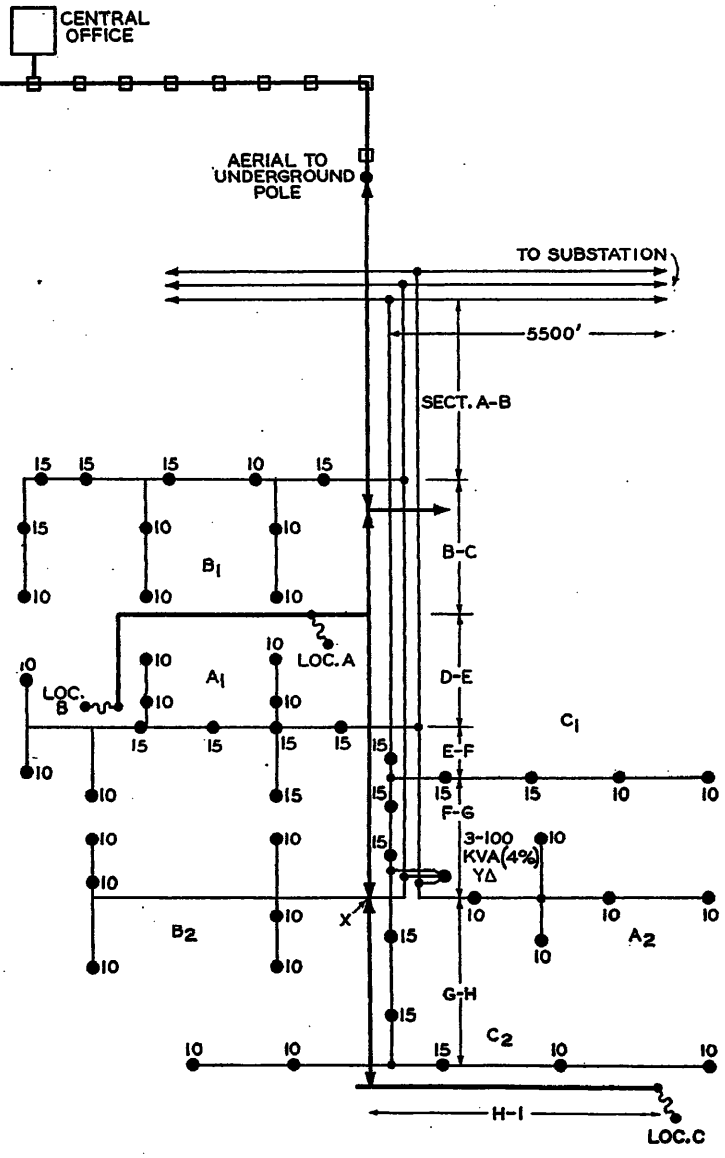



Fig. 4. Example of possible rearrangement of feeder layout shown in figure 3 to reduce magnitudes of "ground-return" currents

## Table III—Magnetic Shielding for Various Frequencies and Sizes and Lengths of Telephone Cables and Various Grounding Resistances

Calculated Values of $e_r/e_i$ (in per cent); $e_r$ = Voltage Remaining After Shielding and $e_i$ = Voltage Present With Sheath Grounded at One Point Only

| Frequency in Cycles per Second | Full-Sized Cable (2.61 In. Outside Diameter) | | | | | | 101-Pair 24-Gauge Cable (0.85 In. Outside Diameter) | | | | | | 54-Pair 24-Gauge Cable (0.64 In. Outside Diameter) | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 1 Mile* | | | 3 Miles* | | | ½ Mile* | | | 1 Mile* | | | ½ Mile* | | | 1 Mile* | | |
| | 0ω** | 5ω** | 10ω** | 0ω | 5ω | 10ω | 0ω | 5ω | 10ω | 0ω | 5ω | 10ω | 0ω | 5ω | 10ω | 0ω | 5ω | 10ω |
| 180 | 14 | 82 | 94 | 14 | 50 | 71 | 60 | 95 | 99 | 60 | 89 | 95 | 71 | 96 | 99 | 71 | 92 | 96 |
| 300 | 8.5 | 65 | 85 | 8.5 | 33 | 52 | 42 | 89 | 96 | 42 | 77 | 89 | 57 | 91 | 96.5 | 57 | 82 | 91 |
| 420 | 6 | 52 | 76 | 6 | 24 | 40 | 31.5 | 81 | 93 | 31.5 | 65 | 81 | 44.5 | 84 | 93.5 | 44.5 | 71 | 84 |
| 540 | 5 | 43.5 | 71 | 5 | 19 | 32 | 25 | 73 | 88 | 25 | 55.5 | 73 | 37 | 77 | 90 | 37 | 63 | 77 |
| 660 | 4 | 37 | 64 | 4 | 16 | 27 | 21 | 66 | 84 | 21 | 47.5 | 66 | 31 | 71 | 86 | 31 | 55 | 71 |
| 1000 | 3 | 25.5 | 44.5 | 3 | 11 | 18 | 15 | 51 | 72 | 15 | 35 | 51 | 22 | 56 | 74.5 | 22 | 41 | 56 |

* Refers to distances along cable sheath between the 2 grounding points.
** Refers to total grounding impedance (approximate d-c resistance) of the 2 ground connections, expressed in ohms.

portant, transpositions in power-distribution circuits may be found helpful.

Table I shows the average harmonics present on 3-phase 4-wire industrial and residential feeders under light- and heavy-load conditions. The reduced magnitudes of the nontriple frequencies in the residual current (neutral and ground-return) are evident. The importance of this as regards noise induction is further indicated in the illustrative examples of the appendix.

The triple-harmonic currents present on a feeder supplied from a delta-star substation transformer bank are generally due to the exciting currents of the single-phase load transformers. Under this condition no excessive triples are impressed on the feeder at its source as is sometimes the case where the source is a star-connected grounded-neutral generator directly connected to the feeder. The exciting currents flow from the individual single-phase transformers toward the delta-star transformer in the substation. The presence on the feeder of a large 3-phase star-delta load transformer with its neutral connected to the system neutral, provides a parallel path for supplying part of these triple-harmonic exciting currents as well as part of the unbalanced nontriple and fundamental currents and, under certain conditions, may substantially decrease the over-all inductive influence of a feeder by reducing the ground-return current flowing through an exposure. The effect of such a connection in reducing the noise is dependent upon the location of the bank with respect to the exposure and its relative impedance to the various harmonics as compared to that of the path back to the substation. From the power operating standpoint such a bank tends to supply part of the unbalanced load and also, in case of the interruption of one phase between it and the substation, tends to supply the power to that portion of the phase still connected to it. Under certain conditions, the action of such a bank may prove detrimental to the operation of the power feeder due to its action in attempting to balance the voltages at the point of its connection to the feeder. Under other conditions the neutral of an existing bank can readily be connected to the feeder neutral with distinctly beneficial effects on the inductive influence and with little or no adverse effects on the power-system operation. The tendency of such banks toward noise reduction and toward unbalanced load supply is shown in 2 of the illustrative examples in the appendix.

## Telephone Circuits

The voltages induced into a telephone circuit may be divided into: (1) metallic-circuit induction, that is, a voltage induced between the 2 sides of the circuit with a resultant current flowing around the circuit; and (2) the longitudinal-circuit induction, that is, a

## Table IV—Relative Susceptiveness of Several Types of Station Sets

| General Description of Station Set | Noise in Receiver Branch for 100 Noise Units to Ground—Average Power Wave Shape (One Station on Line—Effect of Set Only) |
|---|---|
| **Class 1—Types of Sets in Most Common Use Today** | |
| (*a*) Side-tone type of party-line set using 8A ringers or equivalents (one end of ringer grounded). (Common-battery talking and signaling) | 350 noise units, approximately |
| (*b*) Same type—local-battery talking | 120 noise units, approximately |
| (*c*) Magneto party-line set (52A ringer or equivalent) | 120 noise units, approximately |
| (*d*) Individual-line set—any type | Negligible |
| **Class 2—Types of Sets Frequently Encountered** | |
| (*a*) Side-tone type of 4-party full-selective or 8-party semiselective set (using relay or cathode tube to connect ringer to circuit during ringing period) | Negligible |
| (*b*) Four-party selective or 8-party semiselective sets employing high impedance ringers or relays connected to ground | About 30 noise units |
| (*c*) Eight-party selective (harmonic ringing) sets employing ringers connected to ground and tuned to 4 different ringing frequencies | Limited data indicate that, depending on frequency for which ringer is tuned, noise will range from about 100 to about 400 units |
| (*d*) Ground-return rural circuits (usually of magneto type and having code ringing) | 3,500 or more noise units |
| **Class 3—Special Types of Sets** | |
| (*a*) Side-tone type of party-line set using split-condenser and higher-impedance ringer (one end of ringer grounded) | About 20 noise units |
| (*b*) Type of party-line set using split-condenser arrangement with 8A ringer or equivalents (one end of ringer grounded) | About 90 noise units |

voltage induced along the conductors such that the resultant current flows in a circuit having the telephone conductors as one side and the earth as the other. This latter voltage may also result in noise, due to its action upon telephone-circuit unbalances, setting up currents in the voice channel (metallic circuit). For either type of voltage, the induction may be "electric," that is, from the voltage on the power circuit, or "magnetic" from the current in the power circuit.

The local telephone circuit may be divided into 3 parts: (*a*) the central-office equipment, (*b*) the line conductors, and (*c*) the subscriber equipment. Interoffice circuits include only the first 2 items.

### (*a*) Central-Office Equipment

The central-office equipment associated with a subscriber circuit consists essentially of 2 elements: (1) line signaling equipment connected to the circuit for indicating to the operator, or to the dial equipment, the desire of a subscriber to start a call; and (2) a linking or switching circuit or circuits for interconnecting 2 subscriber circuits either directly or through intervening trunk circuits and providing supervision during the call.

The line signaling equipment with its associated relay is either bridged across the line or arranged so that when 2 subscriber circuits are interconnected, any ground connections on the line relays are automatically opened. The line signaling equipment is not, therefore, ordinarily a factor in noise considerations. Occasionally, however, the effect on noise of the ground connection on the line signaling equipment requires specific treatment when the longitudinal-circuit induction is sufficiently high. The noise in such instances occurs either during the preanswering period before the line relay is "cut-off" or, in certain types of switchboards, on conversations between 2 persons on the same line (party-line) where the use of a switching circuit in the office is unnecessary.

The linking or switching equipment in the central office may consist of a pair of wires with bridged supervisory relays, as in the case of a magneto office, or may be a complicated arrangement of relays, repeating coils, condensers, etc., as in the case of common-battery offices of the manual or dial type. The necessary ground connections of the latter type of apparatus introduce the possibility of the unbalances in the equipment contributing to the over-all noise when the longitudinal-circuit induction on the outside conductors is impressed on the switching circuits. Ordinarily in urban areas, due either to the frequency make-up of the longitudinal-circuit induction or to the relationships of the various impedances-to-ground, the amount of noise contributed by the central-office equipment is relatively low. This is readily evident from table II which shows, at 500 and 1,000 cycles, the relative proportions of over-all noise due to the action of induced voltages on station, cable, and central-office unbalances. Cases arise, however, quite frequently where the relative circuit impedances or the frequency

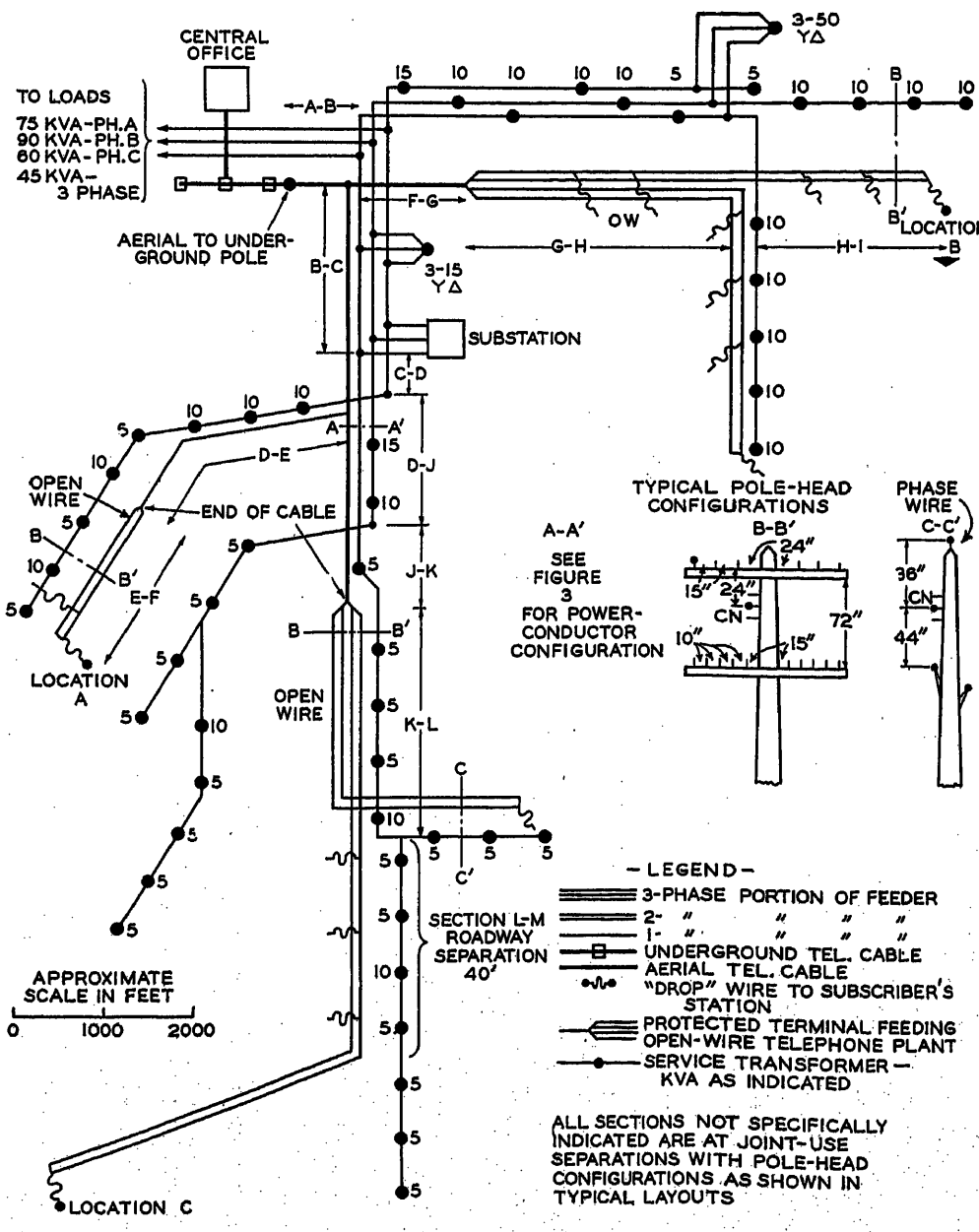



**Fig. 5. Example of exposure conditions between 2,300–4,000-volt distribution feeder and exchange telephone plant in suburban and rural area**

make-up of the induction or both are such that the noise contribution from the unbalances in the central-office equipment becomes important. Such cases usually involve long subscriber or interoffice trunk circuits and particularly where sections of open-wire construction are present. Values of the unbalances in certain types of central-office equipment are given on page 91 of volume I of the Engineering Reports of the Joint Subcommittee on Development and Research.

### (*b*) Line Conductors

Where the telephone line conductors are in open wire, the induced voltage between conductors (metallic-circuit) as well as along these conductors (longitudinal-circuit) must be considered. The direct metallic-circuit induction can be greatly reduced by systematic transpositions in the telephone circuit. Due to the physical limitations in a practical layout of telephone transpositions, the reduction in metallic-circuit induction is, on the average, from 60 to 80 per cent on nonpole pairs and about 90 per cent on pole pairs. Transpositions also tend to lessen the capacitance and inductance unbalances of the 2 sides to ground and to other circuits, thereby reducing the effect of the longitudinal-circuit induction on such unbalances. The improved balance of the mutual impedances between the various telephone conductors is, of course, distinctly beneficial in reducing cross talk, and transpositions are generally used for limiting the cross talk where open-wire telephone circuits extend for substantial distances.

The construction of telephone cables is such that there is inherently very close spacing between the conductors, and they are frequently transposed due to the continuous twisting of the pairs in manufacture. Due to this close spacing and frequent transposing there is practically no voltage induced between the wires of a cable pair or quad (group of 4 conductors). The unbalance to ground of the conductors of the present type of cable is so small that it is not ordinarily a contributing factor to noise induction. It may be noted, however, from table II that in cases where the central-office unbalances are of importance, the effect of shunt or series unbalances in the cables also needs consideration.

The lead sheath of a telephone cable provides practically perfect shielding against induction from power-system voltages when it is grounded at one or more points. The sheath likewise provides substantial magnetic shielding when it is grounded more or less continuously, as in underground construction, or is grounded at both ends of the aerial section or near both ends of an exposure. The degree of magnetic shielding effected varies, depending on the size of the cable and the resistance of the ground connections, reaching optimum values of over 90 per cent. Table III gives the magnitude of this shielding for various selected sizes and lengths of cable. Table III brings out distinctly the variation in the magnetic shielding due to the factors mentioned above. The effect of cable sheath shielding in several typical cases is further indicated in the appendix.

### (*c*) Station Apparatus

Individual-line stations employ a "bridged" ringer connection, that is, the ringer is, in effect, connected between the 2 line conductors. However, for selective signaling purposes party-line stations, frequently have the ringer connected, in effect, between one of the line

**Table V—Noise Contributions (Figure 3) of Various Harmonics and Sections of Exposure**

| Section of Exposure | RMS Magnitude of Residual Current in Amperes | Approximate Total Noise Contribution* (Noise Units) | Approximate Noise Contribution (Noise Units) From: 180 Cycles | 300 Cycles and Higher Frequencies |
|---|---|---|---|---|
| *A-B* | 210 | 1,240 | 270 | 1,215 |
| *B-E* | 157 | 1,130 | 250 | 1,100 |
| *E-I* | 30–107 | 500 | 100 | 490 |
| Total | | 2,870 | 620 | 2,800 |

* Location *C*—For party-line service using 8*A* ringers, during heavy power loads.

**Table VI—Comparison of Effectiveness of Various Remedial Measures (Figure 3 Conditions)**

| Type of Remedial Measure | Approximate Noise Units on Party-Line Stations (Heavy Power Loads) Location A or B | Location C |
|---|---|---|
| 1. Before applying remedial measures | 1,800 | 2,870 |
| 2. Using special telephone station sets | 75 | 125 |
| 3. Avoiding exposure in section *A-B* by co-operative planning of routes | 560 | 1,630 |
| 4. Cable-sheath shielding by tying aerial and underground telephone cables at junction pole and connecting aerial sheath to 1-ohm ground at point *X* | 1,160 | 1,700 |
| 5. Interconnecting 300-kva star-delta bank with system neutral | 1,430 | 1,600 170 kva of unbalanced load |
| 6. Combination of measures 3, 4, and 5 | 365 | 420 |

**Table VII—Noise Contributions (Figure 4) of Various Harmonics and Sections of Exposure**

| Section of Exposure | RMS Magnitude of Residual Current in Amperes | Total Noise Contribution* (Noise Units) | Noise Contribution (Noise Units) From: 180 Cycles | 300 Cycles and Higher |
|---|---|---|---|---|
| *A-B* | 6 | 280 | 270 | 75 |
| *B-E* | 45 | 370 | 250 | 275 |
| *E-I* | 5–45 | 150 | 100 | 115 |
| Total | | 735 | 620 | 375 |

* Location *C*—for party-line service using 8*A* ringers, during heavy power loads.

conductors and ground. The unbalance of the party-line station equipment is therefore affected by the impedance of the ringer and its point of connection in the station equipment. The relative susceptiveness of several types of station sets to noise-frequency induction is shown in table IV.

Table IV shows that, with advance planning in areas where noise induction is or may likely become a matter of importance, much can be accomplished by the use of station sets of decreased inductive susceptiveness. Where such types of apparatus are substituted in existing plant, except in gradual replacements or in connection with general rearrangement programs, the expense is, naturally, increased.

## Inductive Coupling

As stated above, the inductive coupling between exchange telephone plant and power-distribution circuits in urban areas is largely controlled by such factors as the street layouts and the joint use of poles. However, by co-operative planning of routes it is frequently practicable to secure lower coupling by avoiding long exposures between the main feeds of the 2 plants. As shown by the illustrative examples this procedure is, where applicable, very beneficial.

In rural areas where both distribution services must ordinarily be carried along the highways the opportunity for controlling the coupling between the 2 classes of circuits by co-operative planning of routes is much reduced.

Some benefit may be gained, however, in the case of open-wire construction, particularly at joint-use separations, by arangements of the conductors on the pole so as to avoid excessive spacings. As shown on figure 2, certain arrangements tend to minimize the amount of noise induction arising from the power-circuit voltages and currents. This beneficial effect is, however, much less noticeable at roadway separations.

**Table VIII—Comparison of Effectiveness of Various Remedial Measures (Figure 4)**

| Type of Remedial Measure | Approximate Noise Units on Party-Line Stations (Heavy Power Loads) | |
|---|---|---|
| | Location A or B | Location C |
| 1. Before applying remedial measures | 480 | 735 |
| 2. Using special telephone station sets | 25–30 | 40–50 |
| 3. Avoiding exposure in section *a-b* by co-operative planning of routes | 190 | 460 |
| 4. Interconnecting 300-kva star-delta bank with system neutral | 330 | 535 |
| | | 26 kva of unbalanced load |
| 5. Cable-sheath shielding—grounding at junction pole and to 1-ohm ground at *X* | 325 | 420 |
| 6. Combinations of measure 3, 4, and 5 | 85 | 245 |

## Summary and Conclusions

Since about 1915 there has been a continued increase in the use of the multigrounded or common-neutral arrangement of power distribution in this country. At the present time, approximately half of the distribution is by 4,000-volt multigrounded or common-neutral circuits. A large part of the higher-voltage rural distribution is also operating with this arrangement.

In general it may be said that for the lower-voltage 2,300/4,000-volt distribution circuits, the use of the multigrounded or common-neutral arrangement may be expected to increase the inductive influence of the power circuits. Unless attention is given to co-operative planning to secure features beneficial from the inductive-co-ordination standpoint, noise problems may result either in restricted or extensive areas. With proper attention to the co-ordination features[9] such noise situations as develop are largely in the nature of isolated cases and can usually be cared for by relatively minor changes or adjustments in either or both plants.

For the higher-voltage (11–13 kv) rural distribution circuits, there seems to be little difference, from the noise-induction standpoint, between the uni-grounded 4-wire system and the multigrounded or common-neutral arrangement.[10] Under many conditions the placing of multiple grounds on the neutral will result in noise reductions due to the effect, previously mentioned, of the multigrounded neutral on the line-charging currents. It is interesting to note that experience to date with the multigrounded or common-neutral circuit in rural areas has shown that many of the measures of co-ordination applicable in urban areas will prove similarly helpful in rural communities.

The measures of co-ordination which investigations

**Table IX—Noise at Various Locations (Figure 5) and for Various Types of Telephone Service**

| Location | Type of Telephone Service | Total Noise Units | Contribution (Noise Units) From: Cable Exposures | Contribution (Noise Units) From: Open-Wire Exposures | Remarks |
|---|---|---|---|---|---|
| *A* | 1. Common-battery party-line stations (class 1-*a* table IV) | 225–345 | 220–270 | 45–215 | Open-wire noise dependant on effectiveness of telephone transpositions |
| | 2. Magento party-lines (class 1-*c* table IV) | 85–225 | 75 app. | 40–215 | |
| | 3. Individual line (class 1-*d* table IV) | 40–210 | 25–35 | About 10–210 | Lower values of noise on circuits controlled by effects of station sets — higher values by effectiveness of telephone transpositions |
| *B* | 1 | 170–1,200 | 10–100 | 170–1,190 | |
| | 2 | 75–1,175 | 20– 35 | 70–1,175 | |
| | 3 | 60–1,175 | About 20 | 55–1,175 | |
| *C* | 1 | 400–975 | 285–325 | 275–925 | Noise in cable section due to office and cable unbalances |
| | 2 | 150–870 | 110–125 | 110–860 | |
| | 3 | 100–860 | 60 | 75–860 | |

and operating experiences have shown to be practicable and effective include:

1. Co-operative planning by both parties to avoid not only severe exposure conditions but also types of equipment likely to aggravate the possible noise-induction situation.

2. A reasonable degree of balance of the loads between the 3 phases of the power circuit. In the higher-voltage rural circuits this also includes the lengths of branches consisting of 1 or 2 phase wires and neutral.

3. The avoidance of unnecessarily heavily loaded branches consisting of 1 or 2 phase wires and neutral.

4. The prevention of excessive overexcitation of transformers.

5. The grounding, where necessary, of aerial telephone cables at or near both ends of an exposure to obtain the benefits of magnetic shielding.

6. The use of adequately co-ordinated telephone transpositions on open-wire extensions and the avoidance of severe unbalances in the open-wire conductors.

7. The correction of badly distorted voltage or current wave shape on the power system.

8. The connection of the neutral point of 3-phase star-delta load banks to the system neutral conductor.

9. The use of telephone station apparatus, on party-line service, of lower susceptiveness.

10. Occasionally the use of arrangements or apparatus to minimize the effects from unbalances in central office equipment.

It is, of course, essential in successfully co-ordinating the power distribution and telephone circuits that, as in other co-ordination situations, the power and telephone people view the matter as a mutual responsibilty and fully co-operate in the application of the tools available. Experience over a period of years has now shown that where this is done adequate over-all co-ordination can be readily secured.[12]

## Appendix

For the sake of brevity, the detailed calculations and some of the minor assumptions for the following examples have been omitted.

### Illustrative Example 1

The purpose of this example is to show, for average power-system wave shapes:

1. The noise-induction problem that might be created by the exposure of a reasonably long aerial telephone cable in an urban area with a heavily loaded single-phase feeder. It features:
(*a*) The relative importance of triple and nontriple harmonic induction, and
(*b*) The extent to which planning of routes, grounding of cable sheaths, etc., might improve the situation.

2. The change in the noise magnitudes for the same situation with the various single-phase loads well distributed among all 3 phases. Under this condition, attention is directed to:
(*a*) The change in the relative importance of the triple and nontriple harmonic induction.
(*b*) The amount of reduction obtained by the same remedial measures tried in 1-*b* above.

Figure 3 shows a possible method of supplying the single-phase loads in a rather extensive part of an urban area. The general layout shown in figure 3 is such that all of the current for the feeder area traverses a considerable part of the exposure. Under this quite extreme condition—essentially single-phase supply for a relatively large area—the noise at location *C* under heavy-load conditions would be about as shown in table V.

**Table X—Comparison of Effectiveness of Various Remedial Measures**

| Type of Remedial Measure | Approximate Noise Units at: Location A 1* | A 2 | A 3 | Location B 1 | B 2 | B 3 | Location C 1 | C 2 | C 3 |
|---|---|---|---|---|---|---|---|---|---|
| 1. Before applying measures.. | 225–345 | 85–225 | 40–210 | 170–1,200 | 75–1,175 | 60–1,175 | 400–975 | 150–870 | 100–860 |
| 2. Using special telephone sets. | 40–210 | 40–210 | Neg. change | 60–1,175 | 60–1,175 | Neg. change | 100–860 | 100–860 | Neg. change |
| 3. Avoiding exposure section *B-C* by co-operating planning | 130–250 | 65–220 | Neg. change | Neg. change | | | 350–950 | 115–860 | Neg. change |
| 4. Interconnecting neutral of 150-kva star-delta bank..... | 180–310 | Neg. change | | 150–1,175 | Neg. change | | 370–950 | Neg. change | |
| 5. Average degree of co-ordinated telephone transpositions..... | 250 | 80 | 50 | 200 | 175 | 175 | 340 | 175 | 130 |
| 6. Telephone transpositions + cable - sheath shielding**... | 210 | 70 | 50 | 180 | 175 | 175 | 320 | 165 | 130 |
| 7. Combination of 4, 5, and 6.. | 185 | 65 | 50 | 160 | 155 | 155 | 310 | 160 | 125 |

* Type of station apparatus shown on table IX.
** Cable was assumed to be grounded at junction pole at end of section *F-G* to 2.5-ohm ground; at other junction poles to grounds exceeding 10 ohms.

It is evident from table V that most of the party-line stations fed by the aerial telephone cable would need treatment. It will be noted from table VI that completely replacing the existing party-line stations with special station apparatus will, to a large extent, care for the situation since, in this case, the amount of noise contributed by the cable and central-office unbalances would aggregate less than 150 units. Other measures either singly or in combination, probably more economical in their application, would provide substantial reductions in noise, but would not be adequate for the more severely exposed stations.

Assume, however, that instead of supplying the single-phase loads in the area shown on figure 3 from one phase only, the single-phase loads were distributed reasonably uniformly among the phases. This would be advantageous not only by the noise-reduction possibilities, which will be more fully discussed, but also by the improved regulation attainable on the feeder. Figure 4 shows a possible rearrangement of figure 3 along these lines and table VII shows the noise conditions with the feeder arrangements of figure 4.

A comparison of tables V and VII shows that the noise from the nontriple harmonics has been very materially reduced by the balancing of loads made possible by the more favorable feeder arrangement of figure 4, although that from the triple harmonics has been inappreciably changed. The net effect has been a reduction of nearly 75 per cent in the noise on the party-line stations served by the telephone cable. The reductions afforded by various remedial measures are shown in table VIII.

It is evident from table VIII that, by the application of various of the measures of co-ordination, the need for an extensive rearrangement of either plant is avoided.

### Illustrative Example 2

The purpose of this example is to show the extent to which remedial measures of the type generally applicable in urban areas (see example 1) may be applied in a less thickly settled area where exposures to 2.3/4-kv multigrounded-neutral arrangements are encountered under average conditions of power-system wave shape. In detail the example covers:
(*a*) The extent to which such measures as co-operative planning of routes and use of star-delta load banks may be ineffective.
(*b*) The importance, particularly under joint-use conditions, of noise directly induced into the metallic circuit of open-wire tele-

(*Concluded on page 189*)

# Two-Reaction Theory of Synchronous Machines

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**An extension of the 2-reaction theory of synchronous machines as developed by R. H. Park is given in this paper for machines having capacitance in the armature circuit. General equations for predetermination of the performance under certain abnormal conditions of machines having balanced 3-phase capacitance in the armature circuit are presented.**

THIS PAPER is an extension of the method of analysis by R. H. Park[1,2,3] in that the effect of armature circuit capacitance is included in the general equations for the performance of a salient-pole synchronous machine. These equations are of sufficient generality so that the operation of a synchronous or induction machine having balanced 3-phase capacitance in the armature circuit can be predetermined for the condition of 3-phase short circuit, sudden application of capacitance load, self-excitation, running out of synchronism, hunting, pulling into step, etc. The method of approach is such that the general impedance operators which have been utilized by recent writers[5-10] can also be used in studying the effect of capacitance in the armature circuit. Such impedance operators include the effect of additional rotor circuits. It is believed that a theoretical basis for the study of the performance of synchronous or induction machines as influenced by capacitance is particularly important at this time, with the increased use of series and shunt capacitors for voltage regulation purposes.

An interesting application of the general equations is to the problem of self-excitation of a machine connected to a circuit containing capacitance. Criteria are developed which indicate the regions in which self-excitation may occur for the case of a synchronous machine connected to a capacitance load or through series capacitance to a system.

## List of Symbols

All constants are in per-unit values in terms of normal kilovolt-amperes and voltage, and correspond wherever possible with established nomenclature.

$x_c = 1/c$ = capacitance reactance
$x_d$ = synchronous reactance of direct-axis armature circuit
$x_d'$ = direct-axis transient reactance
$x_d''$ = direct-axis subtransient reactance
$x_d(p)$ = impedance operator relating the direct-axis armature flux linkages with the direct-axis armature current
$x_q$ = synchronous reactance of quadrature-axis armature circuit
$x_q'$ = quadrature-axis transient reactance
$x_q''$ = quadrature-axis subtransient reactance
$x_q(p)$ = impedance operator relating the quadrature-axis armature flux linkages with the quadrature-axis armature current
$G_d(p)$ = operator relating the direct-axis armature linkages with the direct-axis field excitation voltage
$G_q(p)$ = operator relating the quadrature-axis armature flux linkages with the quadrature-axis field excitation voltage
$r$ = armature circuit resistance
$e$ = system voltage
$E_{fd}$ = direct-axis field-excitation voltage
$E_{fq}$ = quadrature-axis field-excitation voltage
$e_d$ = direct-axis armature voltage
$e_q$ = quadrature-axis armature voltage
$e_0$ = zero-sequence armature voltage
$\psi_d$ = direct-axis armature flux linkages
$\psi_q$ = quadrature-axis armature flux linkages
$\psi_0$ = zero-sequence armature flux linkages
$i_d$ = direct-axis armature current
$i_q$ = quadrature-axis armature current
$i_0$ = zero-sequence current
$e_a, e_b, e_c$ = phase voltages
$i_a, i_b, i_c$ = phase currents
$\psi_a, \psi_b, \psi_c$ = phase flux linkages
$T_o$ = open-circuit field time constant in electrical radians
$p$ = $d/dt$
$s$ = slip
$t$ = time in electrical radians; unit time is the time required for the rotor to pass one electrical radian at normal frequency
$\delta$ = angular displacement in electrical radians
1 = Heaviside's unit function

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1. For all numbered references see list at end of paper.

## General Analysis

This analysis is based on the definition of an ideal synchronous machine as given in reference 1. A knowledge of the material in references 1 and 2 by R. H. Park is assumed in the following development.

Park gives the following relations:

$$\left.\begin{aligned} i_d &= \tfrac{2}{3}[i_a\cos\theta + i_b\cos(\theta-120) + i_c(\cos\theta + 120)] \\ i_q &= -\tfrac{2}{3}[i_a\sin\theta + i_b\sin(\theta-120) + i_c(\sin\theta + 120)] \end{aligned}\right\} \quad (1)$$

$$\left.\begin{aligned} e_d &= \tfrac{2}{3}[e_a\cos\theta + e_b\cos(\theta-120) + e_c\cos(\theta + 120)] \\ e_q &= -\tfrac{2}{3}[e_a\sin\theta + e_b\sin(\theta-120) + e_c\sin(\theta + 120)] \end{aligned}\right\} \quad (2)$$

$$\left.\begin{aligned} \psi_d &= \tfrac{2}{3}[\psi_a\cos\theta + \psi_b\cos(\theta-120) + \psi_c\cos(\theta + 120)] \\ \psi_q &= -\tfrac{2}{3}[\psi_a\sin\theta + \psi_b\sin(\theta-120) + \psi_c\sin(\theta + 120)] \end{aligned}\right\} \quad (3)$$

$$\left.\begin{aligned} e_a &= p\psi_a - ri_a \\ e_b &= p\psi_b - ri_b \\ e_c &= p\psi_c - ri_c \end{aligned}\right\} \quad (4)$$

and

$$\left.\begin{aligned}\psi_d &= G_d(p)\,E_{fd} - x_d(p)i_d\\ \psi_q &= G_q(p)\,E_{fq} - x_q(p)i_q\end{aligned}\right\}\ (5)$$

If the effect of armature circuit capacitance is to be included, equations 4 become

$$\left.\begin{aligned}e_a &= p\,\psi_a - \left(r + \frac{x_c}{p}\right)i_a\\ e_b &= p\,\psi_b - \left(r + \frac{x_c}{p}\right)i_b\\ e_c &= p\,\psi_c - \left(r + \frac{x_c}{p}\right)i_c\end{aligned}\right\}\ (6)$$

or

$$\left.\begin{aligned}pe_a &= p^2\psi_a - (p\,r + x_c)\,i_a\\ pe_b &= p^2\psi_b - (p\,r + x_c)\,i_b\\ pe_c &= p^2\psi_c - (p\,r + x_c)\,i_c\end{aligned}\right\}\ (7)$$

Differentiating equations 2,

$$\left.\begin{aligned}pe_d &= \frac{2}{3}\left[\cos\theta\,pe_a + \cos(\theta-120)\,pe_b + \cos(\theta+120)\,pe_c\right] -\\ &\quad \frac{2}{3}\left[e_a\sin\theta + e_b\sin(\theta-120) + e_c\sin(\theta+120)\right]p\theta\\ pe_q &= -\frac{2}{3}\left[\sin\theta\,pe_a + \sin(\theta-120)\,pe_b + \sin(\theta+120)\,pe_c\right] -\\ &\quad \frac{2}{3}\left[e_a\cos\theta + e_b\cos(\theta-120) + e_c\cos(\theta+120)\right]p\theta\end{aligned}\right\}\ (8)$$

Using equations 2 and 7, equations 8 become

$$\left.\begin{aligned}pe_d - e_q p\theta &= \frac{2}{3}\left[\cos\theta\,p^2\psi_a + \cos(\theta-120)\,p^2\psi_b + \cos(\theta+120)\,p^2\psi_c\right] -\\ &\quad \frac{2}{3}r\left[\cos\theta\,pi_a + \cos(\theta-120)\,pi_b + \cos(\theta+120)\,pi_c\right] -\\ &\quad \frac{2}{3}x_c\left[\cos\theta\,i_a + \cos(\theta-120)\,i_b + \cos(\theta+120)\,i_c\right]\\ pe_q + e_d p\theta &= -\frac{2}{3}\left[\sin\theta\,p^2\psi_a + \sin(\theta-120)\,p^2\psi_b + \sin(\theta+120)\,p^2\psi_c\right] +\\ &\quad \frac{2}{3}r\left[\sin\theta\,pi_a + \sin(\theta-120)\,pi_b + \sin(\theta+120)\,pi_c\right] +\\ &\quad \frac{2}{3}x_c\left[\sin\theta\,i_a + \sin(\theta-120)\,i_b + \sin(\theta+120)\,i_c\right]\end{aligned}\right\}\ (9)$$

In order to express equations 9 in terms of direct- and quadrature-axis quantities rather than phase quantities, the following relations will be used. Differentiating equations 3,

$$\left.\begin{aligned}p\psi_d &= \frac{2}{3}\left[\cos\theta\,p\psi_a + \cos(\theta-120)\,p\psi_b + \cos(\theta+120)\,p\psi_c\right] + \psi_q p\theta\\ p\psi_q &= -\frac{2}{3}\left[\sin\theta\,p\psi_a + \sin(\theta-120)\,p\psi_b + \sin(\theta+120)\,p\psi_c\right] - \psi_d p\theta\end{aligned}\right\}\ (10)$$

Differentiating equations 10,

$$p^2\psi_d = \frac{2}{3}\left[\cos\theta\,p^2\psi_a + \cos(\theta-120)\,p^2\psi_b + \cos(\theta+120)\,p^2\psi_c\right] -$$
$$\frac{2}{3}\left[\sin\theta\,p\psi_a + \sin(\theta-120)\,p\psi_b + \sin(\theta+120)\,p\psi_c\right]p\theta +$$
$$p\theta\,p\psi_q + \psi_q p^2\theta \qquad (11a)$$

$$p^2\psi_q = -\frac{2}{3}\left[\sin\theta\,p^2\psi_a + \sin(\theta-120)\,p^2\psi_b + \sin(\theta+120)\,p^2\psi_c\right] -$$
$$\frac{2}{3}\left[\cos\theta\,p\psi_a + \cos(\theta-120)\,p\psi_b + \cos(\theta+120)\,p\psi_c\right]p\theta -$$
$$p\theta\,p\psi_d - \psi_d p^2\theta \qquad (11b)$$

Substituting equations 10 in equations 11,

$$\left.\begin{aligned}&\frac{2}{3}\left[\cos\theta\,p^2\psi_a + \cos(\theta-120)\,p^2\psi_b + \cos(\theta+120)\,p^2\psi_c\right] =\\ &p^2\psi_d - 2p\theta\,p\psi_q - \psi_d(p\theta)^2 - \psi_q p^2\theta -\\ &\frac{2}{3}\left[\sin\theta\,p^2\psi_a + \sin(\theta-120)\,p^2\psi_b + \sin(\theta+120)\,p^2\psi_c\right] =\\ &p^2\psi_q + 2p\theta\,p\psi_d - \psi_q(p\theta)^2 + \psi_d p^2\theta\end{aligned}\right\}\ (12)$$

Differentiating equations 1,

$$\left.\begin{aligned}&\frac{2}{3}\left[\cos\theta\,pi_a + \cos(\theta-120)\,pi_b + \cos(\theta+120)\,pi_c\right] = pi_d - i_q p\theta -\\ &\frac{2}{3}\left[\sin\theta\,pi_a + \sin(\theta-120)\,pi_b + \sin(\theta+120)\,pi_c\right] = pi_q + i_d p\theta\end{aligned}\right\}\ (13)$$

Substituting equations 1, 12, and 13 in equations 9 and simplifying,

$$p(e_d - p\psi_d + ri_d + \psi_q p\theta) + x_c i_d = p\theta(e_q - p\psi_q + ri_q - \psi_d p\theta) \qquad (14)$$

$$p(e_q - p\psi_q + ri_q - \psi_d p\theta) + x_c i_q = -p\theta(e_d - p\psi_d + ri_d + \psi_q p\theta) \qquad (15)$$

The expression for the zero-sequence voltage may be obtained by substituting equations 6 in the equation for the zero-sequence voltage given in reference 2, equation 6. This yields

$$e_0 = p\psi_0 - \left(r + \frac{x_c}{p}\right)i_0 \qquad (15a)$$

where

$$\psi_0 = \frac{1}{3}\left(\psi_a + \psi_b + \psi_c\right)$$

$$i_0 = \frac{1}{3}\left(i_a + i_b + i_c\right)$$

Equations 14, 15, and 15*a* can be used directly in place of equations 8, 9, and 10 of reference 2 in order that the effect of balanced armature circuit capacitance can be included in determining the performance of a synchronous machine. It may be noted that if $x_c = 0$, the case when $c = \infty$, the solution of equations 14, 15, and 15*a* is that given by equations 8, 9, and 10 of reference 2.

In the following are applications of equations 14 and 15 to problems involving the performance of a synchronous machine and balanced capacitance.

## Application to Self-Excitation of a Synchronous Machine

The phenomenon of self-excitation of a synchronous machine connected to a capacitive load or to a system through series capacitance is evidenced by the building up of machine armature voltage to values which are limited by machine or circuit saturation, it being impossible to control completely the terminal voltage by variation in the field-excitation voltage. A common cause for the occurrence of the

phenomenon is the connection of a synchronous machine to a transmission circuit whose line-charging kilovolt-amperes exceed the line-charging capacity of the generator. The following analysis indicates the regions in which this phenomenon will and will not occur. Saturation can be neglected in such an analysis as its effect is chiefly to limit the voltage of self-excitation and not to alter the values of circuit constants which cause it to occur, except for the case when the initial excitation is high enough to produce appreciable saturation.

Consider the case of a machine running at constant speed with constant excitation voltage and connected to a balanced shunt capacitive load or through a balanced series capacitance to an infinite bus, $p\theta = (1-s)$, $\Delta E_{fd} = \Delta E_{fq} = 0$. Substituting equations 5 in equations 14 and 15 for these conditions and simplifying,

$$pe_d-(1-s)e_q = \{[(1-s)^2-p^2]x_d(p)-pr-x_c\}i_d+(1-s)[2px_q(p)+r]i_q \quad (16)$$

$$pe_q+(1-s)e_d = -(1-s)[2px_d(p)+r]i_d+\{[(1-s)^2-p^2]x_q(p)-pr-x_c\}i_q \quad (17)$$

Solving equations 16 and 17 simultaneously for the currents $i_d$ and $i_q$,

$$i_d = -\frac{\{[p^2+(1-s)^2]Z_q(p)+px_c\}e_d+\{[p^2+(1-s)^2](1-s)x_q(p)-(1-s)x_c\}e_q}{A(p)} \quad (18)$$

$$i_q = \frac{\{[p^2+(1-s)^2](1-s)x_d(p)-(1-s)x_c\}e_d-\{[p^2+(1-s)^2]Z_d(p)+px_c\}e_q}{A(p)} \quad (19)$$

where

$$A(p) = [p^2+(1-s)^2][Z_d(p)Z_q(p)+(1-s)^2x_d(p)x_q(p)]+x_c[pZ_d(p)+pZ_q(p)-(1-s)^2x_d(p)-(1-s)^2x_q(p)+x_c] \quad (20)$$

and

$$Z_d(p) = px_d(p)+r \qquad Z_q(p) = px_q(p)+r$$

The currents $i_d$ and $i_q$ will increase indefinitely if any of the roots of the denominator of the operational expression for $i_d$ and $i_q$, which is obtained by rationalizing $A(p)$, have positive real values. Therefore, the criterion of Hurwitz[11] or of Routh,[12] for determining if a positive real root exists, can be used for testing whether or not self-excitation will occur for a given set of machine and circuit constants.

Equation 20 is a general expression which may be used for determining if self-excitation will occur in a salient pole or a symmetrical rotor machine having any number of rotor circuits.

Using the roots of the denominator to determine if self-excitation will occur is similar to the method employed by M. Takahashi.[4] He analyzed quite completely the case of a symmetrical rotor machine with a single rotor winding and to a limited extent a salient-pole machine with a single field winding. When the same special cases were studied the results obtained from equation 20 were found to be in general agreement with his work.

An analysis by Rudenberg[13] based on graphical methods describes the chief aspects of the phenomenon and can be used for determining the effect of saturation in limiting the voltage of self-excitation. The graphical method of analysis is limited, however, in that it cannot be used for a quantitative determination of the effect of additional rotor circuits on the regions of self-excitation.

Consider the special case of a salient-pole machine running at synchronous speed, with no rotor circuits other than the direct-axis field circuit. For this case, $s = 0$,

$$x_d(p) = \frac{x_d'T_op+x_d}{T_op+1}$$

and

$$x_q(p) = x_q$$

Substituting these values in equation 20 and rationalizing, the operational expression for the denominator of the currents is

$$D(p) = x_qx_d'T_op^5+[x_dx_q+rT_o(x_d'+x_q)]p^4+[2x_qx_d'T_o+r(x_d+x_q)+T_ox_c(x'_d+x_q)+T_or^2]p^3+[2x_qx_q+rT_o(x_d'+x_q)+x_c(x_d+x_q)+r^2+T_o2rx_c]p^2+[x_qx_d'T_o+r(x_d+x_q)-T_ox_c(x_d'+x_q)+2rx_c+T_o(x_c^2+r^2)]p+[x_dx_q-x_c(x_d+x_q)+x_c^2+r^2] \quad (21)$$

Self-excitation will occur if any of the roots of $D(p)$, equation 21, have a positive real value.

For the numerical case of

$x_d = 1.0$, $x_d' = 0.30$, $x_q = 0.6$, $T_o = 1{,}000$, and $T_o = 0$

the regions of self-excitation are shown on figure 1. The shaded area is a region of self-excitation for the case of $T_o = 1{,}000$ as well as for the case when $T_o = 0$, indicating that the phenomenon of self-excitation is possible in a salient-pole machine for the condition when the field circuit is open. For normal values of armature resistance, $r$, when the field circuit is closed, self-excitation occurs for values of $x_c$ between $x_d$ and $x_d'$.

*Armature Resistance Neglected.* For the case of $r = 0$, equation 21 reduces to

$$D(p) = x_d'x_qT_op^5+x_dx_qp^4+T_o[2x_d'x_q+x_c(x_q+x_d')]p^3+[2x_dx_q+x_c(x_q+x_d)]p^2+T_o[x_d'x_q-x_c(x_q+x_d')+x_c^2]p+[x_dx_q-x_c(x_q+x_d)+x_c^2]p \quad (22)$$

By applying Routh's criterion the following array is obtained (common coefficients which are positive in value are omitted following the first 2 rows):

| | | |
|---|---|---|
| $x_d'x_qT_o$ | $T_o[2x_d'x_q+x_c(x_q+x_d')]$ | $T_o[x_d'x_q-x_c(x_q+x_d')+x_c^2]$ |
| $x_dx_q$ | $[2x_dx_q+x_c(x_q+x_d)]$ | $[x_dx_q-x_c(x_q+x_d)+x_c^2]$ |
| $x_q$ | $[x_c-x_q]$ | |
| $x_q[3x_d+x_c]$ | $[x_d-x_c][x_q-x_c]$ | |
| $[x_c-x_q]$ | | |
| $[x_c-x_q][x_d-x_c][x_q-x_c]$ | | |

Therefore, self-excitation occurs when

$$x_c < x_q \quad \text{and} \quad x_q < x_c < x_d \quad \text{or} \quad x_c < x_d \quad (23)$$

Accordingly, with zero resistance the phenomenon of self-excitation can occur for any value of capacitance less than that corresponding to the direct-axis synchronous reactance. Practically, however, as shown in figure 1, only a small amount of resistance decreases the range of self-excitation from ($x_d$ to 0) to $x_d$ to $x_d'$).

*Field Switch Open.* For the case of $T_o = 0$, equa-

tion 21 yields the following array when Routh's criterion is applied:

$$x_d x_q \qquad 2x_d x_q + x_c(x_d + x_q) + r^2 \qquad x_d x_q - x_c(x_d + x_q) + x_c^2 + r^2$$

$$r(x_d + x_q) \qquad r(x_d + x_q) + x_c^2 \qquad 0$$

$$\left\{ \begin{matrix} (x_d + x_q)x_d x_q + \\ x_c(x_d^2 + x_q^2) + r^2(x_d + x_q) \end{matrix} \right\} \qquad \left\{ \begin{matrix} (x_d + x_q)x_d x_q - x_c(x_d + x_q)^2 \\ + (x_c^2 + r^2)(x_d + x_q) \end{matrix} \right\}$$

$$\left\{ \begin{matrix} 2(x_d + x_q)^2 + 2r^2(x_d + x_q) \\ + x_c(x_d - x_q)^2 \end{matrix} \right\}$$

$$[x_d x_q - x_c(x_d + x_q) + (x_c^2 + r^2)]$$

Therefore, the values of $x_c$ which will result in self-excitation when the field circuit is open are

$$\frac{x_d + x_q - \sqrt{(x_d - x_q)^2 - 4r^2}}{2} < x_c < \frac{x_d + x_q + \sqrt{(x_d - x_q)^2 - 4r^2}}{2} \quad (24)$$

If $x_d = x_q$, which is the case of a machine with laminated cylindrical rotor, self-excitation cannot occur when the field circuit is open. Equation 24 describes the region of self-excitation for values of $x_c$ between $x_d$ and $x_q$ as shown in figure 1.

*Infinite Field Time Constant.* For the case of $T_o = \infty$ equation 21 yields a similar expression to that obtained for the case when $T_o = 0$ except $x_d'$ replaces $x_d$. Accordingly, the values of $x_c$ which will result in self-excitation when $T_o = \infty$ are

$$\frac{x_d' + x_q - \sqrt{(x_d' - x_q)^2 - 4r^2}}{2} < x_c < \frac{x_d' + x_q + \sqrt{(x_d' - x_q)^2 - 4r^2}}{2} \quad (25)$$

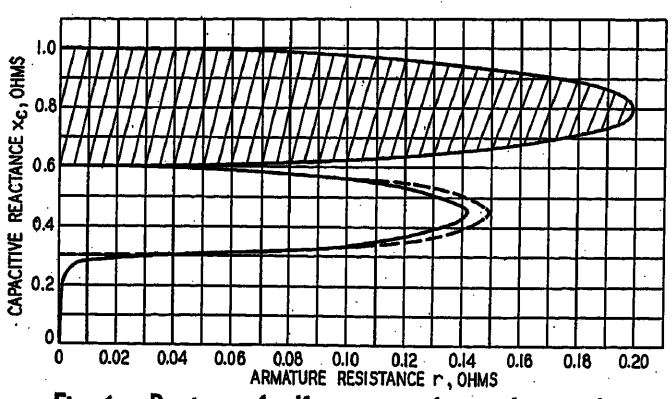



**Fig. 1. Regions of self-excitation for a salient-pole synchronous machine**

$x_d = 1.0$ $\qquad x_d'' = x_d' = 0.30$
$x_q'' = x_q' = x_q = 0.60$ $\qquad T_o = 1{,}000$
Shaded area applies for field circuit opened or closed
Dotted line applies for $T_o = \infty$ (approximate solution)

Equation 25 is a good approximation to the actual case when $T_o$ is large for the region between $x_q$ and $x_d'$ as shown by figure 1.

This section may be summarized as follows:

1. For a machine having rotor circuits additional to the field circuit, the regions of self-excitation can be determined by numerical substitution in equation 20.

2. For most practical purposes the regions of self-excitation can be determined by equations 24 and 25 for the case of a synchronous machine without an amortisseur winding.

3. For normal values of armature circuit resistance, values of capacitive reactance between $x_d$ and $x_d'$ for a machine without an amortisseur will result in self-excitation.

4. A value of series armature resistance greater than both $(x_d - x_q)/2$ and $(x_q - x_d')/2$ will prevent the phenomenon from occurring, for a machine without an amortisseur.

5. The above results are a theoretical explanation of the difficulties sometimes encountered (*a*) when a capacitance shunt load greater than the line charging capacity is connected to a synchronous machine and (*b*) when a synchronous machine is connected to a source of voltage through a series capacitance.

## Applications to a 3-Phase Fault

Equations 14 and 15 will be applied to the case of a 3-phase fault on a synchronous machine running at synchronous speed initially open-circuited having capacitance in its armature circuit. This is also equivalent to suddenly throwing on a capacitive load. The currents $i_d$ and $i_q$ for this case can be determined by substituting $e_d = 0$, $e_q = -e_{q0}1$, and $s = 0$ in equations 18 and 19. This yields

$$i = \frac{(p^2 + 1)x_q(p) - x_c}{A(p)} e_{q0}1 \quad (26)$$

$$i_q = \frac{(p^2 + 1)Z_d(p) + px_c}{A(p)} e_{q0}1 \quad (27)$$

where $A(p)$ is given by equation 20 with $s = 0$.

Equations 26 and 27 are operational expressions for the currents $i_d$ and $i_q$ which can be solved by means of Heaviside's expansion theorem, the roots of the denominator being determined by means of Graeffes[14] root-squaring method. Having determined the current $i_d$ and $i_q$, the phase currents $i_a$, $i_b$, and $i_c$ are obtained by substituting in equation 14 of reference 2.

The general solution of the operational expressions for the current, particularly when the effect of more than one rotor circuit is considered, involves a great deal of algebraic work. However, considerable information as regards the phenomena being studied can be obtained by making use of certain simplifying assumptions. The following is an example to illustrate this.

Suppose that it is required to determine the maximum possible voltage which may occur across the terminals of a synchronous machine when it is suddenly thrown on to a very large capacitive load. This also corresponds to the case of a short circuit occurring on the system side of the capacitance of a machine having series capacitors in its armature circuit. Let the machine and capacitor constants be as follows:

$x_d = 1.0$, $x_q = 0.60$, $x_d' = 0.35$, $r = 0.05$, $T_o = 1{,}000$, $x_c = 0.20$

From the values chosen it is apparent that the value of capacitance of 0.20 does not lie between $x_d'$ and $x_d$ and therefore it will be assumed that self-excitation does not occur for these constants. Practically, for this assumption to be valid, $x_c$ should be definitely less than $x_d'$ by a small amount, as the effect of saturation, which has been neglected, is to reduce the effective value of transient reactance.

The maximum short-circuit current can be calculated on the basis that $T_o = \infty$ and $r = 0$, which neglects the decrements in current and voltage. This results in a fair approximation for the current and voltage during the first few cycles after the fault is

applied and in a considerable simplification in the algebraic work. For these conditions equations 26 and 27 yield

$$i_d = \frac{0.60\,p^2 + 0.40}{0.21\,p^4 + 0.61\,p^2 + 0.06}\,1$$

$$i_q = \frac{0.35\,p^3 + 0.55\,p}{0.21\,p^4 + 0.61\,p^2 + 0.06}\,1$$

which gives

$$i_d = 6.67 - 0.81\cos 1.67\,t - 5.83\cos 0.32\,t$$
$$i_q = 0.452\sin 1.67\,t + 2.82\sin 0.32\,t$$

Substituting the values of $i_d$ and $i_q$ in

$$i_a = i_d\cos(t+\alpha) - i_q\sin(t+\alpha)$$

and simplifying,

$$i_a = 6.67\cos(t+\alpha) - 0.63\cos(0.67\,t-\alpha) - 4.33\cos(0.68\,t-\alpha) - 0.18\cos(2.67\,t+\alpha) - 1.51\cos(1.32\,t+\alpha)$$

The voltage across the capacitor is

$$V_a = \frac{1}{c}\int i_a\,dt$$

$$= 1.33\sin(t+\alpha) - 0.01\sin(2.67\,t+\alpha) - 0.23\sin(1.32\,t+\alpha) - 1.29\sin(0.68\,t-\alpha) - 0.19\sin(0.67\,t-\alpha)$$

indicating a possible maximum transient voltage across the capacitor of 3 times normal. The actual maximum voltage across the capacitor would be somewhat less because the effect of armature circuit resistance, which was neglected, would be to damp out the components having frequencies other than normal frequency. The voltage across the capacitor immediately after the armature circuit transients have died away corresponds to that given in the first term of the above expression for voltage.

From these results, the conclusion is reached that during the first few cycles immediately following the short circuit, the voltage across the capacitor will be from 1.3 to 3.0 times normal line-to-ground voltage, depending upon the value of armature circuit resistance.

The sustained voltage is

$$V_a = \frac{0.20\times 1}{1.0 - 0.20}\times\sin(t+\alpha) = 0.25\sin(t+\alpha)$$

By these comparatively simple calculations, it is evident that the transient voltage across the capacitance will be considerably greater than that corresponding to the sustained voltage, and that the maximum possible voltage is approximately 3.0 times normal.

*Approximate Field Time Constant.* An approximate value for the time constant of the field circuit under the condition of capacitive load can be determined by dividing the coefficient of $p^1$ by the coefficient of $p^0$ in equation 21. This yields, when terms in the coefficient for $p^1$ which do not include $T_o$ are neglected,

$$T_d' = \frac{(x_d - x_c)(x_q - x_c) + r^2}{(x_d' - x_c)(x_q - x_c) + r^2}\,T_o \qquad (28)$$

This time constant is valid only when $T_d'$ and $T_o$ are comparatively large. Although approximate, it does indicate with good accuracy the values of $x_c$ which will cause $T_d'$ to become negative and accordingly produce self-excitation.

## Application to Small Angular Oscillation

Park gives for the change in electrical torque for small changes in angular displacement of a synchronous machine connected to an infinite bus (equation 60, reference 1)

$$\Delta T = [\psi_{d0} + i_{d0}x_q(p)]\,\Delta i_q - [\psi_{q0} + i_{q0}x_d(p)]\,\Delta i_d \qquad (29)$$

By substituting the following relations in equations 14 and 15, $\Delta i_d$ and $\Delta i_q$ can be determined:

$$\psi_d = \psi_{d0} + \Delta\psi_d \qquad e_d = e_{d0} + \Delta e_d \qquad i_d = i_{d0} + \Delta i_b$$
$$\psi_q = \psi_{q0} + \Delta\psi_q \qquad e_q = e_{q0} + \Delta e_q \qquad i_q = i_{q0} + \Delta i_q$$
$$p\theta = 1 + p\Delta\delta$$

This yields,

$$\left.\begin{aligned} e_{q0} &= \psi_{d0} + x_c i_{d0} - r\,i_{q0} \\ e_{d0} &= -\psi_{q0} - x_c i_{q0} - r\,i_{d0} \end{aligned}\right\} \qquad (30)$$

and

$$\left.\begin{aligned} &p\Delta e_d - \Delta e_q - e_{q0}p\Delta\delta = p^2\Delta\psi_d - 2p\Delta\psi_q - 2\psi_{d0}p\Delta\delta - \Delta\psi_d - \psi_{q0}p^2\Delta\delta - rp\Delta i_d + r\Delta i_q + ri_{q0}p\Delta\delta - x_c\Delta i_d \\ &p\Delta e_q + \Delta e_d + e_{d0}p\Delta\delta = p^2\Delta\psi_q + 2p\Delta\psi_d - 2\psi_{q0}p\Delta\delta - \Delta\psi_q + \psi_{d0}p^2\Delta\delta - rp\Delta i_q - r\Delta i_d - ri_{d0}p\Delta\delta - x_c\Delta i_q \end{aligned}\right\} \qquad (31)$$

$$\left.\begin{aligned} \psi_{d0} &= E_{fd} - x_d i_{d0} \\ \psi_{q0} &= -x_q i_{q0} \end{aligned}\right\} \qquad (32)$$

Substituting equations 32 in equations 30 and solving for the initial currents,

$$i_{d0} = \frac{E_{fd}(x_q - x_c) - (x_q - x_c)e\cos\delta_0 - r\,e\sin\delta_0}{(x_d - x_c)(x_q - x_c) + r^2} \qquad (33)$$

$$i_{q0} = \frac{E_{fd}\,r - e\,r\cos\delta_0 + (x_d - x_c)\,e\sin\delta_0}{(x_d - x_c)(x_q - x_c) + r^2} \qquad (34)$$

From equation 28 of reference 1,

$$e_d = e\sin(\delta_0 + \Delta\delta) \qquad e_q = e\cos(\delta_0 + \Delta\delta)$$

Since $\Delta\delta$ is small,

$$\Delta e_d = e\cos\delta_0\,\Delta\delta \qquad \Delta e_q = -\,e\sin\delta_0\,\Delta\delta$$

Also from equations 5,

$$\Delta\psi_d = -\,x_d(p)\,\Delta i_d \qquad \Delta\psi_q = -\,x_q(p)\,\Delta i_q$$

Substituting these relations in equations 31,

$$\left.\begin{aligned} &[-e\cos\delta_0 - 2\psi_{q0}p + \psi_{d0}p^2 - ri_{d0}p]\,\Delta\delta = [2px_d(p) + r]\,\Delta i_d + [p^2x_q(p) - x_q(p) + rp + x_c]\,\Delta i_q \\ &[-e\sin\delta_0 - 2\psi_{d0}p - \psi_{q0}p^2 + ri_{q0}p]\,\Delta\delta = [p^2x_d(p) - x_d(p) + rp + x_c]\,\Delta i_d - [2px_q(p) + r]\,\Delta i_q \end{aligned}\right\} \qquad (35)$$

Equations 35 can be solved for $\Delta i_d$ and $\Delta i_q$ and substituted in equation 29 for the incremental torque. Therefore,

$$\Delta T = f(p)\,\Delta\delta$$

The response to a sudden change in the electrical angular displacement, $\Delta\delta 1$, may be determined by

(*Concluded on page 36*)

# Proposed Transformer Standards

By J. E. CLEM
MEMBER AIEE

**During the past 2 years the AIEE transformer subcommittee* has proposed changes in the AIEE transformer standards; this paper is presented to bring these changes before the Institute.**

## 1—Transformer Insulation Levels

DURING previous years the transformer subcommittee established insulation levels for transformers connected to circuits operating at standard voltages. These requirements have been passed on to the ASA sectional committee on transformers (V. M. Montsinger, chairman), and on to the standards sub-committee (W. M. Dann, chairman). The ASA transformer standards subcommittee has taken these insulation levels and incorporated them in the standards with slight modifications not affecting the fundamental requirements. A memorandum of the proposed ASA standards was submitted to the transformer subcommittee and approved with minor changes and recommended for immediate use. These proposed standards follow and are essentially as given in the proposed ASA transformer standards as material in Sections II, III, and IV.

### A—Standards Common to Transformers, Regulators, and Reactors

*Insulation Level.* Table I gives the relations between established rated circuit voltages, limits of rated apparatus voltages, and required basic insulation levels, for transformers and other induction apparatus covered by the standards. Column 1 gives the values of established circuit voltages. Column 2 gives the limits of rated apparatus voltages permissible for the corresponding insulation levels. Columns 3 and 4 give the required standard insulation levels in terms of the spacings of rod gaps used in making impulse tests, and of the low-frequency dielectric test.



A bank of modern large transformers

Table I

| Rated Circuit Voltage—Volts | Limit of Rated Apparatus Voltage—Kv | Basic Insulation Level: Impulse Test Gap Spacing—Inches | Basic Insulation Level: Alternating Voltage Dielectric Test—Kv |
|---|---|---|---|
| 120 | | | |
| 240 | | | |
| 480 | | | |
| 600 | 1.2 | 0.8 | 10 |
| 2,400 | | | |
| 2,500 | 2.5 | 1.6 | 15 |
| 4,160 | | | |
| 4,330 | | | |
| 4,800 | 5.0 | 2.2 | 19 |
| 6,900 | 8.66 | 3.3 | 26 |
| 11,500 | | | |
| 13,800 | 15.0 | 4.5 | 34 |
| 25,000 | 25.0 | 7.1 | 51 |
| 34,500 | 34.5 | 10.2 | 70 |
| 46,000 | 46.0 | 13.5 | 93 |
| 69,000 | 69.0 | 20.6 | 139 |
| 92,000 | 92.0 | 27.5 | 185 |
| 115,000 | 115.0 | 34.7 | 231 |
| 138,000 | 138.0 | 42.1 | 277 |
| 161,000 | 161.0 | 49.0 | 323 |
| 196,000 | 196.0 | 60.0 | 393 |
| 230,000 | 230.0 | 70.4 | 461 |
| 287,500 | 287.5 | 88.0 | 578 |
| 345,000 | 345.0 | 105.6 | 691 |

Note 1—When apparatus is suitable for wye connection, the name plate shall be so marked and the circuit (line-to-line) voltage rating shall determine the required basic insulation level and bushing requirements. For example, if a transformer is designed for a high voltage of 6,900/11,950Y the name plate shall be marked accordingly and the transformer will be in the 15-kv insulation class.

Note 2—Exceptions to these standards will be found in the specific sections.

### B—Standards for Distribution and Power Transformers

In the ASA standards for distribution and power transformers the same introductory paragraphs and the table will be reproduced, with footnotes essentially as follows:

Note 1—When transformers are suitable for wye connection the name plate shall be so marked and the circuit (line-to-line) voltage rating shall determine the insulation level. For example:
Single-phase transformers for 8,660 volts or below shall be suitable for connection in star (wye) and shall be capable of withstanding tests as shown in table II.

### C—Standards for Instrument Transformers

In the ASA standards for instrument transformers the introductory paragraph on insulation level is again reproduced, with suitable wording to make it apply to instru-

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## Table II

| Transformer Voltage Rating | Impulse Test Gap Spacing—Inches | Alternating Voltage Dielectric Test—Kv |
|---|---|---|
| Single-phase transformers | | |
| 2,400 delta/4,160 star | 2.2 | 19 |
| 4,800 delta/8,320 star | 3.3 | 26 |
| 6,900 delta/11,950 star | 4.5 | 34 |
| 3-phase transformers | | |
| 2,400 delta or star | 1.6 | 15 |
| 4,800 delta or star | 2.2 | 19 |
| 6,900 delta or star | 3.3 | 26 |

(The reference to table II appears as a note in the main table opposite 1.2–2.5–5.0–8.66 kv transformer voltages.)

Note 3—*Exception*—Transformers designed to permit star-connected operation on circuits of 92,000 volts and above with the neutral solidly grounded, may be designed, when so specified, to be capable of withstanding only an induced-voltage test corresponding to that required for the next lower rated circuit voltage class.

Note 4—Transformers may be provided with regulation taps for voltages not exceeding 10 per cent above the rated circuit voltage.

## Table III

| Transformer Voltage Rating | Impulse Test Gap Spacing—Inches | Alternating Voltage Dielectric Test—Kv |
|---|---|---|
| Single-phase transformers | | |
| 2,400 delta/4,160 star | 2.2 | 19 |
| 4,800 delta/8,320 star | 3.3 | 26 |
| 6,900 delta/11,950 star | 4.5 | 34 |
| 3-phase transformers | | |
| 2,400 delta or star | 1.6 | 15 |
| 4,800 delta or star | 2.2 | 19 |
| 6,900 delta or star | 3.3 | 26 |

(The reference to table III appears as a note in the main table opposite 1.2–2.5–5.0–8.66 kv transformer voltages.)

Note 3—The next-lower insulation level may be specified when it is adequate. For example:

(*a*) For potential transformers for 15 kv or below when exposure to impulse voltage is low.
(*b*) *Exception*—Transformers designed to permit star-connected operation on circuits of 92,000 volts and above with the neutral solidly grounded, may be designed, when so specified, to be capable of withstanding only an induced voltage test corresponding to that required for the next lower rated circuit voltage class.

Note 4—Voltage ratings of current transformers are the maximum voltages for which they are applicable. For co-ordinated insulation, current transformers having the same test-gap ratings as other apparatus in the circuit should be selected.

ment transformers, together with the table, and the footnotes are essentially as follows:

Note 1—When potential transformers are suitable for wye connection, the name plate shall be so marked and the circuit (line-to-line) voltage rating shall determine the insulation level. For example: Single-phase potential transformers for 8,660 volts or below shall be suitable for connection in star (wye) and shall be capable of withstanding tests as shown in table III.

## 2—Impulse Tests on Transformers

Initially the impulse test code required 5 tests to be made. In the "Recommended Transformer Standards" by Putman and Clem, published in ELECTRICAL ENGINEERING, December 1934, this was changed to require 3 tests. Since that time the wording designating the tests has been changed to the following:

(*a*) Apply a wave just sufficient to cause flashover of the specified test gap under existing conditions of humidity and air density.
(*b*) Apply a wave sufficient to cause flashover of the bushing. For this test the applied voltage must be at least 5 per cent in excess of the standard minimum flashover voltage for the standard bushing under standard conditions of humidity and air density.

Note—When oversized bushings are used they shall be equipped with suitable gaps to provide the same standard minimum impulse flashover as for the standard bushing.

(*c*) Apply a wave having a crest not less than 90 per cent of the standard minimum flashover voltage of the standard bushing under existing conditions of humidity and air density. No flashover of the bushing shall occur during the test.

Standard atmospheric conditions for these tests are a temperature of 25 degrees centigrade, air density corresponding to 760 millimeters of mercury and a humidity corresponding to a vapor pressure of 15.46 millimeters.

These changes in wording are the result of changes made from time to time to make the test requirements more explicit.

## Table IV—Insulation Requirements for Current Limiting Reactors

| Limit of Rated Apparatus Voltage—Kv | Low-Frequency Dielectric Test Applied Voltage—Kv | |
|---|---|---|
| | Oil Insulated | Air Insulated |
| 1.2 | 12 | 20 |
| 2.5 | 17 | 25 |
| 5. | 21 | 30 |
| 8.66 | 29 | 40 |
| 15.0 | 36 | 60 |
| 25.0 | 58 | 85 |
| 34.5 | 80 | 115 |
| 46.0 | 106 | |
| 69.0 | 157 | |
| 92 | 209 | |
| 115 | 261 | |
| 138 | 312 | |
| 161 | 364 | |
| 196 | 444 | |
| 230 | 520 | |
| 287.5 | 648 | |
| 345 | 780 | |

## 3—Insulation Requirements—Current Limiting Reactors

There are, in general, 2 types of construction for current-limiting reactors—oil insulated and air insulated. The insulation has in practice departed somewhat from former Institute standards and the ASA sectional committee has modified these values in accordance with table IV and the AIEE transformer subcommittee recommends that these values be put into immediate use.

## 4—Transformer for Mercury Arc Rectifiers

The transformer subcommittee does not agree with the present recommendations of the mercury arc rectifier. Subcommittee for the insulation of mercury-arc-rectifier transformers. It recommends higher test voltages based

## Table V

| D-C Voltage —Volts | Limit of Rated Apparatus Voltage —Kv | Alternating Voltage Dielectric Test —Kv |
|---|---|---|
| 0– 700 | 1.2 | 10 |
| 701– 1,500 | 2.5 | 15 |
| 1,501– 3,000 | 5.0 | 19 |
| 3,001– 5,000 | 8.66 | 26 |
| 5,001– 8,750 | 15.0 | 34 |
| 8,751–15,000 | 25.0 | 51 |
| 15,001–20,000 | 34.5 | 70 |

on voltage classifications which agree with those for other transformers.

It is reasonable to insulate primaries of rectifier transformers according to conventional transformer practice. The secondaries of these transformers are not, as a rule, exposed to lightning directly, and, accordingly, the next lower insulation level might be considered. However, the secondaries are exposed to overvoltages inherent in the operation of the rectifying equipment, so that a reduction in the low-frequency dielectric test does not seem advisable. Accordingly, the insulation of the secondary windings of these transformers should also follow conventional transformer practice after the proper insulation class of the transformer secondary winding has been agreed upon. However, the impulse tests for other transformers have been set up with overvoltages for lightning in mind. Rectifier transformers are subject only to overvoltages inherent in their operation which may be different in their character and frequency of occurrence, and, therefore, it seems advisable to study the question of the proper impulse test further.

There might be some question as to the secondary voltage rating to be used in selecting the insulation level on account of the variation in connections used to obtain the same d-c voltage. This occurs because the transformer secondary voltage for the same d-c voltage may be different for different schemes of connections. It appears reasonable that the most consistent results would be obtained if the d-c voltage was made the basis for determining the voltage class. It was agreed that the voltage class should be determined by the formula:

$$\text{Voltage class} = 2 \times \frac{\text{Rated d-c voltage}}{1.17}$$

The rated d-c voltage divided by 1.17 gives the corresponding open-circuit voltage to neutral of the rectifier

## Table VI—Bushing Characteristics

Transformers Larger than 500 Kva (Power). Transformers 500 Kva and Smaller (Distribution)

| Rated Circuit Voltage—Kv (1) | Maximum Rated Apparatus Voltage—Kv (2) | Power Transformers: Equivalent Rod Gap—Inches (3) (4) | Power Transformers: Impulse Flashover Kv (5) (6) | Power Transformers: 60-Cycle Flashover Dry—Kv (6) (8) | Power Transformers: 60-Cycle Flashover Wet—Kv (7) (8) | Distribution Transformers: Equivalent Rod Gap—Inches (3) (4) | Distribution Transformers: Impulse Flashover Kv (5) (6) | Distribution Transformers: 60-Cycle Flashover Dry—Kv (6) (8) | Distribution Transformers: 60-Cycle Flashover Wet—Kv (7) (8) |
|---|---|---|---|---|---|---|---|---|---|
| 0.12 | | | | | | | | | |
| 0.24 | | | | | | | | | |
| 0.48 | | | | | | | | | |
| 0.60 | 1.2 | 2.25 | 64 | 25 | 12 | 0.875 | 35 | 11 | 7 |
| 2.4 | | | | | | | | | |
| 2.5 | 2.5 | | | | | | | | |
| 4.16 | | | | | | | | | |
| 4.33 | | | | | | | | | |
| 4.80 | 5.0 | 3.4 | 82 | 40 | 27 | 2.3 | 65 | 27 | 18 |
| 6.9 | 8.66 | 4.5 | 98 | 50 | 35 | 3.5 | 83 | 40 | 27 |
| 11.5 | | | | | | | | | |
| 13.8 | 15.0 | 5.75 | 120 | 65 | 45 | 4.7 | 102 | 53 | 37 |
| 23.0 | 25.0 | 8.1 | 160 | 85 | 60 | 7.5 | 150 | 78 | 55 |
| 34.5 | 34.5 | 11.4 | 215 | 115 | 85 | 10.6 | 200 | 110 | 80 |
| 46.0 | 46.0 | 15.0 | 270 | 150 | 120 | 14.1 | 255 | 140 | 105 |
| 69 | 69 | 22.3 | 385 | 215 | 165 | 21.6 | 375 | 205 | 155 |
| 92 | 92 | 29.6 | 500 | 280 | 210 | | | | |
| 115 | 115 | 36.7 | 600 | 340 | 260 | | | | |
| 138 | 138 | 44.0 | 710 | 405 | 310 | | | | |
| 161 | 161 | 51.2 | 815 | 460 | 355 | | | | |
| 196 | 196 | 62.3 | 980 | 555 | 430 | | | | |
| 230 | 230 | 73.0 | 1,135 | 640 | 500 | | | | |
| 287.5 | 287.5 | 92.3 | 1,400 | 760 | 610 | | | | |
| 345 | 345 | 110.5 | 1,675 | | | | | | |

For circuit voltages 92 kv and above use power transformer bushing values.

1. Column 1 gives the values of rated circuit voltages recommended in the NEMA-NELA report on preferred voltage ratings dated October 1928, for the purpose of establishing values to be used in designing and testing electrical apparatus.

Note: Rated circuit voltages of 92,000, 196,000, and 287,500 volts have been added to the NEMA-NELA list.

2. Column 2 gives the maximum rated apparatus voltages permissible for the corresponding insulation levels.

3. The equivalent rod gap for distribution transformer bushings is based on the transformer subcommittee recommendation standardizing the minimum impulse flashover for bushings at 5 per cent above the flashover of the test gap. The equivalent rod gap for power-transformer bushings for voltage classifications 69 kv and below represents existing practice. These values are minimum and must be met.

4. When bushing and equivalent rod gap are tested in parallel at minimum gap flashover with the 1.5 x 40 microsecond positive wave. 50–50 flashover of the equivalent gap and bushing should occur at minimum flashover voltage.

5. Average minimum flashover voltage with the 1.5x40 microsecond positive wave. Based on curves and tolerance of rod-gap flashover data agreed upon by the NEMA-EEI subcommittee on correlation of laboratory data, September 26, 1935. The tolerance applies to the recorded flashover voltage only (see note 3).

6. Flashover voltages are average values and are given for standard conditions of air density and humidity.

7. Wet flashover voltages are average values based on 0.1-inch precipitation per minute at an angle of 45 degrees with water having a resistivity of 12,000 ohms per centimeter cube and at standard air density.

8. The tolerance on the 60-cycle dry- and wet-flashover voltages shall be 5 per cent under standard conditions of air density and humidity.

9. All flashover values are based on the revised sphere-gap calibration data agreed upon by the sphere gap calibration subcommittee of the instruments and measurements committee. See ELECTRICAL ENGINEERING, page 783, July 1936.

transformer for any half wave 3-phase connection or double-Y connection with interphase. For the same d-c voltage, 6 or more phase half-wave connections have slightly lower corresponding transformer open-circuit voltages; single-phase connections, which are not common in power sizes, have somewhat greater open-circuit voltages. Commutation effects will, in general, result in a slightly higher a-c/d-c voltage ratio than at open circuit. Twice the maximum a-c voltage to neutral of the transformer secondary winding is equal to or greater than the maximum a-c voltage between secondary bushings and so is used to define the voltage class.

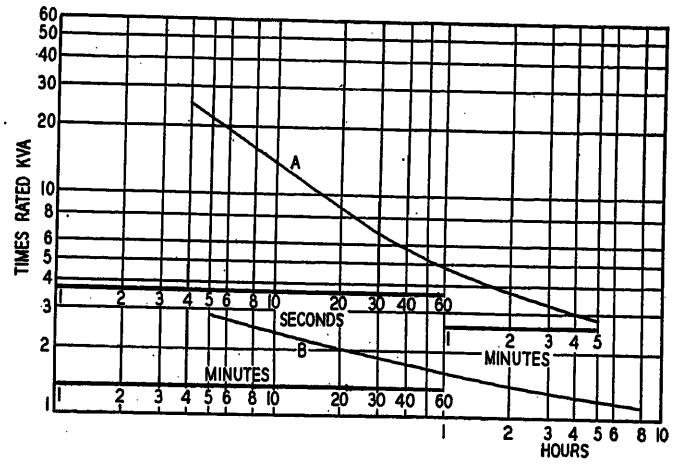



Fig. 1

| Duration of Load | Load in Multiples of Continuous Rating | Curve |
|---|---|---|
| 4 seconds | 25 | A |
| 10 seconds | 13.7 | A |
| 30 seconds | 6.7 | A |
| 60 seconds | 4.75 | A |
| 5 minutes | 2.8 | A |
| 30 minutes | 1.85 | B |
| 60 minutes | 1.6 | B |
| 2 hours | 1.4 | B |
| 5 hours | 1.2 | B |

Application of this formula gives the following, with some slight rounding off of values:

### Required Insulation Level of Transformers for Mercury Arc Rectifiers

PRIMARY WINDINGS

The primary windings of rectifier transformers shall be insulated in accordance with standard transformer requirements.

SECONDARY WINDINGS

The secondary windings of rectifier transformers shall be insulated in accordance with table V. It is recommended that this practice be put into immediate use.

## 5—Bushing Standards

Due to recent changes in the sphere-gap calibration curves it became necessary to modify the 60-cycle flashover data of transformer bushings. In addition the NEMA-EEI laboratory subcommittee on correlation of laboratory data revised the rod-gap flashover data which in turn required a slight change in the tabulation bushing impulse-flashover voltages. The standard bushing characteristics with these changes shown in table VI was approved and is recommended for immediate use.

Tests to verify the flashover of bushings should be made on the basis of the new calibration curve and the new flashover values. If, however, it is required to verify the old flashover values then the old calibration curves shall be used.

## 6—Use of Sphere-Gap Calibration Curves

Since the subcommittee of the instruments and measurements committee on sphere gap calibration has revised the sphere-gap calibration curves, it is recommended that these new calibrations be put into immediate use in the testing of transformers. The new calibration curves have been published on page 783 of the July 1936 issue of ELECTRICAL ENGINEERING.

The new calibration curves are given only for the case of one sphere grounded. It was recommended that these same curves also be used for the case of nongrounded spheres, providing the ratio of gap spacing to sphere diameter does not exceed $1/4$. A review of the data has indicated that with this precaution the error will be quite small.

## 7—Short-Time Heating and Overloading of Distribution Transformers

The subcommittee's report on the short time overloading of oil-immersed power transformers were given in a paper entitled "Overloading of Power Transformers" by V. M. Montsinger and V. M. Dann, ELECTRICAL ENGINEERING, October 1934, page 1353. Since that time the subcommittee has drawn up a guide for the short-time heating and overloading of certain sizes of distribution transformers. These curves apply to transformers 100 kva and smaller below 15,000 volts, and to network transformers 500 kva and smaller. Other distribution transformers are covered by the paper just mentioned.

## Guide—Short-Time Heating and Overload—Distribution Transformers

Distribution transformers operate under varying load-time curves, generally with relatively low load factor. It is possible to apply higher than rated load for short periods without encroaching too seriously on the life of the insulation or the oil. Since the shape of the load curve is variable from day to day and from season to season, and is not subject to easy control, there is no exact method of calculating the correct size of transformer for a given location.

The deterioration of insulation proceeds at different rates, depending upon the temperature, and the end point is not definite unless some characteristic is arbitrarily chosen. Calculations of the life on the basis of assumed

load curves are therefore of somewhat uncertain value. Many such calculations integrating the effect of time and temperature have been made, however, and they tend to check data from experience which in itself is not exact, but this agreement gives some foundation for setting up a curve which should prove a useful guide in overloading distribution transformers without materially affecting the length of life which has been obtained in the past.

Such a curve representing the magnitude and duration of permissible daily overloads starting at no-load temperature has been compiled and is shown as that portion of figure 1 for times longer than 5 minutes, curve *B*. This section of the curve should be of value in the application of distribution transformers, particularly in determining the economic size of transformer required to carry the expected load, with due regard for short-time peak overloads.

The short-time portion of the curve, that is, for times less than 5 minutes, curve *A*, is based on what may be termed, in general, short circuits, whose occurrence is accidental and not premeditated as with a daily recurrent load. They may occur at any time, and hence the worst condition—occurrence after full load—must be assumed. The frequency with which they occur can only be estimated. This portion, curve *A*, of the curve will be useful in the application of primary fuse links or network transformer fuses to meet thermal protective requirements. This portion of the curve is essentially a time-current curve of distribution transformers based on not reducing their normal expected life. A fuse link to provide thermal protection for such a transformer should lie below and to the left of the transformer curve. The inherent thermal ability of fuse links is much smaller than that of the transformer windings and therefore it cannot be expected that such links will provide thermal protection for periods exceeding approximately 5 minutes.

The short-time portion, curve *A*, of the curve may also be used to determine the ability of distribution transformers to operate as grounding transformers only, and to indicate the required time and current settings of protective devices used in the neutral of such transformers to clear them in the case of sustained faults. If distribution transformers connected as grounding transformers are also required to carry load, it should be recognized that the probable more frequent occurrence of line-to-ground faults will result in a shorter life than if the transformers were operated as normal distribution units subjected to occasional secondary faults. In addition, the normal impedance of distribution transformers is usually too low for them to function as grounding transformers unless additional external impedance is added, thus requiring a study of each particular case.

These 2 proposed curves are blended to form a composite continuous curve based on the limiting condition of a 30-degree daily average ambient. For lower ambients the same increase of load may be permitted as has been standardized for use on power transformers, one per cent for each degree below 30 degrees centigrade, but no further increase shall be made below a temperature of zero degrees centigrade.

Continuous duty on distribution transformers in high ambients is so unusual as to constitute a special situation which should be presented when transformers for such service are purchased.

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## Two-Reaction Theory of Synchronous Machines

(*Continued from page 31*)

evaluating $f(p)$ by Heaviside's expansion theorem.

In the manner shown by Park[3] the synchronizing and damping component of electrical torque can be determined for any sinusoidal angular oscillation by introducing a system of vectors rotating at $s$ per unit angular velocity, where

$\Delta\delta = [\Delta\delta] \sin st$

$T_s =$ real part of $f(jS)$

$sT_d =$ imaginary part of $f(jS)$

In using the method outlined in this section for the study of sustained hunting or oscillation of a synchronous machine connected through capacitance to a system, it was found that the capacitive reactance could be subtracted from the external inductive reactance and the problem analyzed in the usual manner with good approximation, for those cases when the natural oscillation frequency of the machine being studied was small compared with normal frequency of the terminal voltage.

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# Sealed-Off Ignitrons for Welding Control

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**Accurate control of high currents for resistance welding may be obtained by igniter-type mercury-cathode tubes capable of conducting 7,000 amperes in impulses of from less than 0.01 second to several seconds duration. This paper describes design principles and manufacturing technique for tubes of the sealed-off type.**

IN THE PROCESS of resistance welding, parts to be welded are placed between high-conductivity electrodes, pressure is applied, and an impulse of current passed through the electrodes and work. The region of highest resistance, where most of the heat is developed when the current flows, is the point of contact between the pieces being welded.

When making large welds, very high currents are required to produce sufficient heat to melt the metals. It is desirable to accomplish this heating and subsequent cooling very quickly so that the melted zone does not travel from the joint through the pieces to their outer surfaces. In this way short weld timing leaves a bridge of cooler metal adjacent to each electrode, thus minimizing oxidation and deformation. This short timing, if coupled with high accuracy of current and time control, simplifies the welding of metals otherwise very difficult to weld. Thus there are encountered 2 principal requirements of any device used to control current to a resistance welder:

1. Ability to pass very high currents. Welding depends upon high currents to develop the necessary heat.

2. Quick response. The device must respond quickly if it is to follow the signal impulses and so give the desired short and accurate timing.

## The Ignitron

These requirements have been satisfied by the ignitron,[1,2,3] which may be either a sealed-off tube or a continuously pumped tank, the fundamentals of operation being the same in both cases. The ignitron is a mercury-arc rectifier having a special control electrode or igniter used for initiating the arc. Once the arc is established by passing an impulse of current through the igniter, it continues for the remainder of that half-cycle during which the anode is positive with respect to its cathode. During the negative half-cycle the arc is completely extinguished and control is regained. When the anode again becomes more positive than the cathode the arc may be re-established if desired by passing another impulse of current through the igniter. In this way alternating voltage enables one to regain control every cycle. Thus the ignitron and thyratron effect similar control over the flow of current.

In welding service, 2 ignitrons are connected "back to back" in series with the welding transformer primary as shown in figure 1. By energizing the igniter of each unit at the proper instant during each conducting cycle, 2-way or alternating conduction of current is permitted. Each ignitron passes current during half of each conducting cycle, and so control is regained every half-cycle. When the weld has been completed, conduction is stopped by removing excitation from the igniters. Two ignitrons thus act as a quickly responding contactor.

The ignitron satisfies the 2 requirements previously stated for the following reasons:

1. Use of a mercury-pool cathode makes possible the conduction of extraordinarily high instantaneous currents. Cathode life at these high currents should be very long.

2. Quick and accurate response is attained through use of the igniter electrode. When the proper impulse of current is applied to the igniter, the arc starts in less than 100 microseconds. Conduction stops at the instant an anode becomes negative, thus all conducting periods end at approximately the same point on the voltage wave.

It is therefore evident that the ignitron is sufficiently responsive for use in the welding field. If it is coupled with some suitable igniter firing circuit the necessary degree of over-all timing accuracy may be obtained.

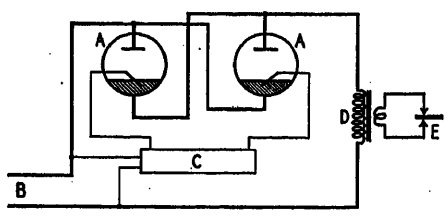



**Fig. 1. Schematic diagram of "back to back" connection**

A synchronous thyratron control[4] panel is commonly used with ignitrons in welding installations to supply this igniter firing control. This control panel or "brain" of the device makes possible initiation of the arc at any predetermined point on the voltage wave. Very short timing may be attained by firing only one ignitron and doing so just before the end of the positive half cycle. This procedure makes possible a conduction period much

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1. For all numbered references see list at end of paper.

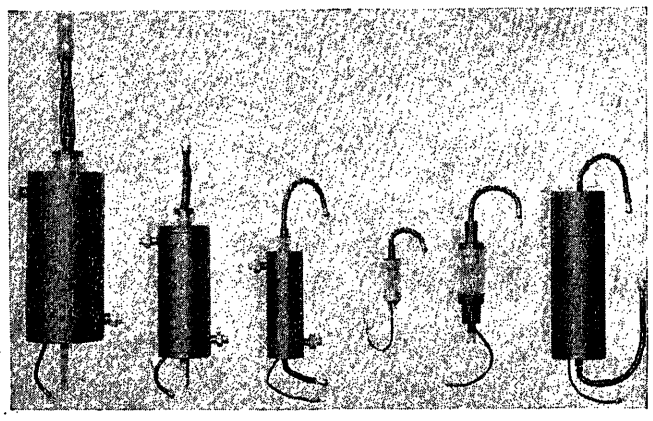


**Fig. 2. Sealed-off ignitrons of the water-cooled (3 at left) and air-cooled (3 at right) types**

shorter than one-half cycle. By uniformly starting the arc at one point on the voltage wave, the variability of current transients and hence of welds is minimized.

## Design Problems of the Sealed-Off Tube

In the development of a line of sealed-off ignitrons the design problems appear in the following natural divisions:

1. The igniter must be properly designed and located in each tube if reliable ignition of the arc is desired.

2. A current path through the tube of good conductivity must be provided to carry the high current. Peak, average, and root-mean-square currents must all be considered.*

3. Heat removal must be sufficiently effective to limit cathode, arc stream, and anode temperatures to values at which reliable operation and good life result.

4. Manufacturing technique must be such that a vacuum-tight product is obtained. This is of course essential if the unit is to be sealed off and still maintain its vacuum over an extended period of life.

The igniter is the "firing pin" of the tube. The design that has been adopted consists of a small rod of treated silicon carbide with the part dipping in the mercury pointed to a logarithmic shape.[5] The igniter is mounted on an insulating bushing in the mercury pool, making it possible to have terminals at the ends of the tube only.

The electron current from the cathode comes from a number of small spots on the pool of mercury.[6] The first spot is started by a spark from the igniter, and it divides into more spots as the current demand is increased until at high currents the emission comes from a great many small spots, each supplying from 5 to 15 amperes. One condition for determining pool size is satisfied by providing sufficient area so that the cathode spots, starting at the igniter, do not travel to the edge of the pool and anchor on the envelope in the time allotted to a single conduction interval. If this occurs, material may be sputtered from the metal walls of the tube. This requirement is easily fulfilled in normal operation since the arc has only one-half cycle during which to travel. Another consideration at the cathode is to provide large contact area between the pool and the cathode lead for the dual purpose of current and heat conduction.

The cross-sectional area of the tube influences the maximum peak current the tube will conduct without failure. As the current density in the arc stream is increased above a certain value the voltage drop in the tube, and consequently the loss per unit current, increases rapidly. This and other considerations set a current density above which it is not practical to operate. In 550-volt welder service successful operation has been obtained with arc stream current densities exceeding 500 amperes per square inch. The envelope sizes have been selected from a preferred number series of standard seamless steel tubing, thus tending to cause peak current capacities to fall in a similar series.

The anode size is determined by both the average and root-mean-square or effective currents. The heat generated at the surface depends upon the average current. The heat generated in the conducting parts is a function of the effective current. Thus both the area and the conduction cross section must be considered. The anode lead must be designed to conduct the effective current.

## Heat Removal

When conducting, a gas-filled tube has a voltage drop from anode to cathode of the same order of magnitude as the ionization potential of the gas. This voltage is roughly independent of the current being carried by the arc and in the case of these mercury-pool tubes is approximately 15 volts. This drop causes power loss which appears as heat within the tube.

A mercury-pool tube of any one design and operating under certain current and voltage conditions will perform satisfactorily only when the temperatures of the various parts lie below definite limiting values. It is particularly important to limit the mercury-vapor pressure in the tube. This pressure is determined by the temperature of the cooler parts. If the temperature limits are exceeded, current may be carried in either direction when the igniter is not energized and conduction is not desired. Bad welds may result from such failures. A tube which fails by carrying current in the forward direction is commonly said to "shoot through." One which carries current in the reverse direction is said to "arc back."

The limiting condensed-mercury temperatures of ignitrons now available lie between 50 and 125 degrees centigrade. This means that relatively small temperature differences, between some tube parts and cooling medium, are available for removal of heat.

In the case of low-power ignitrons, air cooling of both ends has been accomplished by providing good paths for conduction of heat from anode and cathode to larger and cooler external parts. An example of this type of

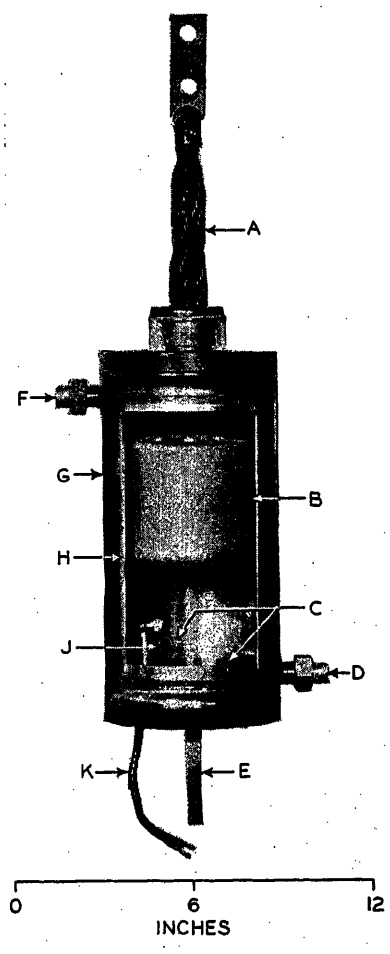
*The highest instantaneous value of current conducted will be referred to hereafter as peak anode current or simply peak current. Large welds require high peak currents.
Average anode current per tube is obtained by averaging the instantaneous values over the rated averaging period. This period is usually sufficiently long to include several welds and the intervening off periods. Both the size of the welds and the frequency at which they are made determine the average current.
Root-mean-square current, as referred to in this paper, is measured or calculated in the usual manner considering both the time of current flow and the time off included in the rated averaging period of the tube.

cooling is seen in the 2 smaller tubes shown in figure 2. Radiation and forced ventilation are utilized to remove the heat from tubes of intermediate size. Parts of the tube, the anode in particular, are allowed to operate at high temperatures and so radiate effectively. Parts controlling mercury temperature, such as those parts in the region of the pool cathode, are cooled mainly by forced ventilation. An example of this class of ignitron is the tube on the right side of figure 2.

The amount of heat generated at the cathode of a high-current tube cannot easily be transmitted by conduction through the mercury pool and other cathode parts. It is also difficult to conduct this heat through glass side walls. Temperature drop along either of these paths may be sufficiently great to give inner or effective temperatures higher than are allowable even though the outside of the tube is kept at low temperature. This fact has caused the adoption of metal construction for higher power tubes.

Coupling the metal design with water cooling, as shown in figure 3, results in the cooling water and arc stream being separated only by about $^1/_{16}$ inch of metal, the thickness of the inner envelope. As shown in this illustration, the sides of the ignitron are cooled over their entire length by use of a water jacket. Rather close spacing between the 2 cylinders forming the jacket is used to increase water velocity and so provide better heat transfer.

**Fig. 3. Cutaway view of a large water-cooled ignitron**




*A*—Anode connection
*B*—Anode
*C*—Space for mercury pool
*D*—Water inlet
*E*—Cathode connection
*F*—Water outlet
*G*—Water jacket
*H*—Tube envelope
*J*—Igniter
*K*—Igniter connection

In order to avoid air pockets and to keep coolest water in contact with the pool cathode, water enters at the bottom of the jacket and flows out at the top.

The top seal and the central part of the mercury pool are kept cool by use of heavy tube-end pieces, or headers, welded to the cooled envelope. In one tube of large diameter, these ends are over $^1/_8$ inch thick, thus providing a good path for heat conduction. In this way effective cooling, and hence effective control of mercury-vapor pressure, has been attained.

## Corrosion and Hydrogen Diffusion With Water Cooling

Water cooling, though it solved many problems, introduced the new ones of corrosion and hydrogen diffusion.

Early developmental tube models employed ordinary steel envelopes and water jackets. Passage of water through the cooling chamber caused considerable rusting. In addition, many of the hydrogen ions* present in the water filtered through the steel envelope into the tube and soon rendered it gassy and inoperable. Ordinary steel is no effective barrier to the hydrogen ion, and while the water may be treated to prevent corrosion and diffusion this does not appear at present to be economical in welding applications. While this seepage of hydrogen through the envelope might be tolerated if the unit were being pumped continuously, it obviously cannot be permitted in sealed-off tubes.

These difficulties of corrosion and hydrogen diffusion were overcome by the use of stainless steel envelopes and jackets. This material is practically impervious to the hydrogen ion at operating temperatures. Since water comes in contact only with stainless steel and the brass pipe fittings, corrosion should be extremely slow, thus permitting very long tube life from this consideration.

## Metal Tube Manufacturing Technique

Initially ignitrons were made of glass by adopting the technique then used in making hot-cathode rectifiers and thyratrons. A new glass-to-metal seal, utilizing an alloy called "fernico," and the application of thyratron control to welding introduced an entirely new technique which is now utilized in ignitron manufacture. Fernico, which is an alloy of iron, nickel, and cobalt, has an expansion characteristic which closely matches that of certain glasses.[7] It can be drawn, machined, and welded. This material makes possible strain-free glass-to-metal seals which are relatively easy to manufacture and free from leaks. All of the insulating bushings of these sealed-off ignitrons are made with such seals. The anode bushing of a large water-cooled tube is shown in figure 4.

This figure also shows some of the important welds. The fernico cup on the top is welded onto the anode lead which is designed to carry 1,500 amperes, effective value. The fernico piece on the bottom is welded onto

* Ordinary tap water has a hydrogen concentration of roughly $1 \times 10^{-7}$ mole per liter.

the steel head which forms the end of the tube. This head is seam welded into a piece of seamless steel tubing forming the envelope. If a water jacket is desired, the tube envelope is flared out at each end beyond the header and a longer cylinder is seam welded on the outside as shown in figure 3. Welding machines equipped with thyratron control, using ignitron or thyratron power tubes, make these vacuum-tight welds and other welds where consistent high quality is essential. Thus ignitrons are an important part of ignitron manufacture.

Even the air-cooled tubes made mainly of glass have been manufactured with metal tube technique. The essential difference in this case is that a larger piece of glass is used between the 2 fernico seals, for the glass is the insulating bushing and tube envelope as well. Although this glass construction has been quite popular, metal tubes are being made in all except the smaller sizes where the glass involved is of about the same size as the anode bushing of a larger tube. Figure 5 shows the smallest ignitron tube before being evacuated beside an anode bushing of a larger ignitron. This tube is made from parts of a similar but larger bushing.

This new technique used in ignitron manufacture has many advantages over older methods:

1. The vacuum-tight seals are mechanically strong and provide good support for heavy anodes and leads required by high current capacity.

2. The metal construction provides good heat transfer and simplifies water cooling.

3. The manufacturing processes may be closely controlled and do not require highly skilled labor, therefore they are less costly.

4. The metal construction gives a product more accordant with industrial psychology.

Some of these construction features have promise of use in other fields. The metal-to-glass seals may be used as insulating bushings in other apparatus. The stainless-steel seam-welded water-jacket construction offers a simple cooler for heat transfer in other devices, and the welding used throughout the line exemplifies what can be done with modern welding technique.

## Performance of the Tubes

These general design principles have been applied to ignitrons for a wide range of applications. All of the smaller tubes are air-cooled, and are used where the welds are either small or are made infrequently. The smallest tube is $1^1/_2$ inches in diameter and 3 inches long, yet it will control currents up to several hundred amperes. With this tube small welds such as are used in jewelry manufacture may be controlled. The demand for larger air-cooled tubes has been met with several other sizes, the largest of which will pass peak currents up to several thousand amperes, and can be used to time large welds which are not made in rapid succession.

Application of water cooling to tubes of intermediate rating has brought a great reduction in size and cost. An example is the small water-cooled unit shown in figure 6 which has a slightly higher capacity than the large air-cooled tube shown in the same picture.

Large sealed-off water-cooled tubes are now practical for controlling peak currents of 7,000 amperes or more and average currents, at lower peaks, as high as 250 amperes per tube. They are applied where either high peak current, high average current, or both are encountered.

(*Concluded on page 66*)

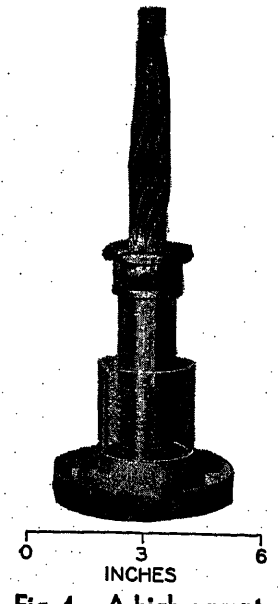



Fig. 4. A high-current anode bushing before seals have been made

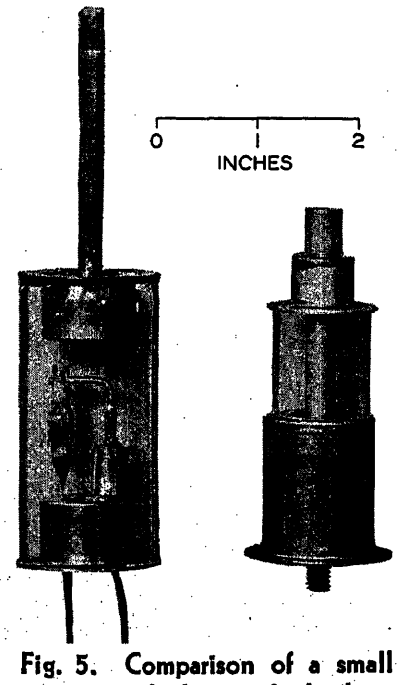



Fig. 5. Comparison of a small ignitron with the anode bushing of a larger tube

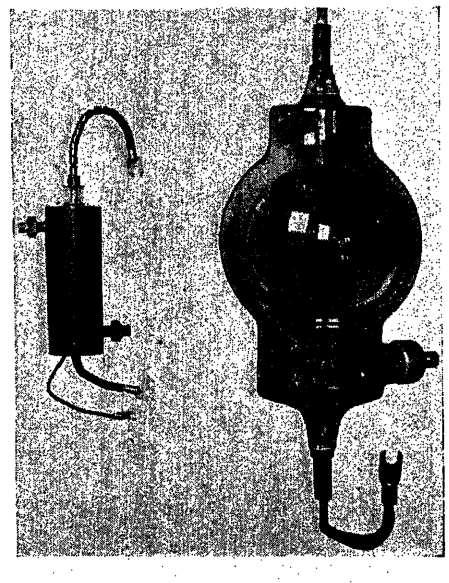


Fig. 6. A small water-cooled tube (left) that has greater current capacity than the air-cooled tube (right)

# Contributions to Synchronous-Machine Theory

By A. S. LANGSDORF
FELLOW AIEE

**In this paper the 2-reaction theory of synchronous machines is extended, for steady-state conditions, to present some new deductions apparently not previously known.**

IT HAS long been known that the cylindrical-rotor theory, based essentially upon the concept that the synchronous impedance is a constant for all loads and for all positions of the armature winding relative to the rotor, leads to gross inconsistencies when applied to salient-pole machines. The Blondel 2-reaction theory, and its extension by Doherty and Nickle,[1] have pointed the way to numerous improvements which bring the theory much more nearly into accord with the facts, but the conclusions thus far published have stopped short of a complete presentation of some exceedingly interesting deductions. It is the purpose of this paper to point out some features, apparently not previously known, which follow quite simply and naturally from the 2-reaction theory. This treatment is here limited to steady-state operation, perhaps not as important as the transient case of sudden short circuit, but the results are nevertheless of fundamental interest.

It is desirable, partly by way of introduction, but mainly to facilitate future comparisons, to review briefly the essential features of the cylindrical-rotor theory, as applied to the case of a synchronous motor; the extension to the case of the generator then follows directly. Thus, in figure 1, let

$V$ = terminal voltage
$E$ = counter electromotive force or excitation voltage
$I$ = armature current
$Z_s$ = synchronous impedance
$X_s$ = synchronous reactance
$R_a$ = effective resistance
$\varphi_s = \tan^{-1} X_s/R_a$
$\varphi$ = angle of phase displacement between $V$ and $I$

all of these quantities referring to one phase of the winding.

The power (per phase) developed by the machine, including core loss, friction, and windage, is

$$P = VI \cos \varphi - I^2 R_a \tag{1}$$

whence

$$I^2 - \frac{V}{R_a} I \cos \varphi = -\frac{P}{R_a} \tag{2}$$

Adding to both sides of this equation the constant term $(V/2R_a)^2$, it becomes

$$I^2 + \left(\frac{V}{2R_a}\right)^2 - 2\left(\frac{V}{2R_a}\right) I \cos \varphi = \left(\frac{V}{2R_a}\right)^2 - \frac{P}{R_a} \tag{3}$$

The quantity $V/(2R_a)$ is obviously a current in phase with $V$, and it is a constant. Consequently the equation states that the sum of the squares of $I$ and $V/(2R_a)$, minus twice their product times the cosine of the included angle, is a constant, provided $P$ is constant. This suggests the ordinary cosine law of trigonometry, and indicates the well-known construction, figure 2, for the circular current locus subject to the condition of constant power.

The vector diagram, figure 1, shows further that

$$(IZ_s)^2 = V^2 + E^2 - 2VE \cos \delta \tag{4}$$

where $\delta$ is the variable torque angle, whence

$$I^2 = \left(\frac{V}{Z_s}\right)^2 + \left(\frac{E}{Z_s}\right)^2 - 2\left(\frac{V}{Z_s}\right)\left(\frac{E}{Z_s}\right) \cos \delta \tag{5}$$

Here $V/Z_s$ is a constant current lagging behind $V$ by angle $\varphi_s$, as in figure 3, and $E/Z_s$ is a constant provided the excitation is held fixed. The same cosine law then shows that the current locus for a fixed excitation is a circle, figure 3, having its center at $D$, and it is readily shown that $D$ is a point on the zero-power circle. It is to be particularly noted that this construction points to the conclusion that an unexcited motor ($E = 0$) can develop no power, which is not in accord with experimental facts.

## Equivalent Impedance, 2-Reaction Theory

Applying the 2-reaction theory, the vector diagram takes the form of figure 4, where, as usual, $\psi$ is the phase displacement between the armature current and the component $(-E)$ of the impressed voltage which balances the counter electromotive force. In this diagram

$$I_q = I \cos \psi \tag{6}$$
$$I_d = I \sin \psi$$

represent, respectively, the components of armature current in the transverse (cross) axis and in the direct axis of the machine; also

$$X_q = X_q' + X_l \tag{7}$$
$$X_d = X_d' + X_l$$

where $X_q'$ and $X_d'$ are the reaction reactances in the 2 axes; and $X_l$ is the true leakage reactance, assumed to be the same in both axes.

From the diagram it is seen that

$$V \sin \delta = I_q X_q + I_d R_a \tag{8}$$

$$E - V \cos \delta = I_d X_d - I_q R_a \tag{9}$$

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1. For all numbered references see list at end of paper.

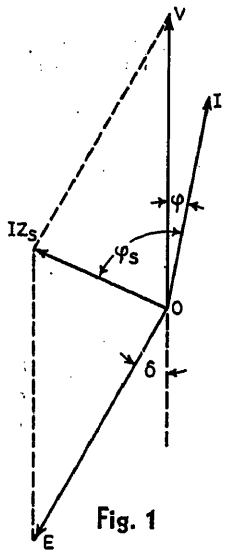


Fig. 1

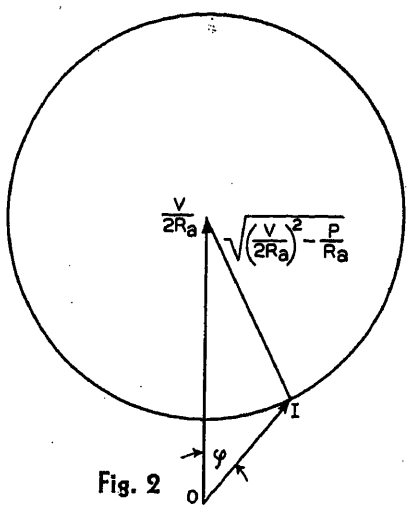


Fig. 2

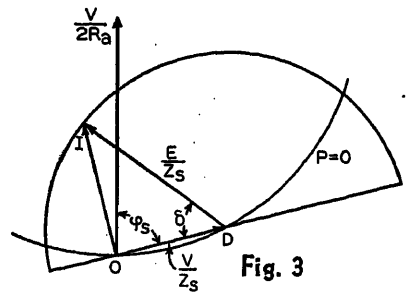


Fig. 3

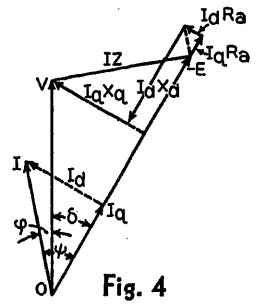


Fig. 4

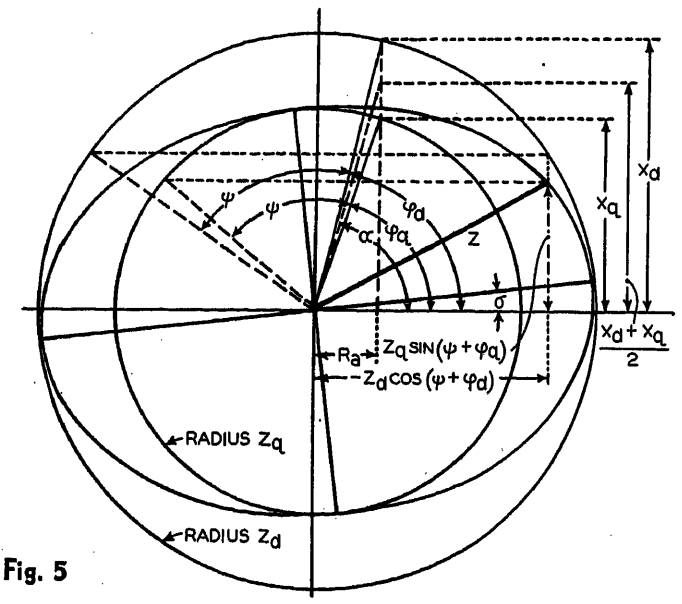


Fig. 5

which may be written in the form

$$V \sin \delta = I(X_q \cos \psi + R_a \sin \psi) = IZ_q \sin (\psi + \varphi_q) \tag{10}$$

$$E - V \cos \delta = I(X_d \sin \psi - R_a \cos \psi) = -IZ_d \cos (\psi + \varphi_d) \tag{11}$$

where

$$\left.\begin{aligned} Z_q &= \sqrt{R_a^2 + X_q^2} \\ Z_d &= \sqrt{R_a^2 + X_d^2} \\ \varphi_q &= \tan^{-1} \frac{X_q}{R_a} \\ \varphi_d &= \tan^{-1} \frac{X_d}{R_a} \end{aligned}\right\} \tag{12}$$

It is also plain from figure 4 that the equivalent impedance drop in the machine is the vector sum of $V$ and $E$, that is, $IZ$, and

$$(IZ)^2 = (V \sin \delta)^2 + (E - V \cos \delta)^2 \tag{13}$$

Substituting equations 10 and 11 in equation 13,

$$Z^2 = [Z_q \sin (\psi + \varphi_q)]^2 + [-Z_d \cos (\psi + \varphi_d)]^2 \tag{14}$$

which is at once recognizable as the polar equation of an ellipse with $Z$ and $\psi$ as the dependent and independent variables.

The graph of $Z$ as a function of $\psi$ may be quite simply constructed as in figure 5. The positions of the major and minor axes, which define the maximum and minimum values of $Z$, are found by differentiating equation 14 with respect to $\psi$ and setting the result equal to zero; thus

$$\frac{d}{d\psi}(Z)^2 = -Z_d^2 \sin 2(\psi + \varphi_d) + Z_q^2 \sin 2(\psi + \varphi_q) = 0 \tag{15}$$

which, when solved for $\psi$, gives

$$\tan 2\psi = \frac{Z_q^2 \sin 2\varphi_q - Z_d^2 \sin 2\varphi_d}{Z_d^2 \cos 2\varphi_d - Z_q^2 \cos 2\varphi_q} \tag{16}$$

On substituting in equation 16 the relations grouped as equation 12, this reduces to

$$\tan 2\psi = \frac{2 \tan \psi}{1 - \tan^2 \psi} = \frac{R_a}{\frac{1}{2}(X_d + X_q)} = \cot \alpha \tag{17}$$

or

$$\tan \psi = -\frac{\frac{1}{2}(X_d + X_q)}{R_a} \pm \sqrt{1 + \left(\frac{\frac{1}{2}(X_d + X_q)}{R_a}\right)^2} \tag{18}$$

thus defining 2 values of $\psi$, 90 degrees apart, one of which corresponds to the maximum, the other to the minimum, value of $Z$. It may be noted in passing that the major axis of the ellipse is tipped up from the horizontal axis of reference at an angle $\sigma$ such that

$$\tan \sigma = \frac{Z_q \sin \left(\frac{\pi}{4} + \frac{\alpha}{2} - \varphi_q\right)}{Z_d \cos \left(\frac{\pi}{4} + \frac{\alpha}{2} - \varphi_d\right)}$$

The maximum and minimum values themselves are most simply determined by transforming equation 14 to the form

$$Z^2 = \frac{Z_d^2 + Z_q^2}{2} + \frac{Z_d^2}{2} \cos 2(\psi + \varphi_d) - \frac{Z_q^2}{2} \cos 2 (\psi + \varphi_q) \tag{19}$$

which, when expanded and rearranged, using equation 12, becomes

$$Z^2 = \frac{Z_d^2 + Z_q^2}{2} - (X_d - X_q)\sqrt{R_a^2 + \left(\frac{X_d + X_q}{2}\right)^2} \times \sin (2\psi + \alpha) \tag{20}$$

where the angle $\alpha$, defined by equation 17, has the meaning indicated in figure 5.

The variation of the equivalent impedance $Z$ as a function of $\psi$ may be studied in another way by observing from figure 5 that its complex value may be written

$$Z = -Z_d \cos(\psi + \varphi_d) + jZ_q \sin(\psi + \varphi_q)$$
$$= \left(-R_a + j\frac{X_d + X_q}{2}\right)\epsilon^{-j\psi} - j\frac{X_d - X_q}{2}\epsilon^{j\psi} \qquad (21)$$

This equation has the simple geometrical interpretation shown in figure 6; that is, when $\psi = 0$, $Z$ is made up of the directed magnitude $OA = \left(-R_a + j\frac{X_d + X_q}{2}\right)$ combined with the directed magnitude $AB = -j\frac{X_d - X_q}{2}$, giving as resultant $Z_{\psi=0} = OB = -R_a + jX_q$. For any arbitrary value of $\psi$, $OA$ swings clockwise, to $OA'$, while $AB$ swings in a counterclockwise direction to $A'B'$, thus giving $Z = OB'$ for the particular value of $\psi$ indicated in the diagram. It will be noted that the angle between $OA'$ and $A'B'$ is always $2\psi - \alpha'$, where $\alpha'$ is the complement of the constant angle $\alpha$ that appears in figure 5 and which is defined by equation 17. Finally, therefore, the variation of $Z$ may be illustrated by the extremely simple diagram, figure 7, from which

$$Z^2 = (OC)^2 + (CP)^2 - 2(OC)(CP)\cos(2\psi - \alpha')$$
$$= \frac{Z_d^2 + Z_q^2}{2} - (X_d - X_q)\sqrt{R_a^2 + \left(\frac{X_d + X_q}{2}\right)^2} \times \cos(2\psi - \alpha') \qquad (22)$$

which is the same as equation 20.

The variation of $Z$ as a function of $\psi$ may now be shown as in figure 8, which is constructed from figure 7 by assigning various values to $\psi$ and plotting the results in rectangular co-ordinates. It is seen that $Z$ passes through 2 complete cycles of values for each cycle in the value of $\psi$, but the curve is not a simple harmonic function of $\psi$ as might at first glance be supposed to be the case; it fluctuates between limits equally spaced on either side of the ordinate $\sqrt{R_a^2 + (X_d + X_q)^2/2}$, but the upper loops are slightly longer than the lower ones, as may be seen from the fact that in figure 7 the arc through $C$, having $O$ as center, divides the small circle into 2 unequal parts, so that $a > b$ in figure 8.

Otherwise expressed, when the square root of such an expression as equation 22 is evaluated by means of the binomial theorem, terms appear that involve the ascending powers of the term $\cos(2\psi - \alpha')$, which means that the curve of figure 8 really consists of a fundamental (of double frequency) and a series of higher harmonics.

It has long been known that the reactance of a salient-pole machine varies cyclically when measured at a series of successively different positions of the field poles relatively to the winding, but it has heretofore been assumed[2] that the reactance is expressible as

$$X = X_{aver} + X' \cos(2\theta + \gamma)$$

where $X_{aver}$ is the average value over an arc of one pole pitch, $X'$ is the maximum deviation from the average, and $\theta$ is the angle, in electrical degrees, measured from an arbitrarily selected reference point on the armature surface. The analysis here presented shows conclusively that this assumption is not strictly correct, though it becomes very nearly so if $X_d$ and $X_q$ are not greatly different.

## Current Locus, Constant Excitation

Equations 8 and 9, when solved for $I_q$ and $I_d$, yield the following relations:

$$I_q = \frac{VX_d \sin\delta - R_a(E - V\cos\delta)}{X_dX_q + R_a^2} = \frac{VZ_d \cos(\delta - \varphi_d) - ER_a}{X_dX_q + R_a^2} \qquad (23)$$

$$I_d = \frac{VR_a \sin\delta + X_q(E - V\cos\delta)}{X_dX_q + R_a^2} = \frac{VZ_q \sin(\delta - \varphi_q) + EX_q}{X_dX_q + R_a^2} \qquad (24)$$

The form of these 2 expressions suggests a simple geo-

Fig. 6

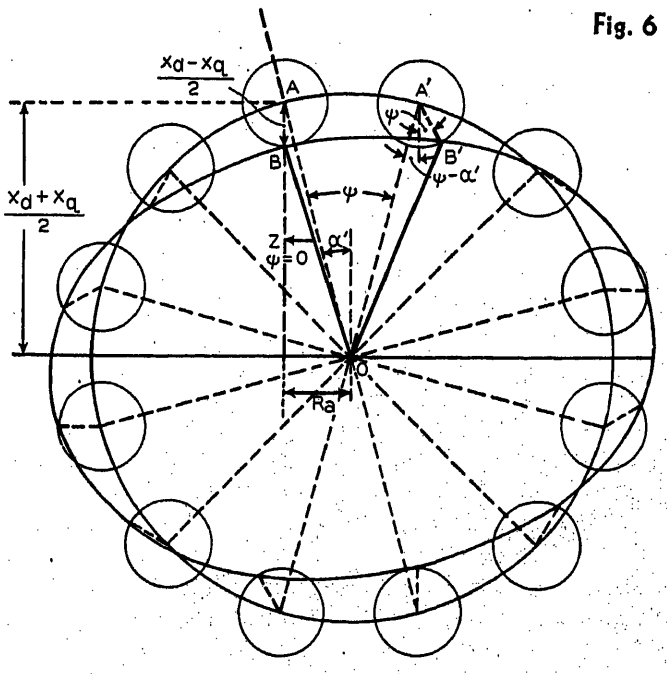



Fig. 7 (right)

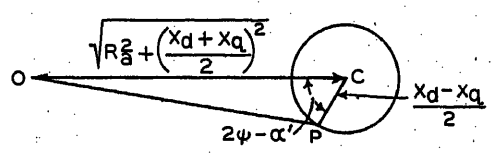
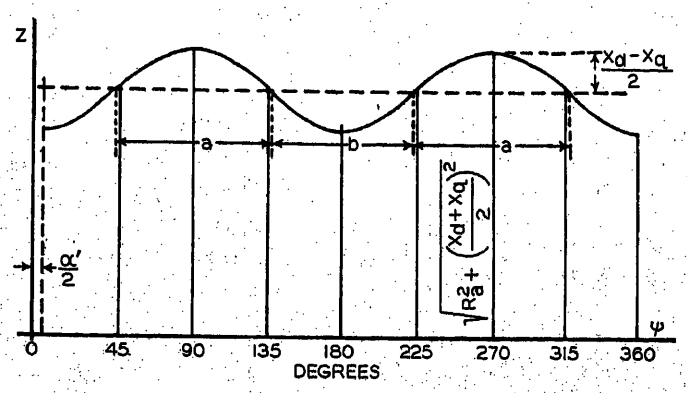



Fig. 8 (below)



metrical construction for the current locus if $E$ is maintained constant. Thus, in figure 9, $OV$ represents the fixed terminal voltage and $-OE$ is the excitation voltage, fixed as to magnitude, but displaced from $OV$ by the variable torque angle $\delta$. The lines $OD = (VZ_d)/(X_dX_q + R_a^2)$ and $OC = (VZ_q)/(X_dX_q + R_a^2)$, representing the constant coefficients that appear in equations 23 and 24, are drawn at the fixed angles $\varphi_d$ and $\varphi_q$, respectively, with $OV$. Accordingly, when perpendiculars are dropped from the points $D$ and $C$ upon the line $OE$, it follows that

$$OK = \frac{VZ_d}{X_dX_q + R_a^2} \times \cos(\delta - \varphi_d)$$

and

$$GC = \frac{VZ_q}{X_dX_q + R_a^2} \times \sin(\delta - \varphi_q)$$

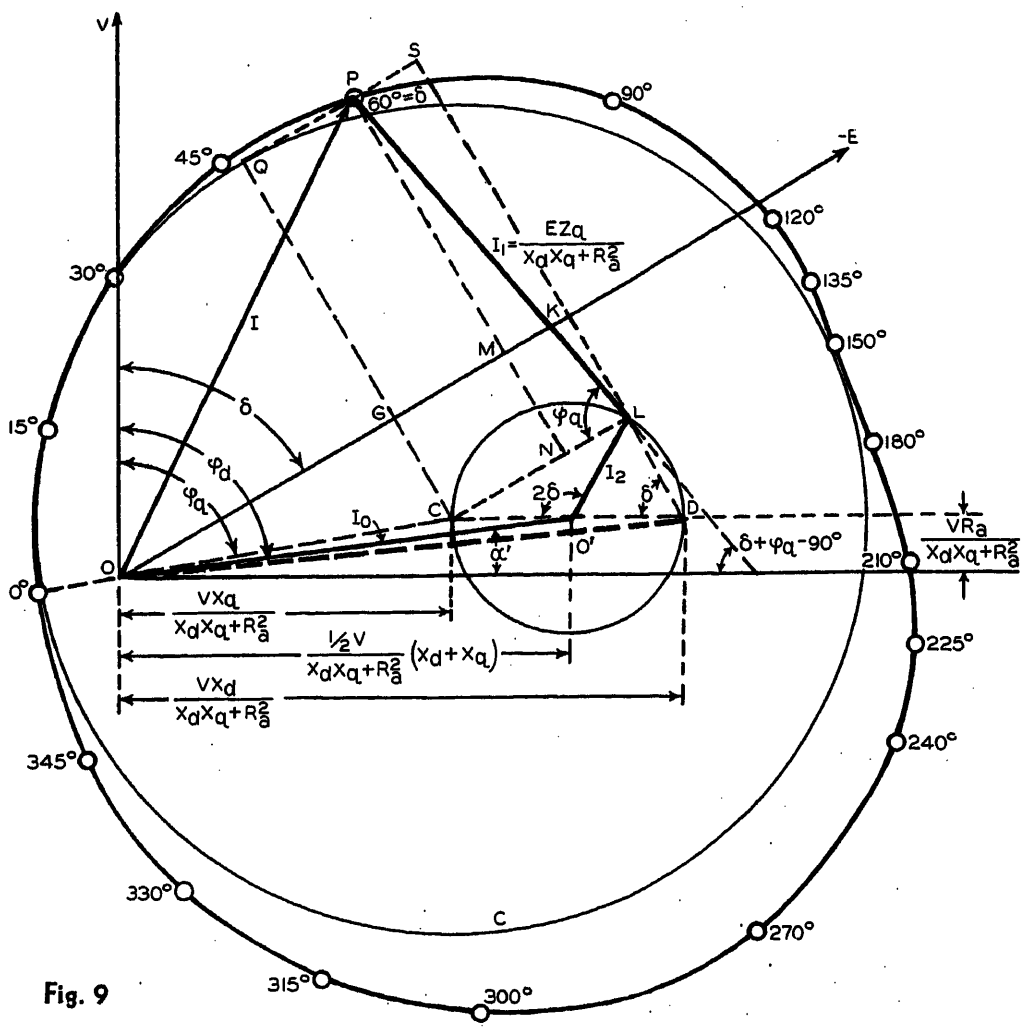



Fig. 9

On subtracting from $OK$ the fixed length

$$KM = LN = \frac{ER_a}{X_dX_q + R_a^2}$$

and adding to $GC$ (which must be considered negative in the diagram since $\delta < \varphi_q$) the fixed length

$$CQ = NP = \frac{EX_q}{X_dX_q + R_a^2}$$

it is clear that in accordance with equations 23 and 24

$$OM = I_q$$
$$MP = I_d$$

and

$$OP = \sqrt{(OM)^2 + (MP)^2} = I$$

Now it is apparent from figure 9 that no matter what value is assigned to $\delta$, the angle $CLD$ is necessarily a right angle, hence its locus is a circle having $CD$ as a diameter. The magnitude and position of $CD$ are readily fixed in terms of the co-ordinates of points $C$ and $D$ as indicated on the diagram, from which it appears that $CD$ is perpendicular to $OV$ and that

$$CD = \frac{V(X_d - X_q)}{X_dX_q + R_a^2}$$

The center of the circle $CLD$ is at $O'$, which has the co-ordinates

$$\left(\frac{V}{X_dX_q + R_a^2} \cdot \frac{X_d + X_q}{2}, \frac{VR_a}{X_dX_q + R_a^2}\right)$$

consequently the line $OO' = I_0$ is fixed in length and is tipped up from the horizontal by the same angle $\alpha'$ that appears in figure 6. Since the angle $CDK = \delta$ by construction, it follows that the radius vector $O'L = I_2$ is inclined to $O'C$ at an angle $2\delta$. Finally, the vector

$$LP = I_1 = \sqrt{\left(\frac{ER_a}{X_dX_q + R_a^2}\right)^2 + \left(\frac{EX_q}{X_dX_q + R_a^2}\right)^2} = \frac{EZ_q}{X_dX_q + R_a^2}$$

is also fixed in length so long as $E$ remains constant, and it is inclined to the horizontal at an angle $(\delta + \varphi_q - 90)$, as indicated in figure 9.

So there develops the remarkably interesting fact that the current vector $OP = I$ is the vector sum of 3 components, 2 of which, $I_0$ and $I_2$, are permanently constant in magnitude, and the third component, $I_1$, is constant for a fixed excitation; for different excitations $I_1$ is directly proportional to the excitation. But while the 3 components are constant in magnitude (for a given value of $E$), they are linked together at phase angles which change with $\delta$ in an interesting manner, with the result that the current locus has the irregular form shown in

figure 9, which has been drawn for the condition $E = (5/4)V$, and $Z_d/Z_q = 5/3$.

Expressed in complex notation,

$$I = I_0 + I_2 + I_1 \tag{25}$$

where

$$I_0 = \frac{V}{X_d X_q + R_a^2}\sqrt{R_a^2 + \left(\frac{X_d + X_q}{2}\right)^2}\epsilon^{j\alpha'} = I_0(\cos\alpha' + j\sin\alpha') \tag{26}$$

$$I_2 = -\frac{V}{X_d X_q + R_a^2}\cdot\frac{X_d - X_q}{2}\epsilon^{-j2\delta} = -I_2(\cos 2\delta - j\sin 2\delta) \tag{27}$$

$$I_1 = -j\frac{EZ_q}{X_d X_q + R_a^2}\epsilon^{-j(\delta+\varphi_q)} = -I_1[\sin(\delta+\varphi_q) + j\cos(\delta+\varphi_q)] \tag{28}$$

These results may at this point be compared with those of the cylindrical rotor theory. To do so it is only necessary to impose the condition that $Z_d = Z_q = Z_s$, or $X_d = X_q = X_s$. When this is done, the vector $I_2$ vanishes; the points $O'$ and $D$, figure 9, coalesce with point $C$, which then has the co-ordinates

$$\frac{VX_s}{X_s^2 + R_a^2} = \frac{V}{Z_s}\sin\varphi_s$$

and

$$\frac{VR_a}{X_s^2 + R_a^2} = \frac{V}{Z_s}\cos\varphi_s$$

which are the same as those of point $D$, figure 3; and the irregular current locus of figure 9 degenerates to a simple excitation circle of the type shown in figure 3. This circle is indicated in figure 9 as curve $C'$, having its center at $C$ and a radius equal to $LP$.

To construct the current loci corresponding to different values of the excitation voltage $E$, it is only necessary to modify the dimensions of triangle $LPN$ in the desired ratio; otherwise all construction lines remain the same as in figure 9. The effect of varying $E$ from zero to $(7/2)V$, by steps of $V/2$, is shown in figure 10.

Figure 10 brings out vividly some extremely interesting characteristics. One of them, known to be an experimental fact, is that an unexcited motor ($E = 0$) is capable of carrying a theoretical maximum load corresponding to the power circle $P_1$, drawn tangent to the small circle $E = 0$. The remaining power circles, indicated as $P_2$, $P_3$, . . . $P_8$, are all drawn tangent to the curves of constant excitation, and the points of tangency have as their loci the curve marked "stability limit."

Another point of interest is the shape of the excitation curves, which bulge outward to the left, and descend below the zero power circle more than they rise within it. This is a natural consequence of the difference between the action of the machine as a generator (outside the circle $P = 0$) and the action as a motor within the circle $P = 0$. On the right, beyond the stability limit, the curves are flattened when $E$ is large, they develop a concave depression as $E$ becomes smaller, and finally, for sufficiently small values of $E$, this depression becomes a re-entrant loop.

The nature of this re-entrant loop is shown somewhat more clearly in figure 11, where the points $O$ and $O'$ and the small circle on $CD$ as a diameter have the same meaning as in figure 9. The small triangle shown in successive positions in figure 11 is the same as triangle $LPS$, figure 9; for values of $\delta$ from zero to 150 degrees, inclusive, the triangle is cross-hatched; in the remaining positions it is left blank to avoid confusion.

The interesting linkage of the vectors $OO'$, $O'L$, and $LP$ of figure 9 led to the construction of a working model in which the 2 movable vectors were ruled with India ink on strips of transparent sheet celluloid, suitably pivoted together. Placing these links in the positions corresponding to $\delta = 0$, and then moving them bit by bit as the torque angle was gradually increased from zero to 360 degrees, it was possible to photograph the model in successive positions, thereby yielding a film suitable for use in a moving-picture projector. It is quite interesting to observe this animated vector diagram, which has been

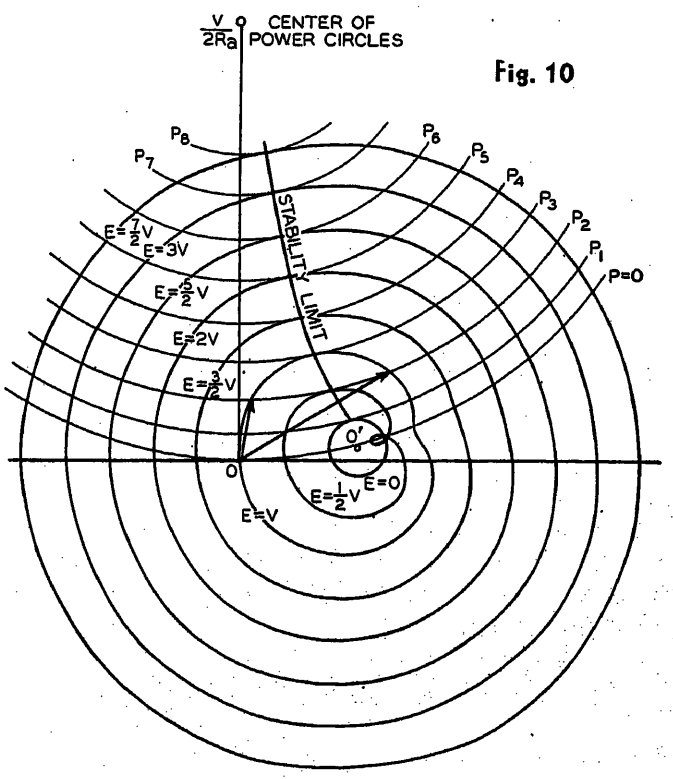



Fig. 10

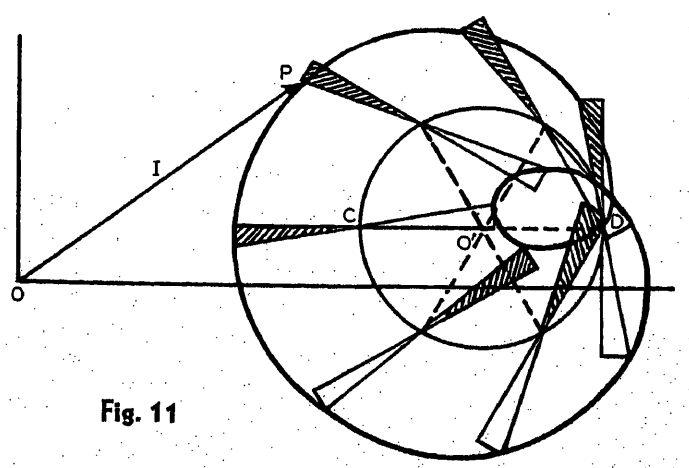



Fig. 11

so made that the excitation locus is drawn as the vectors move.

While no particular importance attaches to the fact, it may be noted that the excitation which marks the point of division between those excitation loops wholly exterior to circle $CD$, and those which lie partly inside it, is determined by the consideration that

$$I_1 = \frac{EZ_q}{X_dX_q + R_a^2} = CD = \frac{V(X_d - X_q)}{X_dX_q + R_a^2}$$

or

$$E = \frac{V(X_d - X_q)}{Z_q} \qquad (29)$$

and that the point of osculation between this limiting loop and the circle occurs at a value of $\delta$ such that $\delta = 180 - \alpha'$.

When the armature current $I(= OP)$, figure 11, is plotted in rectangular co-ordinates as a function of the torque angle $\delta$, curve 1 of figure 12 results. For the sake of comparison, there has been drawn on the same diagram, as curve 2, the variation of armature current when $E = 0$, the ordinates being taken directly from the circle $CD$ of figure 11. Curve 2 will be recognized in terms of the now familiar slip test; it is the envelope of an oscillogram of the armature current taken with the field unexcited and the rotor turned at a speed differing slightly from synchronism.* Curve 1 of figure 12 is then the envelope of the armature current oscillogram taken in the same manner but with the field magnetized to a small fraction of normal excitation. It can be seen from figure 10 that in the case of both curves 1 and 2 the machine is acting as a motor for somewhat less than half of the interval corresponding to slipping a double pole pitch, and is a generator the remainder of the time; but in the case of curve 1, whose polar equivalent has the re-entrant loop projecting outside the zero power circle, the initial motor action is followed by a brief period of generator action, then by another short motoring interval, before the full period of generator action sets in.

One additional feature worthy of consideration is the effect of negative excitation, that is, of reversing the field polarity. It is obvious that if $E$ is reversed in sign, the effect is to reverse the phase of vector $LP$, figure 9; but figure 11 shows that for any position of vector $O'L$ the excitation triangle $LPS$ necessarily appears in 2 diametrically opposite positions, hence the excitation loci with reversed excitation are identical in form with those shown in figures 10 and 11, but the sequence of values is reversed. In any case the locus passes through a region lying within the zero-power circle and motor action is possible.

## The $V$-Curves

The $V$-curves constructed from figure 10 are just as distinctively different from those usually derived from the cylindrical rotor theory as are the excitation curves of figure 10 in comparison with the customary circles (figure 3). The $V$-curves are shown in figure 13, and it will be seen that those portions lying below the stability line $H_2$ resemble quite closely the curves determined by actual test. Curve $H_1$, passing through the lowest points of the curves, defines the condition for unity power factor; unlike the corresponding curve derived from the cylindrical-rotor theory, it does not have a point of minimum excitation at a value of armature current greater than zero; on the contrary, the minimum excitation consistent with unity power factor occurs when $E = V$.

While it is quite true that any discussion of the $V$-curves lying above the stability curve $H_2$ is academic in the sense that these portions of the curves are beyond the practical limits of operation, they still possess several points of theoretical interest. One of them is that the curve corresponding to zero power lies partly *inside* a curve corresponding to a positive amount of (motor) power. This result, when first encountered, was quite unexpected, but it is a consequence of the fact that the

* The slip test seems to have been first developed and used by K. H. Haga; see *L'Eclairage Electrique*, 11, IX, 1909; also article by J. A. Schouten, *Elektrotechnische Zeitschrift*, volume 81, page 877, 1910.

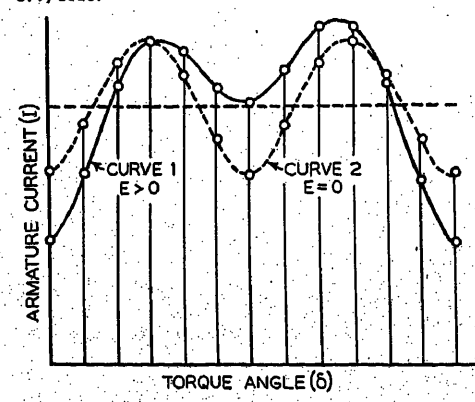



Fig. 12

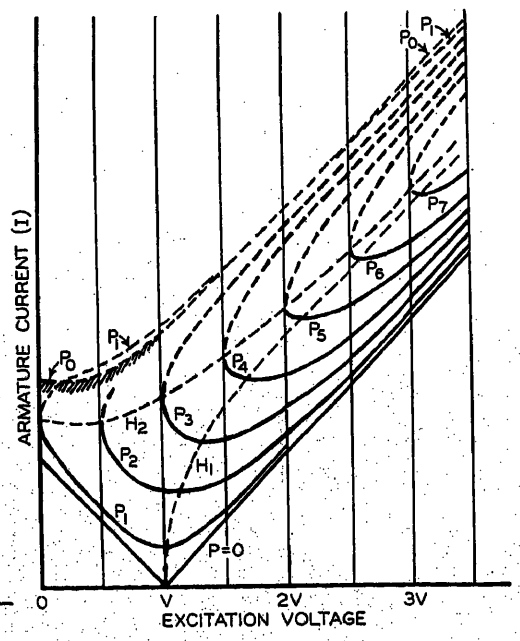



Fig. 13

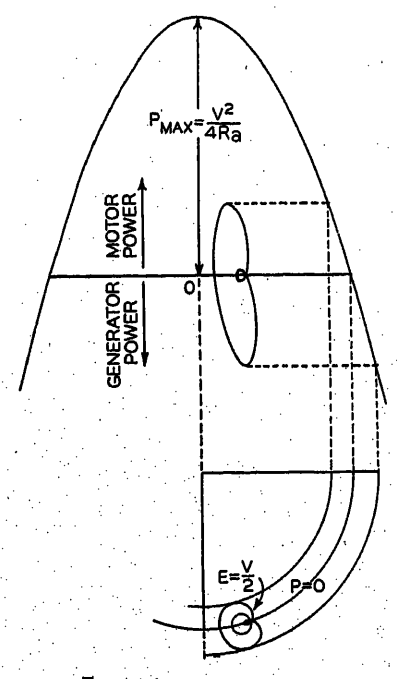
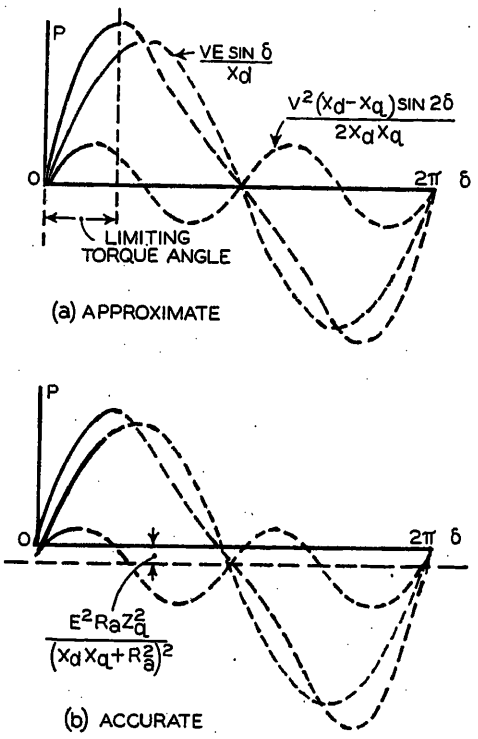



Fig. 14

Fig. 15




excitation loops of figure 10 are indented for values of the torque angle approaching 180 degrees; some indication that this phenomenon actually occurs is to be found in the experimental curves published[3] by Douglas, Engeset, and Jones; the effect is likewise indicated by J. F. H. Douglas's closing remarks in the discussion of that paper.

Perhaps the simplest way to visualize the relations represented by the $V$-curves is to regard them as contour lines of a surface which has as co-ordinates the dependent variable $I$ and the 2 independent variables $E$ and $P$. When this idea is carried back to figure 10, it follows that the power circles $P = 0$, $P_1$, $P_2$, . . . etc., are likewise contour lines of a surface which will be shown to be a paraboloid of revolution; and that the excitation loops are sections of general cylinders having their axes perpendicular to the plane of figure 10. The intersections of the paraboloid and the cylinders then define the armature current and fix the shape of the $V$-curve.

The proof that the power circles of figure 10 are sections of a paraboloid follows immediately from equation 1, which is the equation of a parabola having $I$ and $P$ as the dependent and independent variables, all other quantities, including the phase angle $\varphi$, being constant. The condition $\cos \varphi = 1$ obviously defines the diametral section of the paraboloid, which is shown as figure 14. The vertex of the paraboloid, corresponding to the theoretical maximum power that the machine can develop as a motor, is defined by the condition that the right-hand member of equation 3 cannot become negative, whence $P_{max.} = V^2/(4R_a)$. The base of the paraboloid corresponds to zero motor power ($P = 0$), but the paraboloid extends indefinitely below this particular section, and in that region represents generator power. It is therefore quite simple to visualize conditions when the excitation loops of figure 10 pass outside the zero-power circle; the geometrical meaning is that the excitation cylinder intersects the power paraboloid below the "base" of the latter. The curve of intersection corresponding to $E = (1/2)V$ is shown in vertical projection in figure 14.

## Condition for Unity Power Factor

Inspection of figure 4 shows that when $\varphi = 0$ (i. e., $\cos \varphi = 1$), $\psi = \delta$. Consequently equations 10 and 11 become

$$V \sin \delta = IZ_q \sin (\delta + \varphi_q) \tag{30}$$

$$E - V \cos \delta = -IZ_d \cos (\delta + \varphi_d) \tag{31}$$

from which

$$\sin \delta = \frac{EIX_q}{(V - IR_a)^2 + I^2X_dX_q} \tag{32}$$

$$\cos \delta = \frac{E(V - IR_a)}{(V - IR_a)^2 + I^2X_dX_q} \tag{33}$$

Now it will be seen from figure 9 that when the current vector $I(= OP)$ is in phase with $V$ the algebraic sum of the quadrature components of $I_0$, $I_2$, and $I_1$ is zero. Hence, from equations 26, 27, and 28,

$$I_0 \cos \alpha' - I_2 \cos 2\delta - I_1 \sin (\delta + \varphi_q) = 0 \tag{34}$$

and

$$I \cos \alpha' = \frac{V}{X_dX_q + R_a^2} \cdot \frac{X_d + X_q}{2} \tag{35}$$

$$I_2 = \frac{V}{X_dX_q + R_a^2} \cdot \frac{X_d - X_q}{2} \tag{36}$$

$$I_1 = \frac{EZ_q}{X_dXq + R_a^2} \tag{37}$$

From equations 30 and 31 it is now possible to express $\cos 2\delta$ and $\sin (\delta + \varphi_q)$ in terms of $E$, $I$, and the machine constants, and on substituting all these relations in equation 34 the final result is

$$[(V - IR_a)^2 + I^2X_dX_q]^2 = E^2[(V - IR_a)^2 + I^2X_q^2] \tag{38}$$

which is the complete equation of curve $H_1$, figure 13. It is obviously an equation of the fourth degree, but if it may be assumed that $IX_d$ and $IX_q$ are not large in comparison with $(V - IR_a)$ it is a reasonable approximation to write

$$E^2 = (V - IR_a)^2 + I^2X_dX_q$$

or

$$E^2 = V^2 + I^2X_dX_q \tag{39}$$

which is a hyperbola.

## Condition for Stability

The stability limit indicated in figure 10 (drawn for the region of motor action only), and its counterpart, curve $H_2$ of figure 13, are defined by the condition that the machine is developing the maximum power consistent with the excitation. Hence the stability limit may be found by imposing the condition $dP/d\delta = 0$.

In order to express without any simplifying approximations the power developed ($P$) as a function of the torque angle ($\delta$), use may be made of the concept underlying the 2-reaction theory that the armature winding is subjected to the action of 2 fictitious sets of field poles in addition to the actual poles. One of these fictitious sets of poles lines up with the actual poles and either magnetizes or demagnetizes the latter depending upon the phase conditions; the other fictitious set of poles lies midway between the actual poles. The cross-magnetizing component of armature current, $I_q$, reacts directly with the net flux in the direct axis to produce torque and power, while the direct component of current, $I_d$, reacts directly with the transverse flux. Referring to the particular phase conditions represented in figure 4, it follows that the power developed is given by

$$P = (E - I_dX_d)I_q + (I_qX_q)I_d$$
$$= EI_q - I_qI_d(X_d - X_q) \tag{40}$$

Substituting for $I_q$ and $I_d$ the values given by equations 23 and 24, the complete expression for the power is found to be

$$P = \frac{VEZ_dZ_q^2\cos(\delta-\varphi_d) + VER_aZ_q(X_d-X_q)\sin(\delta-\varphi_q) - V^2Z_dZ_q(X_d-X_q)\sin(\delta-\varphi_q)\cos(\delta-\varphi_d) - E^2R_aZ_q^2}{(X_dX_q+R_a^2)^2} \tag{41}$$

whence the accurate expression for the stiffness or coupling factor is

$$\frac{dP}{d\delta} = \frac{VER_aZ_q(X_d-X_q)\cos(\delta-\varphi_q) - VEZ_dZ_q^2\sin(\delta-\varphi_d) - V^2Z_dZ_q(X_d-X_q)\cos(2\delta-\varphi_d-\varphi_q)}{(X_dX_q+R_a^2)^2} \tag{42}$$

If, in equations 41 and 42 the approximation is made that terms involving $R_a$ may be neglected, and that correspondingly $\varphi_d = \varphi_q = 90$ degrees, they reduce to

$$P = \frac{VE}{X_d}\sin\delta + \frac{V^2(X_d-X_q)}{2X_dX_q}\sin 2\delta \tag{43}$$

$$\frac{dP}{d\delta} = \frac{VE}{X_d}\cos\delta + \frac{V^2(X_d-X_q)}{X_dX_q}\cos 2\delta \tag{44}$$

which are the same as those derived by Doherty and Nickle by a somewhat different procedure, but which has the disadvantage that it masks some of the finer points of the theory. The differences between the accurate and the approximate expressions are shown graphically in figure 15.

## Effect of Saturation

The full effect of saturation of the magnetic circuit is apparently beyond the scope of any reasonably simple analysis. Approximate methods have been proposed by Doherty and Nickle,[1] and also by Blondel.[4,5] Ordinarily it is sufficiently accurate to assume that the saturation in the armature iron and in the path of the cross field is negligible, and that the significant saturation occurs in the pole cores.[1] These assumptions lead to the conclusion that the reactances $X_d$ and $X_q$ may be treated as constant, from which it follows that in figure 9 the only component vector which is affected by saturation is $LP = (EZ_q)/(X_dX_q + R_a^2)$. Analytically, it is fairly accurate to write Froehlich's equation

$$E = \frac{aF}{b+F} \tag{45}$$

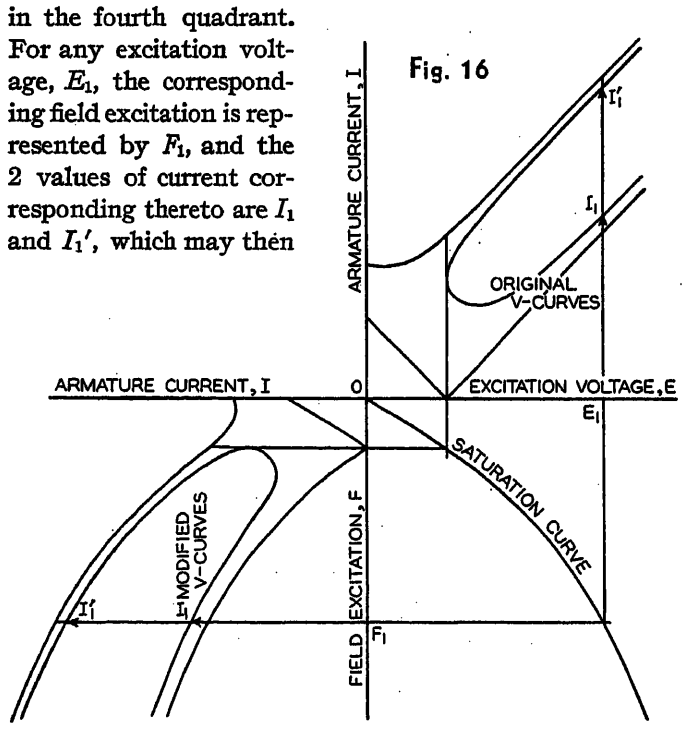
where $a$ and $b$ are constants, and $F$ is the excitation in ampere-turns, which is equivalent to the assumption that the saturation curve of the machine is a hyperbola.

Writing equation 45 in the form

$$F = \frac{bE}{a-E} \tag{46}$$

$F$ may be computed for any assigned value of $E$, and it then becomes possible to correct the $V$-curves of figure 13. The same procedure may be effected quite simply by a purely graphical method in the manner indicated in figure 16. A portion of one of the $V$-curves of figure 13 is reproduced in the first quadrant of figure 16, and the saturation curve is drawn in the fourth quadrant. For any excitation voltage, $E_1$, the corresponding field excitation is represented by $F_1$, and the 2 values of current corresponding thereto are $I_1$ and $I_1'$, which may then be laid off to the left of $F_1$ in the third quadrant. The effect is seen to be to stretch the $V$-curves, the amount of stretch increasing rapidly as the field excitation becomes greater, provided the saturation is sufficient to yield a definite knee to the saturation curve.

Fig. 16




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# Synchronous Machine with Solid Cylindrical Rotor

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**In this paper a rigorous mathematical analysis of a synchronous machine with solid cylindrical rotor is presented. The analysis embodies a departure from the usual method of considering machine performance by means of circuit theory, and presents an attack from the point of view of field-distribution theory. Such an analysis is desirable, for it provides a definite means of considering the effect of eddy currents in the solid iron rotor.**

IN this paper are presented the development and application of the equations of a cylindrical-rotor synchronous machine, taking into account the eddy currents in the solid iron rotor. The equations for the electromagnetic field in the rotor and air gap due to stator and rotor currents are set up in terms of the magnetic vector potential. These field equations are then related to the circuit voltage equations of a symmetric 3-phase stator winding and a single field winding. The final expressions are solved for the case of symmetric 3-phase currents and constant speed and applied to the calculation of 3-phase short-circuit current, field-current build-up, and flux decay.

In previous treatments of electrical machines, circuit analysis has been the predominant tool. Some of the machine constants have been computed with the aid of coefficients found from flux plots, or by taking into account nonuniform distribution of current in conductors, or the actual circuits replaced by equivalent sinusoidally distributed windings, but always the actual analysis has been of a circuit. In this paper a departure is made by considering the behavior of solid-rotor synchronous machines from the point of view of field-distribution theory. This is particularly desirable since no definite circuit in which the rotor eddy currents must flow presents itself in the actual machine. Previous analyses of solid-rotor machine performance have represented the rotor by an equivalent circuit computed from steady-state eddy-current relations. The present treatment by going back to fundamentals and avoiding the short cuts of the ordinary engineering circuit theory thus presents an opportunity to test the validity of such representation for calculations of transient phenomena. The differential equations governing the field distributions are set up from Maxwell's equations. These are expressed in terms of a magnetic vector potential, introduced in order to correlate them for the rotor and stator, since as ordinarily expressed in terms of electric intensity they are valid only for systems at rest.

## Assumptions

The analysis is based on the following assumptions:

1. The rotor permeability is a constant.
2. The stator permeability is infinite.
3. The presence of slots is neglected in both rotor and stator, a uniform equivalent gap being used.
4. The machine is so long that end effects may be neglected; thus the field is 2-dimensional.
5. The circuit conductors are of negligible depth and are distributed on the rotor and stator surfaces (see also assumption 3).
6. The rotor and stator surface curvatures are small compared to the air gap length.
7. To take account of the end effects and slot leakage, provisional corrective terms (so-called leakage inductances) are included in the circuit equations. In correlating the calculations with test results these terms are found to be very important and it is intended to investigate the effect of eddy currents in the leakage fluxpaths as the next step in the development of the theory.

It may be stated broadly that the present purpose is to compute correctly the effect of eddy currents in the main flux path. The results are here compared to similar calculations for a laminated rotor machine, so that the effect of the solid rotor body may be seen directly.

## The Field Equations

Maxwell's equations for the electromagnetic field, for the present case, and for axes fixed in the medium, are

$$\nabla \times H = 0.4\pi i \tag{1}$$

$$\nabla \times E = -10^{-8} \frac{\partial}{\partial t} B = -\mu 10^{-8} \frac{\partial}{\partial t} H \tag{2}$$

$$\nabla \cdot B = 0 \quad (\nabla \cdot H = 0), \quad \nabla \cdot E = 0 \tag{3}$$

where all quantities are in practical cgs units.

In conducting regions they yield

$$\nabla^2 E = 4\pi\mu 10^{-9} \frac{\partial}{\partial t} i \tag{4a}$$

or, since

$$i = \lambda E, \tag{4b}$$

$$\nabla^2 E = 4\pi\lambda\mu\, 10^{-9} \frac{\partial}{\partial t} E = \beta^2 \frac{\partial}{\partial t} E = \beta^2 pE \tag{5a}$$

while in nonconducting regions

$$\nabla^2 E = 0 \tag{5b}$$

At surfaces (such as the rotor and stator surfaces) where current sheets are flowing, the last equations are replaced

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1. For all numbered references, see list at end of paper.

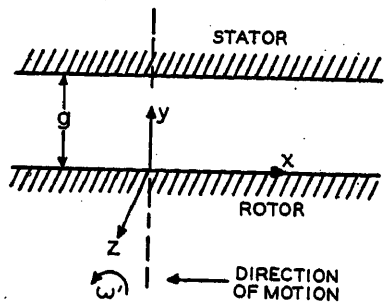



**Fig. 1. Orientation of co-ordinate system in the rotor**

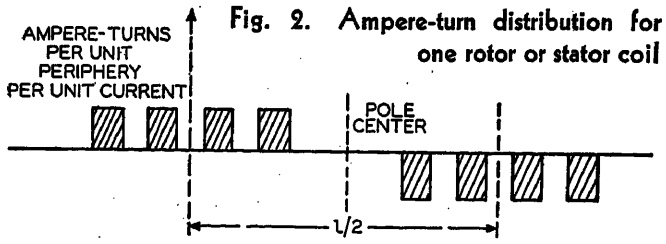



**Fig. 2. Ampere-turn distribution for one rotor or stator coil**

by a boundary condition specifying the discontinuity in the normal derivative of $E$. Thus if along a surface ($y$ = constant) there is a current sheet in the $z$-direction of linear intensity $I$, then:

$$\Delta H_x = -0.4\pi I \tag{6a}$$

where $\Delta H_x$ is the increment or discontinuity in $H_x$.

From equations 6$a$ and 2

$$\frac{\partial}{\partial t}(\Delta H_x) = \Delta \frac{\partial}{\partial t} H_x = -10^8 \Delta \left(\frac{1}{\mu}\frac{\partial E}{\partial y}\right) = -0.4\pi \frac{\partial}{\partial t} I \tag{6b}$$

For long rotors, neglecting end effects, the currents and induced voltages may be assumed to point in the $z$-direction (i.e., to be parallel to the rotor axis) and to be functions only of $x$, $y$; while the magnetic field is normal to the $z$ axis and also independent of $z$. Therefore, let

$$E_z = E = E(x, y)$$

and obtain from equation 2

$$\frac{\partial}{\partial t} H_x = -\frac{10^8}{\mu}\frac{\partial}{\partial y} E \qquad \frac{\partial}{\partial t} H_y = +\frac{10^8}{\mu}\frac{\partial E}{\partial x} \tag{7}$$

This shows that the magnetic field can be expressed in terms of a single (now scalar) function $E$ as far as its changes are concerned. However, this induced electric field $E$ is not invariant under motions relative to the axes employed. Therefore, to compute the proper induced voltages in coils in motion with respect to the field, as e.g., in the stator coils due to the motion of the rotor and to take account of static magnetic fields, we introduce a vector magnetic potential $\psi$ defined in the original system of co-ordinates by the relation

$$\psi = \int_{-\infty}^{t} E dt \tag{8}$$

whereupon equations 2, 3, and 5$a$ may be replaced by

$$H = -\frac{10^8}{\mu} \nabla \times \psi \tag{9}$$

$$\nabla \cdot \psi = 0 \tag{10}$$

$$\nabla^2 \psi = 4\pi\mu\, 10^{-9} i \tag{11}$$

and boundary condition of equation 6$b$ by

$$\Delta\left(\frac{1}{\mu}\frac{\partial \psi}{\partial y}\right) = 4\pi 10^{-9} I \tag{12}$$

The vector potential can be defined by this set of equations and since it points in the $z$-direction still offers the possibility of expressing the magnetic and electric fields in terms of a single scalar function. This function (or rather, $-10^8\ \psi$) may be interpreted as the total flux enclosed between the point in question and a reference point and is in fact perfectly analogous to the flux linkage of circuit theory.

## The Circuit Currents

As explained under the assumptions, it will be assumed throughout the following that a proper mean radius has been chosen both for rotor and stator and that smooth cylindrical surfaces of these mean radii actually replace the slotted rotor and stator surfaces. The armature and field windings are considered to be ribbon-like and to lie on these surfaces. Developing the rotor and stator surfaces along parallel plane surfaces in accordance with assumption 6, and replacing the rotor and stator by semi-

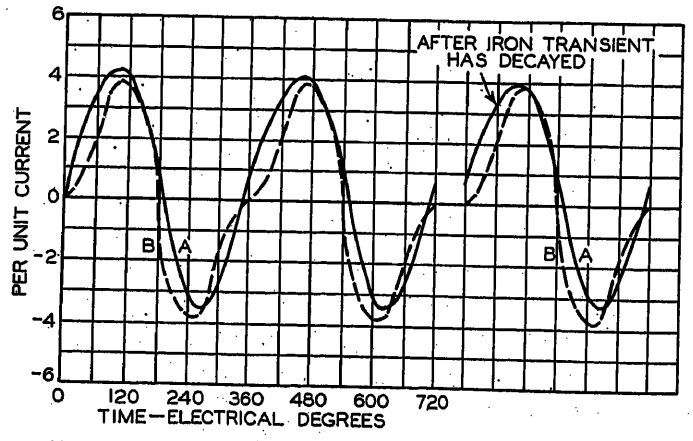



**Fig. 3. Short-circuit current of a turbine generator**
Phase-a switch closed at instant of minimum linkage

Case 1 — $l_s = 0.18$, $\mu = 100$
*A*—With solid rotor *B*—With laminated rotor

infinite blocks and the rotation $\omega'$ about the $z$-axis by an equivalent translation, we arrive at figure 1. Suppose the rotor is rotating with angular velocity $\omega'$. Since Maxwell's equations are for axes fixed in conducting materials, we take $x$, $y$, $z$ axes fixed in the rotor as shown and let $x_1$, $y$, $z$ be similar axes fixed relative to the stator. Thus

$$x_1 = x - r\int \omega' dt \tag{13}$$

Consider one rotor coil with current $I_r$, and several stator coils with currents $I_a$, $I_b$, . . . . The actual ampere-turn distribution due to these currents may be as shown

in figure 2. The rectangular blocks correspond in position to the slots. (It should, of course, be understood that figure 2 is only representative and the number, height, and spacing of the ampere-turn blocks depend on the machine being analyzed.) If the equation of this curve is $a(x)$, then the ampere turns due to rotor current $I_r$ is $I_r a(x)$. The function $a(x)$ is periodic of period $l$, and is odd about the pole center and even about a line midway between adjacent poles.

Hence

$$a(x) = \sum_{n=1,3,5,\ldots} A_n \cos nax, \quad a = \frac{2\pi}{l} \tag{14}$$

Similar ampere turn curves apply to each stator coil. For one of these coils, e.g., we have:

Ampere turns $= I_a\, b\,(x_1)$

where $b$ is again odd and even as above, and

$$b(x_1) = \sum_{n=1,3,\ldots} B_n \cos nax_1 \tag{15}$$

If there are 3 stator coils with similar winding distributions, obtained from that of coil $a$ by translating through 120 and 240 electrical degrees, the total stator ampere turns are

$$I_s(x_1) = I_a b(x_1) + I_b\left(x_1 + \frac{l}{3}\right) + I_c b\left(x_1 - \frac{2l}{3}\right) \tag{16}$$

To find the field, we express the stator ampere turns also in terms of $x$, i.e., in terms of co-ordinates fixed with respect to the rotor and then solve the equations

$$\nabla^2\psi = 0 \tag{17}$$

in the gap, and

$$[\nabla^2 - \beta^2 p]\psi = 0 \tag{18}$$

in the rotor for the vector potential $\psi$, picking the solution which: ($a$) is zero for $y = -\infty$; ($b$) is continuous at the rotor (and stator) surface; and ($c$) is such that at the rotor and stator surfaces $y = 0$, $y = g$, $-\Delta H_x = 0.4\pi$ times the surface current density.

By equation 12 these conditions are:

$$\frac{\partial}{\partial y}\psi\Big|_{y=0+} - \frac{1}{\mu}\frac{\partial}{\partial y}\psi\Big|_{y=0-} = 4\pi 10^{-9} I_r(x) \tag{19}$$

$$-\frac{\partial}{\partial y}\psi\Big|_{y=g-} = 4\pi 10^{-9} I_s(x) \tag{20}$$

The induced electric field $E$ can now be found from the relation

$$E = \frac{\partial}{\partial t}\psi \tag{21}$$

## Coil Voltage Equations

With $E$ known, the voltage equations for the coils may be obtained by adding to the applied voltage the integral of the induced voltage $E$ over the length of the coil. For the rotor coil:

$$RI_r = e_r + Zk\int_0^l a(x)E(x)dx \tag{22}$$

To treat the stator coils which are now moving relative to the $x$, $y$, $z$ system, recall that the function $-10^8\,\psi$ is a measure of the instantaneous flux linking any point.

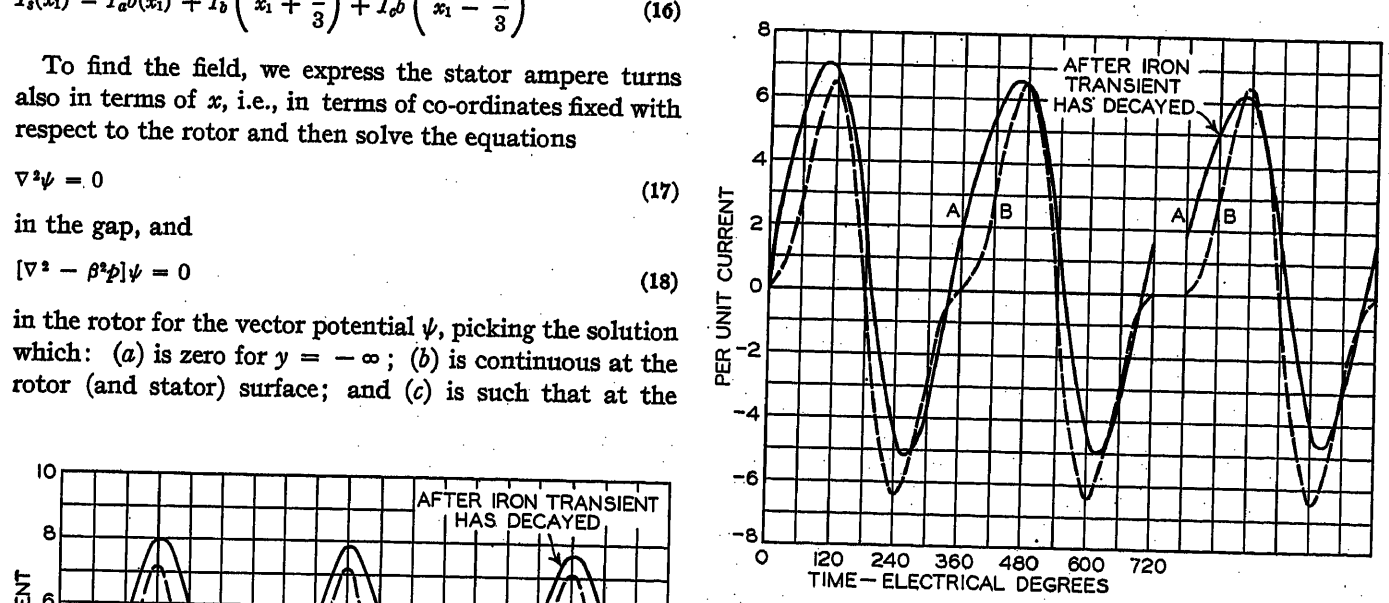



**Fig. 4. Short-circuit current of a turbine generator**

Phase-$a$ switch closed at instant of maximum linkage; other conditions same as for figure 3




**Fig. 5. Short-circuit current of a turbine generator**

Phase-$a$ switch closed at instant of minimum linkage
Case 2—$l_s = 0.09$, $\mu = 100$
$A$ and $B$—Same as for figure 3

Thus to find the induced electromotive force in a coil in motion relative to the $x$, $y$, $z$ system, e.g., a stator coil fixed in the $x_1$, $y$, $z$ axes of the stator, we need only express $\psi$ in terms of $x_1$, $y$, $z$ and then use an equation similar to equation 21:

$$E(x_1) = \frac{\partial}{\partial t}\psi\,(x_1, y, t) \tag{23}$$

For stator coil $a$ the electromotive force equation is

$$r_s I_a = e_a + Zk\int_0^l b(x_1)E(x_1)dx_1 \tag{24}$$

Similar equations hold for the other 2 stator coils.

## Current With Constant Speed

We now assume constant rotor speed. Then from equation 13,

$$\begin{aligned} x_1 &= x - r(\omega' t + \gamma/k) \\ &= x - (\omega t + \gamma)r/k \end{aligned} \tag{25}$$

or

$$ax_1 = ax - \omega t - \gamma.$$

To simplify the solution we represent the applied voltages by the relations

$$\left.\begin{aligned} e_a &= C\,e^{j\omega t} + C'\,e^{-j\omega t} + e_0 \\ e_b &= C\,\alpha^2 e^{j\omega t} + C'\,\alpha\,e^{-j\omega t} + e_0 \\ e_c &= C\,\alpha\,e^{j\omega t} + C'\,\alpha^2\,e^{-j\omega t} + e_0 \end{aligned}\right\} \tag{26}$$

where $\alpha = e^{j2\pi/3} = -1/2 + j\sqrt{3}/2$ is the primitive cube root of unity. In the case of balanced 3-phase sinusoidal voltages, $C$, $C'$ might be chosen so as to yield real voltages $e$ or else $C'$ might be made to vanish and the real parts of the resulting complex voltages and currents identified with the physical voltages and currents.

The stator currents may be expressed in similar form as

$$\left.\begin{aligned} I_a &= D\,e^{j\omega t} + D'\,e^{-j\omega t} + i_0 \\ I_b &= \alpha^2 D\,e^{j\omega t} + \alpha D'\,e^{-j\omega t} + i_0 \\ I_c &= \alpha D\,e^{j\omega t} + \alpha^2 D'\,e^{-j\omega t} + i_0 \end{aligned}\right\} \tag{27}$$

where $D$, $D'$, and $i_0$ are yet to be determined. Then from equation 16 the total stator ampere-turns are:

$$\begin{aligned} I_s(x_1) = De^{j\omega t}&\left[b(x_1) + ab\left(x_1 + \frac{l}{3}\right) + \alpha^2 b\left(x_1 + \frac{2l}{3}\right)\right] + \\ D'e^{-j\omega t}&\left[b(x_1) + \alpha b\left(x_1 + \frac{l}{3}\right) + \alpha^2 b\left(x_1 + \frac{2l}{3}\right)\right] + \\ i_0&\left[b(x_1) + b\left(x_1 + \frac{l}{3}\right) + b\left(x_1 + \frac{2l}{3}\right)\right] \end{aligned} \tag{28}$$

or, after some algebraic reduction utilizing the relation $1 + \alpha^n + \alpha^{2n} = 3$ or 0 according as $n$ is or is not divisible by 3,

$$\begin{aligned} I_s(x) = \frac{3}{2}\sum_{n=0,\,\pm 6,\ldots} B_{|n+1|}\,[De^{j(n+1)(ax-\gamma)-jn\omega t} + \\ D'e^{-j(n+1)(ax-\gamma)+jn\omega t}] + i_0\frac{3}{2}\sum_{n=\pm 1,\,\pm 3,\ldots} B_{|3n|}\,[e^{j3n(ax-\omega t-\gamma)} + \\ e^{-j3n(ax-\omega t-\gamma)}] \end{aligned} \tag{29a}$$

In terms of $x_1$, or referred to the stator,

$$\begin{aligned} I_s(x_1) = \frac{3}{2}\sum_{n=0,\,\pm 6,\ldots} B_{|n+1|}\,[De^{j\omega t+j(n+1)ax_1} + D'e^{-j\omega t-j(n+1)ax_1}] + \\ \frac{3}{2}\sum_{n=\pm 1,\,\pm 3,\ldots} B_{|3n|}\,[e^{j3nax_1} + e^{-j3nax_1}] \end{aligned} \tag{29b}$$

From equation 29 it is seen that if $i_0 = 0$ and $D$ and $D'$ are constants, $I_s$ may be described either as a sinusoidal wave $e^{\pm j(ax-\gamma)}$ stationary relative to the rotor but modulated by a function fixed relative to the stator or as a sinusoidal wave stationary relative to the rotor plus harmonic waves which travel along the rotor with speeds only slightly less than that of the rotor.

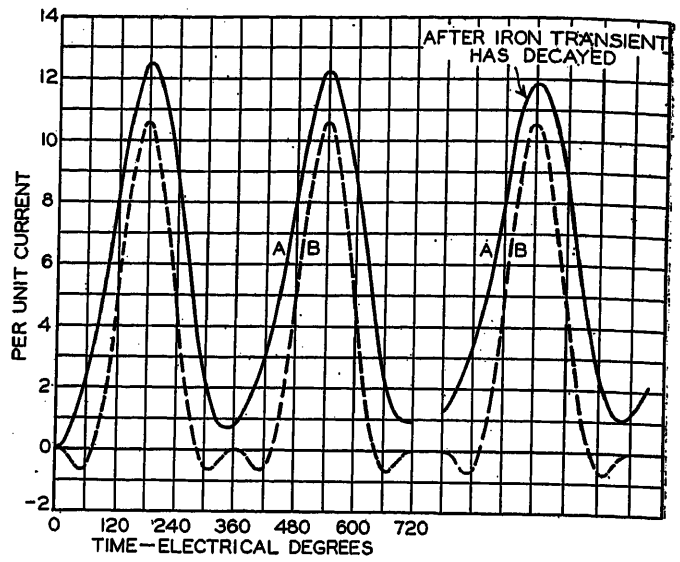



**Fig. 6. Short-circuit current of a turbine generator**

Phase-a switch closed at instant of maximum linkage, other conditions same as for figure 5

Now suppose the $I_r$, $D$, $D'$ vary as $e^{pt}$, i.e., substitute $I_r e^{pt}$ for $I_r$, etc., where the new $I_r$, $D$, $D'$, and $i_0$ are constants, and solve the field equations 17, 18, subject to the boundary conditions expressed by equations 19 and 20, and with the current distributions expressed by equations 14 and 29$a$ simultaneously present. From the resulting $\psi$ find $E$ by means of equations 21 and 23, then substitute in equations 22 and 24 to obtain the circuit voltage equations (see appendix II). Considering only the fundamental components, there result the following 4 linear equations in $I_r$, $D$, $D'$, and $i_0$,

$$\left[(R + Lp) + \frac{KA_1^2}{aQ}\,p\cosh ag\right]I_r + \frac{3KA_1B_1p}{2aQ}\,(De^{-j\gamma} + D'e^{j\gamma}) = e_r \tag{30a}$$

$$\left[\frac{KA_1B_1e^{j\gamma}}{2aQ}\,(p + j\omega)\right]I_r + \left[r_s + \frac{(uq + v)}{Q}\,(p + j\omega)\right]D = C \tag{30b}$$

$$\left[\frac{KA_1B_1e^{-j\gamma}}{2aQ}\,(p - j\omega)\right]I_r + \left[r_s + \frac{(uq + v)}{Q}\,(p - j\omega)\right]D' = C' \tag{30c}$$

$$[r_s + l_0 p]i_0 = e_0 \tag{30d}$$

where

$$K = 2\pi 10^{-8} Z l k$$

$$Q = q\cosh ag + \sinh ag$$

$$q = \frac{\beta}{\mu a}\left[p + \left(\frac{a}{\beta}\right)^2\right]^{\frac{1}{2}}$$

$$u = l_s\cosh ag + \frac{3KB_1^2}{2a}\sinh ag$$

$$v = l_s\sinh ag + \frac{3KB_1^2}{2a}\cosh ag$$

In these equations there have been included field and armature leakage inductances which were omitted from the previous steps of the development in order to avoid undue complication. Solving equations 30 for the currents $I_r$, $D$, $D'$ in terms of the applied voltages, we find

$$\Delta I_r = a^2\{(p^2+\omega^2)(uq+v)^2 + r_s Q\,[r_s Q + 2p(uq+v)]\}e_r - \frac{3}{2}KA_1B_1ap\{r_sQ(Ce^{-j\gamma} + C'e^{j\gamma}) + (uq+v)\,[(p-j\omega)Ce^{-j\gamma} + (p+j\omega)C'e^{j\gamma}]\} \quad (31a)$$

$$\Delta D = -\frac{1}{2}KA_1B_1ae^{j\gamma}[(p^2+\omega^2)(uq+v) + r_s(p+j\omega)Q]e_r + \left[(R+Lp)a^2Q\{(p-j\omega)(uq+v) + r_sQ\} + KA_1^2ap\left\{\frac{1}{2}(p-j\omega)[uQ+\cosh ag(uq+v)] + r_sQ\cosh ag\right\}\right]C + KA_1^2ap\,\frac{3KB_1^2}{4a}(p+j\omega)e^{2j\gamma}C' \quad (31b)$$

$$\Delta D' = -\frac{1}{2}KA_1B_1ae^{-j\gamma}[(p^2+\omega^2)(uq+v) + r_s(p-j\omega)Q]e_r + \left[(R+Lp)a^2Q\{(p+j\omega)(uq+v) + r_sQ\} + KA_1^2ap\left\{\frac{1}{2}(p+j\omega)[uQ+\cosh ag(uq+v)] + r_sQ\cosh ag\right\}\right]C' + KA_1^2ap\,\frac{3KB_1^2}{4a}(p-j\omega)e^{-2j\gamma}C \quad (31c)$$

where

$$\Delta = (R+Lp)a^2\{(p^2+\omega^2)(uq+v)^2 + r_sQ[r_sQ+2p(uq+v)]\} + KA_1^2ap\{(p^2+\omega^2)u(uq+v) + r_s[Q(r_s\cosh ag + up) + \cosh ag\,(uq+v)p]\} \quad (31d)$$

### Electrical Torque

The torque may best be computed by considering the interaction of the stator current with the normal component of flux at the stator surface. We then have in cgs units (ergs),

$$\text{Torque} = -0.1\,rZk\int_0^l I_s(x_1)\,[H_y(x_1)]_{y=g}dx_1 \quad (32)$$

Considering only the fundamental component, we have

$$I_s(x_1) = \frac{3}{2}B_1[De^{j(\omega t+ax_1)} + D'e^{-j(\omega t+ax_1)}] \quad (33)$$

$$[H_y(x_1)]_{y=g} = \frac{0.4\pi A_1}{Q}I_r\sin(ax_1+\omega t+\gamma) + \frac{1.2\pi B_1(\cosh ag + q\sinh ag)}{2jQ}[De^{j(ax_1+\omega t)} - D'e^{-j(ax_1+\omega t)}] \quad (34)$$

If $I_s$ and $H_y$ are real, the expressions above will give the instantaneous torque correctly; however, if they are complex we must either take the real parts before substituting in equation 32 or else add to equation 32 a similar expression obtained by replacing either the field or the current by its conjugate imaginary and take the real part of half the sum.

### The Operational Solution and Its Evaluation

In the above solution time entered as $e^{pt}$ (or $e^{pt\pm j\omega t}$) where $p$ was a constant. The solution can be adapted, however, to the study of arbitrary applied voltages and in particular to various transient problems by regarding them as operational expressions. Thus if the expressions for $I_r$, $D$, $D'$ in equation 31 be considered to operate on the unit function, the result represents the currents obtained when, in the applied voltages, $e_r$, $C$, $C'$ are replaced by $e_r\mathbf{1}$, $C\mathbf{1}$, $C'\mathbf{1}$. According to the modern interpretation of operational calculus the operational solution is obtained merely by superposing the solutions for various values of $p$. More exactly the operational expressions just described are to be viewed as the coefficients of $e^{pt}/p$ in the Bromwich integral.

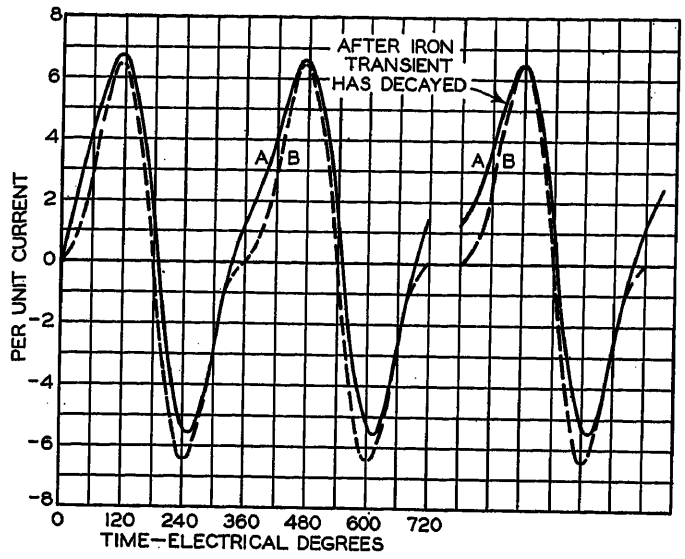



**Fig. 7. Short-circuit current of a turbine generator**

Phase-a switch closed at instant of minimum linkage
Case 3 — $l_s = 0.09$, $\mu = 1{,}000$
*A* and *B*—Same as for figure 3

The equivalent time functions cannot be directly found in tables. To evaluate the operational expressions, note that they are rational fractions in $p$ and $q$, $q$ being the square root of a factor linear in $p$. They may be converted to rational fractional functions of $q$ by expressing $p$ in terms of $q$, as

$$p = \left(\frac{a}{\beta}\right)^2[(\mu q)^2 - 1] \quad (35)$$

If the resulting functions of $q$ are now expanded in partial fractions the result is of the form

$$\sum_n \frac{a_n}{q-q_n}$$

where $q_n$ are the $q$ roots of the denominator $\Delta$ expressed in terms of $q$. Replacing $q$ by its equivalent in $p$, there is obtained

$$f(p) = \sum_n \frac{b_n}{\left[p+\left(\frac{a}{\beta}\right)^2\right]^{\frac{1}{2}} - c_n} \quad (36)$$

In this form $f(p)\mathbf{1}$ may be evaluated (it will be noted that the operational expressions in $p$ correspond to the

integrand of the Fourier rather than the Bromwich integral, and thus operate on $p1$, that is on the unit impulse, rather than on 1) by the formula[1]

$$\frac{1}{(p+\rho)^{\frac{1}{2}}+c}\,1 = \frac{1}{c^2-\rho}\left[c - \rho^{\frac{1}{2}}\,erf(\rho t)^{\frac{1}{2}} - ce^{(c^2-\rho)t}\,erfc(ct^{\frac{1}{2}})\right] \quad (37)$$

where $erf(x)$ is the error function, defined by the equation

$$erf(x) = \frac{2}{\sqrt{\pi}}\int_0^x e^{-x^2}dx$$

and $erfc(x)$ is the complementary error function

$$erfc(x) = 1 - erf(x)$$

As $\Delta$ is a polynomial of the eighth degree in $q$ there will be 8 terms like equation 37 in the final expression for current. Actually it is found that the $q$ roots of $\Delta$ are in general complex so that the value of the error function of $(ct^{\frac{1}{2}})$ cannot be found in tables but must be computed by expansion in series.

It is of interest to indicate the degree of complexity of the result and its simplification as affected by further assumptions:

1. In general an eighth degree equation in $q$ must be solved.
2. If the field resistance $R$ is zero, the degree reduces to 6.
3. If the armature resistance $r$ is zero, only a cubic need be solved.
4. If both field and armature resistance are zero, the denominator is reduced to linear factors.
5. If the $(p\psi)$ terms of the stator induced voltage are neglected in comparison to the $(\omega\psi)$ or "generated" voltage terms, a fourth degree equation must be solved.
6. If in addition to assumption 5 the field resistance is neglected, only a quadratic equation need be solved.

## Applications to 3-Phase Short Circuits

As an example of the application of equations 31 the 3-phase short circuit current of a turbine-generator from no load has been computed. In order to simplify the work the armature and field circuit resistances have been neglected. This should not affect the result very much within the first few cycles.

For this condition the armature current equations may be reduced to:

$$\Delta D = \left[-(p-j\omega)\left\{\left(LaQ + \frac{1}{2}KA_1^2\cosh ag\right)(uq+v) + \frac{1}{2}KA_1^2uQ\right\} + (p+j\omega)\frac{1}{2}KA_1^2\frac{3}{2}\frac{KB_1^2}{a}\right]jVe^{j\gamma} \quad (38a)$$

$$D' = \text{conjugate of } D \quad (38b)$$

where

$$\Delta = (p^2+\omega^2)[La(uq+v) + KA_1^2u](uq+v) \quad (38c)$$

$D$ may be at once evaluated by formula 37 since the 6 $q$-roots of $\Delta$ are evident by inspection.

The current for a solid-rotor machine has been compared directly with that for a similar machine with laminated rotor in order to show clearly the effect of the solid iron.

### Case 1

Figures 3 and 4 show the results for a turbine-generator of normal design. Figure 3 is for short circuit at the instant of zero flux linkage in phase $a$ ($\gamma = 90°$), while figure 4 is for short circuit at the instant of maximum flux linkage in phase $a$ ($\gamma = 0$). The principal constants of this machine are:

Number of poles = 4
Speed = 1,800 rpm
$\pi Z/2l$ = 1.91 = ratio of length to diameter
$2g/l$ = 0.0425 = ratio of air gap to pole pitch
Rotor $\lambda$ = 57,200 (ohms per centimeter cube)$^{-1}$
$L$ = 0.05 per unit (corresponding to field leakage $= \frac{3}{2}\left(\frac{B_1}{A_1}\right)^2 0.05 =$ 0.09 per unit)
$l_s$ = 0.18 per unit
Rotor $\mu$ = 100

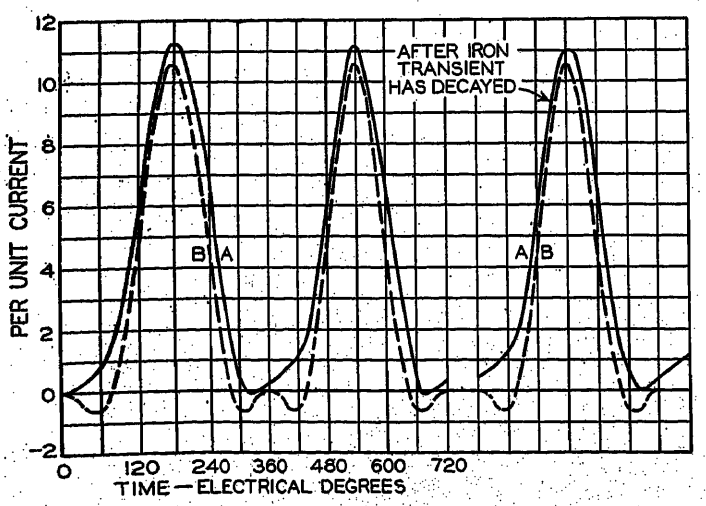



**Fig. 8. Short-circuit current of a turbine generator**

Phase-$a$ switch closed at instant of maximum linkage, other conditions same as for figure 7

### Case 2

Figures 5 and 6 show the effect of reducing the armature leakage $l_s$ to half its previous value, or to 0.09 per unit, all other constants remaining unchanged.

### Case 3

Figures 7 and 8 show the effect of a higher permeability. For this case,

$l_s$ = 0.09 per unit
$\mu$ = 1,000

The expressions for current in the 3 cases given are, with normal full-load current as the unit,

*Case 1.* $l_s = 0.18$, $\mu = 100$

$$i_a = (4.24 - 1.75F_c + 1.02F_s)\cos\gamma - (3.58 + 0.20e^{949t}\,erfc(30.8t^{\frac{1}{2}}))\times \cos(\omega t+\gamma) + (-0.46 + 1.29F_c + 0.12F_s)\cos(2\omega t+\gamma) + (-0.84 + 1.02F_c + 1.75F_s)\sin\gamma + 1.18e^{114.5t}\,erfc(10.7t)^{\frac{1}{2}}\sin(\omega t+\gamma) - (0.33 + 0.12F_c - 1.29F_s)\sin(2\omega t+\gamma) \quad (39a)$$

*Case 2.* $l_s = 0.09$, $\mu = 100$

$$i_a = (5.60 - 3.51F_c + 4.09F_s)\cos\gamma - (5.30 + 0.25e^{1461t}erfc(38.2t^{\frac{1}{2}}))\times \cos(\omega t + \gamma) + (-0.05 + 2.80F_c - 1.41F_s)\cos(2\omega t + \gamma) + (-2.58 + 4.09F_c + 3.51F_s)\sin\gamma + 4.15e^{329t}erfc(18.1t^{\frac{1}{2}})\sin(\omega t + \gamma) - (1.60 - 1.41F_c - 2.80F_s)\sin(2\omega t + \gamma) \quad (39b)$$

*Case 3.* $l_s = 0.09$, $\mu = 1{,}000$

$$i_a = (3.14 - 0.24F_c + 2.43F_s)\cos\gamma - 5.29\cos(\omega t + \gamma) + (2.15 + 0.19F_c - 1.53F_s)\cos(2\omega t + \gamma) + (-0.52 + 2.43F_c + 0.24F_s)\sin\gamma + 0.95e^{3290t}erfc(57.4t^{\frac{1}{2}})\sin(\omega t + \gamma) - (0.42 - 1.53F_c - 0.19F_s)\sin(2\omega t + \gamma) \quad (39c)$$

where $F_c$, $F_s$ are the Fresnel integrals defined by the equations

$$F_c = \int_0^{\omega t} \frac{\cos x\,dx}{(2\pi x)^{\frac{1}{2}}}, \quad F_s = \int_0^{\omega t} \frac{\sin x\,dx}{(2\pi x)^{\frac{1}{2}}} \quad (40)$$

The Fresnel integrals, rather than error functions as might be expected from formula 37, are present since with reasonable values of $\mu$ the significant $q$ roots have very nearly equal real and imaginary components and

$$erf(xe^{\pm j\pi/4}) = \sqrt{2}e^{\pm j\pi/4}\,[F_c(x^2) \mp j\,F_s(x^2)]$$

This relation may be shown as follows:

Let

$$y^2 = \pm jz$$

then at

$$y = xe^{\pm j\pi/4}$$

and

$$z = x^2$$

$$erf(xe^{\pm j\pi/4}) = \frac{2}{\sqrt{\pi}}\int_0^{xe^{\pm j\pi/4}} e^{-y^2}dy = e\sqrt{2}^{\mp j/4}\int_0^{x^2}\frac{e^{\mp jz}dz}{\sqrt{2\pi z}}$$

$$= \sqrt{2}\,e^{\pm j\pi/4}\int_0^{x^2}\frac{(\cos z \mp j\sin 2)dz}{\sqrt{2\pi z}} = \sqrt{2}e^{\pm j\pi/4}[F_c(x^2) \mp jF_s(x^2)]$$

Tables of both the error function and the Fresnel integral are given in reference 7.

The coefficients of the trigonometric functions in equations 39 have been plotted in Figs. 9, 10, 11 so that they may be compared directly to the corresponding coefficients for the laminated-rotor machine without the necessity of considering the instant of short circuit.

For a laminated rotor ($\lambda = 0$) the short-circuit current equations reduce to

CASE 1

$$i_a = 2.23\cos\gamma - 3.59\cos(\omega t + \gamma) + 1.36\cos(2\omega t + \gamma) \quad (41a)$$

CASE 2

$$i_a = 3.11\cos\gamma - 5.28\cos(\omega t + \gamma) + 2.17\cos(2\omega t + \gamma) \quad (41b)$$

CASE 3

$$i_a = 3.08\cos\gamma - 5.27\cos(\omega t + \gamma) + 2.19\cos(2\omega t + \gamma) \quad (41c)$$

These last equations are in the same form as that given by Doherty and Nickle in a previous paper.[2]

Inspection of figures 9, 10, 11 shows the expected reduction in second-harmonic current; a slight reduction

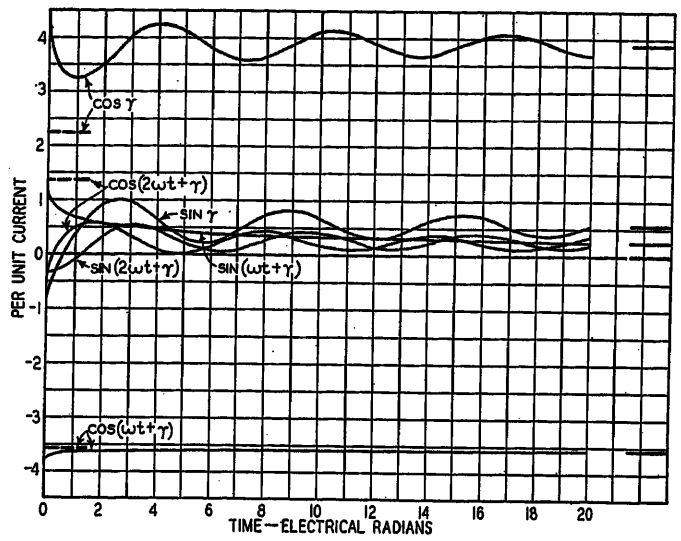



**Fig. 9. Coefficients of trigonometric functions in expression for short-circuit current of solid-rotor turbine generator, case 1**

Dashed lines are for machine with laminated rotor

for the unsaturated case ($\mu = 1{,}000$) and a great reduction for $\mu = 100$, which corresponds roughly to a small degree of saturation. It is interesting to note that the "fundamental" component of current is practically unaffected by the rotor eddy currents and is a function principally of the assumed values of field and armature-leakage reactance. The constant values approached by the coefficients are indicated on the figures and are very closely realized after a few cycles. We observe that although the expressions for current are somewhat complicated the general effect of the rotor eddy currents is simply to produce a more nearly sinusoidal wave shape of current and an effective phase shift. This phase shift is indicated by the presence of sine terms in the current equations 39 in addition to the cosine terms of the laminated rotor case (equations 41). Therefore according to equations 39 there is no switching angle which will completely eliminate the d-c component and result in a perfectly symmetric current.

The results further show that in the laminated-rotor machine the current is not affected appreciably by changes in rotor permeability in the range $\mu > 100$, while even for $\mu = 10$ the change is not great. For example, for $l_s = 0.18$,

$$\mu = \infty,\ i = 2.18\cos\gamma - 3.55\cos(\omega t + \gamma) + 1.37\cos(2\omega t + \gamma) \quad (42a)$$

$$\mu = 10,\ i = 2.46\cos\gamma - 3.64\cos(\omega t + \gamma) + 1.18\cos(2\omega t + \gamma) \quad (42b)$$

for $l_s = 0.09$,

$$\mu = \infty,\ i = 3.07\cos\gamma - 5.26\cos(\omega t + \gamma) + 2.19\cos(2\omega t + \gamma) \quad (43a)$$

$$\mu = 10,\ i = 3.42\cos\gamma - 5.40\cos(\omega t + \gamma) + 1.98\cos(2\omega t + \gamma) \quad (43b)$$

These currents indicate a 2.5 per cent decrease in transient reactance and a 38 per cent decrease (these changes are in

per cent of the unsaturated values; that is, $x_d'$ (sat.)/$x_d'$ (unsat.) = 0.975; $x_d$ (sat.)/$x_d$ (unsat.) = 0.62) in synchronous reactance when compared with the formula of reference 2. Saturation in the main flux path thus has little effect on short-circuit current. This justifies the assumption of infinite stator permeability and shows that in order to account for increased short-circuit current we must include the effect of saturation and eddy currents in the leakage paths. The magnitude of the short-circuit current shown by tests cannot be ascribed wholly to a "subtransient" reactance; it must be accounted for in part by a decrease in transient reactance (or field and armature leakage reactance) due to saturation.

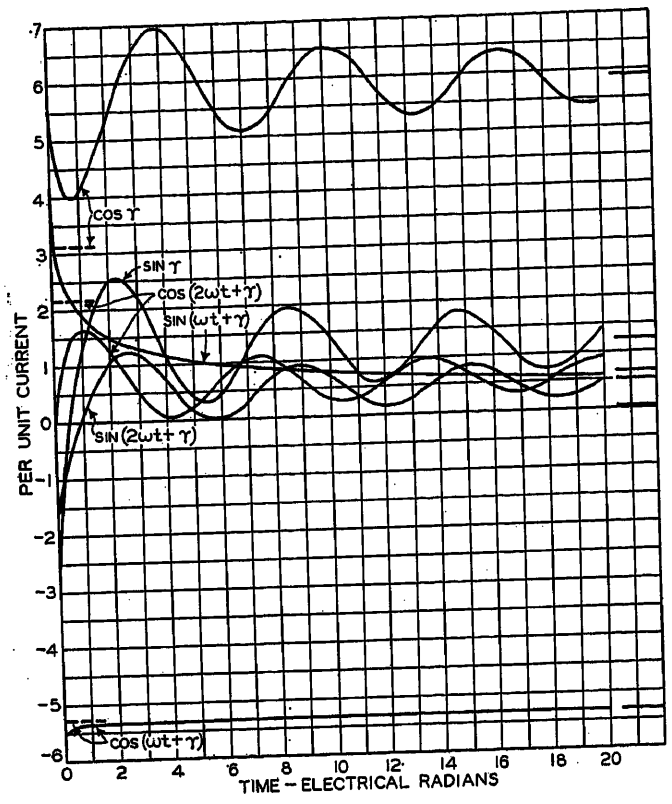



**Fig. 10. Coefficients of trigonometric functions in expression for short-circuit current of solid-rotor turbine generator, case 2**

Dashed lines are for machine with laminated rotor

The subtransient effect has been calculated from figures 9, 10, and 11 by comparing the magnitudes of the oscillatory component of current extrapolated to zero time with those after the iron transient has died out. The subtransient reactance computed on this basis is about 85 or 90 per cent of the transient reactance for $\mu = 100$ and about 97 per cent for $\mu = 1{,}000$. This indicates the importance of taking account of saturation and eddy currents in the leakage paths. In the present work field and armature leakage reactances have been assumed as constant quantities unaffected by the eddy currents, but the effect of eddy currents on the leakage reactances will be shown later.

## Field Current Build-Up

As a second application of the general equations developed in this paper, the field current on sudden application of field voltage (with open-circuited armature) has been determined. The operational expression for field current is:

$$I_f = \frac{Qe_f}{QR + p\left(QL + \frac{KA_1^2}{a}\cosh ag\right)} \tag{44}$$

Taking $\mu = 100$ and solving equation 44, we obtain, for a solid rotor,

$$I_f = 1 + 0.0054\, e^{476t}\, erfc\,(21.8t^{\frac{1}{2}}) - 0.507\,[e^{(-0.214+j0.053i)-j0.130}\, erfc\,(0.452\, e^{j1.44t^{\frac{1}{2}}}) + e^{(-0.214-j0.053i)+j0.130} erfc\,(0.452\, e^{-j1.44t^{\frac{1}{2}}})] \tag{45a}$$

and for a laminated rotor,

$$I_f = 1 - e^{-t/4.24} \tag{45b}$$

Figure 12 shows the computed currents for both a laminated and solid rotor. The curve for the solid rotor case may be approximately represented by an equation of the form

$$I_f = 1 - 0.89e^{-t/4.25} - 0.11\, e^{-t/0.39} \tag{45c}$$

showing that a representation of the solid rotor by an equivalent short-circuited winding is in this case satis-

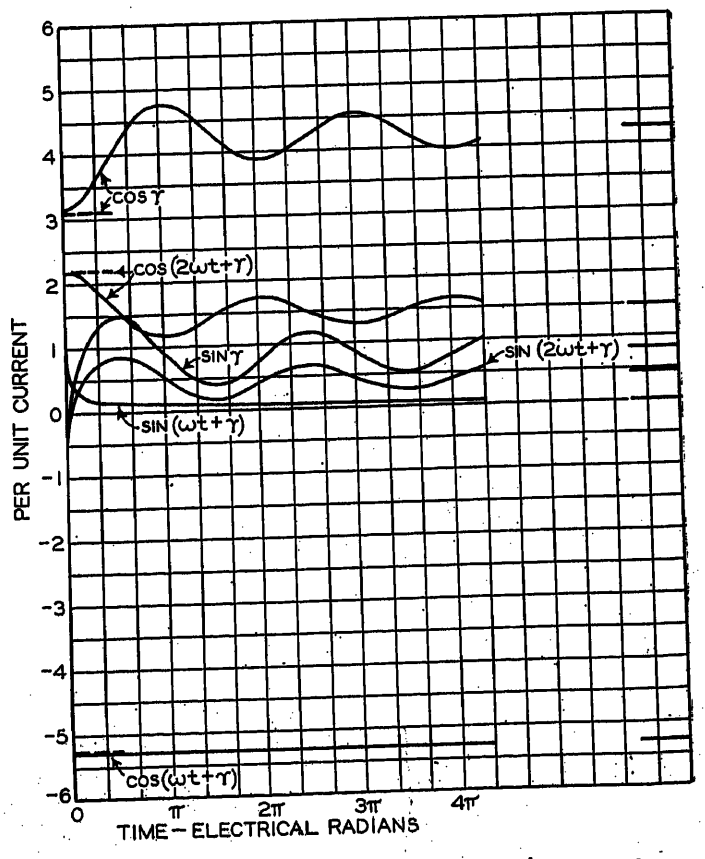



**Fig. 11. Coefficients of trigonometric functions in expression for short-circuit current of solid-rotor turbine generator, case 3**

Dashed lines are for machine with laminated rotor

factory. If the curve of figure 12 is regarded as a single exponential function, the time constant (determined as the time required to reach $(1 - e^{-1})$ of its final value) is 11 per cent less than that for a laminated rotor.

The transient problem of a stationary magnetic circuit linked with a single coil has been presented in a somewhat more simplified form by at least 2 previous writers.[3,4] Here we have taken account of the actual flux distribution in the iron and gap and of the distribution of the field winding, but since the whole effect of rotor eddy currents is seen from figure 12 to be rather small (at least for $\mu > 100$), the results in the case of field build-up show no great discrepancies from their work.

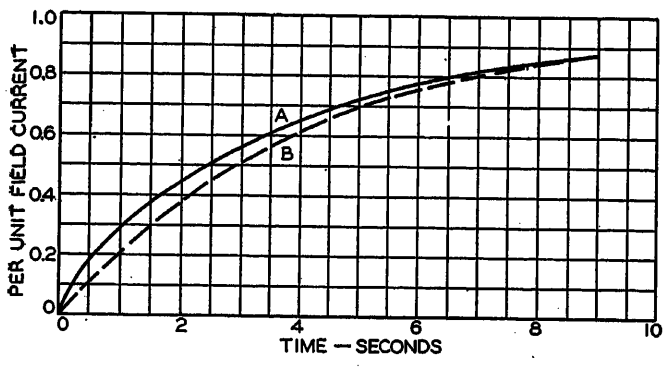



**Fig. 12. Field current of a turbine generator with solid rotor, upon sudden application of field voltage**

*A*—With solid rotor *B*—With laminated rotor

## Flux Decay

A third application of the theory has been to the determination of the rate at which the flux changes following a sudden change in stator current. In the example given here we consider the field to be open-circuited and compute the flux decay following opening of the stator circuit. This will correspond to the decay of the quadrature axis component of flux.

From equation 49 it follows that for sudden changes in stator current there is the operational expression:

$$\psi \text{ is proportional to } \frac{\cosh ag + q \sinh ag}{q \cosh ag + \sinh ag} \qquad (46)$$

Here we are not concerned with the absolute magnitude but only with the shape of the flux-time curve. For a machine for which $2g/l = 0.051$ and $l_s = 0$, we obtain the equations of flux decay (per unit initial value): for $\mu = 1{,}000$,

$$\psi = 0.985\, e^{2.8t}\, erfc\,(4.67t^{\frac{1}{2}}) - 0.007\, erfc\,(0.032t^{\frac{1}{2}}) \qquad (47a)$$

for $\mu = 100$,

$$\psi = 1.048\, e^{2.18t}\, erfc\,(1.48t^{\frac{1}{2}}) - 0.071\, erfc\,(0.10t^{\frac{1}{2}}) \qquad (47b)$$

Note that the flux drops immediately to 98 per cent of its initial value, the drop representing that portion of the quadrature axis flux which did not link the rotor but was only in the air gap. Although the expressions appear rather complicated it becomes evident by inspection that, with less than about 5 per cent error, a very simple relation exists between the flux at any time and the assumed permeability. That is, we may assume the flux to be a function of the product of permeability and time (see figure 13), so that the time constant is inversely proportional to the permeability.

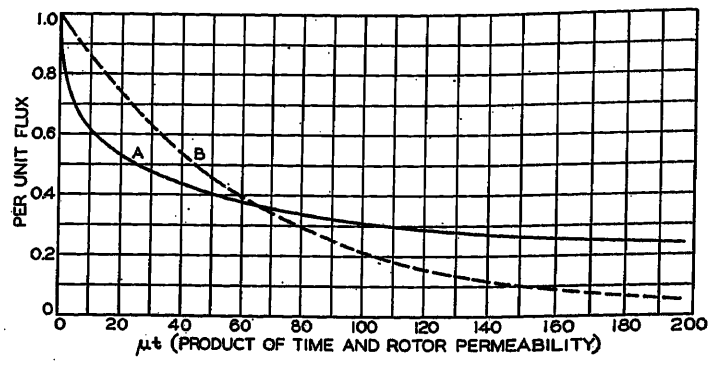



**Fig. 13. Flux decay in a turbine generator, upon sudden removal of armature current**

*A*—Quadrature-axis flux
*B*—Exponential through value $1/e$

## Steady State Impedances

In order to show the relation between the design factors used in the present theory and the circuit constants of ideal synchronous machine theory,[5] we shall find the expression for synchronous impedance. From either equation 30*b* with $p = 0$ and $I_r = 0$, or equation 31*b* with $p = 0$ and $e_r = 0$,

$$\frac{C}{D} = r_s + j\omega\left[l_s + \frac{3KB_1^2}{2a}\left(\frac{\cosh ag + \mu^{-1}\sinh ag}{\mu^{-1}\cosh ag + \sinh ag}\right)\right]$$

Thus

$$\text{Synchronous Reactance} = \omega\left[l_s + \frac{3KB_1^2}{2a}\left(\frac{1 + \mu^{-1}\tanh ag}{\mu^{-1} + \tanh ag}\right)\right]$$

Similarly, from equations 53 the field self-inductance[6] may be recognized as

$$L + \frac{KA_1^2}{a}(\mu^{-1} + \tanh ag)^{-1}$$

## Conclusions

In order to account completely for the observed phenomena of turbine-alternator transient performance and to compute correctly the behavior under specified terminal conditions it may be necessary to include the effects of the slots, of harmonics, of saturation, of hysteresis, of eddy currents, of the rotor surface curvature and of their influence not only on the main flux path but also on the leakage flux paths. For this reason the present paper should be regarded as presenting merely a first step in the complete solution of the general problem. Also, the

final equations of this paper have been established only for the symmetric 3-phase case. This was done because the 3-phase case is susceptible to simple solution by the operational method. However, many problems in addition to those used as examples can be solved by the methods of this paper despite this limitation. For example:

1. Short circuit from any symmetric load condition
2. Sudden (or any) change in field excitation with any symmetric armature load
3. Calculation of flux change, in addition to current and voltage change, for any of the other cases solved
4. Sudden change of load impedance (switching)
5. Prescribed change of terminal voltage.
6. Transient torque and forces for any of the conditions listed above
7. Negative-sequence reactance
8. Current for continuous load pulsation
9. Speed-torque relation for a solid rotor machine running as an induction motor
10. Eddy current losses

From the results of the calculations the following specific conclusions may be drawn:

1. Saturation in the main flux path does not affect appreciably the magnitude of the short-circuit current.
2. Eddy currents in the main body of the solid rotor may account for a 10 to 15 per cent reduction in subtransient reactance below transient reactance.
3. The larger difference between transient and subtransient reactance shown by tests must be due to (*a*) retaining ring saturation and eddy currents; (*b*) tooth tip saturation (and eddy currents in case of the rotor teeth).
4. Eddy currents in the solid rotor may account for about a 10 per cent decrease in the apparent field open circuit time constant.
5. The effective time constant of the quadrature axis flux varies inversely as the rotor permeability (at least in the range of permeability greater than 100).

## Appendix I—Symbols and Nomenclature

$H$ = magnetic intensity vector
$i$ = current-density vector
$E$ = electric-intensity (voltage-gradient) vector
$B$ = magnetic flux-density vector
$t$ = time
$\lambda$ = specific conductivity
$\mu$ = permeability
$\beta^2 p = \beta^2 \frac{\partial}{\partial t} = 4\pi\lambda\mu 10^{-9} \frac{\partial}{\partial t}$
$x, x_1, y, z$ are co-ordinate directions as shown in figure 1; $x$ and $x_1$ tangential, $y$ radial, and $z$ axial; $x$, $y$, $z$ are fixed in the rotor while $x_1$ is fixed in the stator
$\psi$ = vector magnetic potential
$\omega'$ = angular velocity of rotor (see figure 1)
$r$ = radius of rotor
$I$ = coil currents; $I_r$ rotor coil current; $I_a$, $I_b$, . . . stator coil currents; $I_s$ resultant of all stator ampere-turns
$l$ = length along rotor surface of $2\pi$ electrical radians or twice pole pitch
$a = 2\pi/l$
$A_n$, $B_n$ are coefficients of Fourier series for the ampere turn distributions
$R$ = rotor-coil resistance
$L$ = rotor coil leakage inductance
$r_s$ = stator coil resistance
$l_s$ = stator coil leakage inductance in the direct (or quadrature) axis
$l_0$ = zero phase sequence stator coil leakage inductance
$e$ = applied voltage; $e_a$ = voltage applied to coil $a$; $e_r$ = voltage applied to rotor coil, etc.
$k$ = number of pairs of poles
$\omega$ = electrical angular velocity = $k\omega'$
$\gamma$ = angle by which the rotor "leads" the stator
$C, C', e_0$ = coefficients of complex components of stator terminal voltage
$D, D', i_0$ = coefficients of complex components of stator current
$g$ = air-gap length
$Z$ = machine axial length
$K = 2\pi 10^{-9} Z l k$
$q = \frac{\beta}{\mu a}\left[p + \left(\frac{a}{\beta}\right)^2\right]^{\frac{1}{2}}$
$Q = q \cosh ag + \sinh ag$
$u = l_s \cosh ag + \frac{3KB_1^2}{2a} \sinh ag$
$v = l_s \sinh ag + \frac{3KB_1^2}{2a} \cosh ag$
$2V$ = magnitude of open-circuit armature phase voltage

## Appendix II

The solutions of the field equations 17 and 18, subject to the boundary conditions expressed by equations 19 and 20, and considering only the fundamental components, yield:
At the rotor surface, $y = 0$,

$$\psi = \frac{-4\pi 10^{-9} e^{pt}}{\left[\frac{\sqrt{\beta^2 p + a^2}}{\mu a} + \tanh ag\right] a \cosh ag} \times \left[I_r A_1 \cos ax \cosh ag + \frac{3}{2} B_1 (De^{j(ax-\gamma)} + D'e^{-j(ax-\gamma)})\right] \quad (48)$$

At the stator surface, $y = g$,

$$\psi = \frac{-4\pi 10^{-9} e^{pt}}{\left[\frac{\sqrt{\beta^2 p + a^2}}{\mu a} + \tanh ag\right] a \cosh ag} \times \left\{I_r A_1 \cos(ax_1 + \omega t + \gamma) + \frac{3}{2} B_1 \left[\cosh ag + \frac{\sqrt{\beta^2 p + a^2}}{\mu a} \sinh ag\right] \times [De^{j(ax_1+\omega t)} + D'e^{-j(ax_1+\omega t)}]\right\} \quad (49)$$

From equation 48 the electric intensity at the rotor surface is simply

$$E_r(x) = \frac{\partial}{\partial t}\psi = p\psi \quad (50)$$

while, from equations 49 and 23, at the stator surface

$$E_s(x_1) = \frac{\partial}{\partial t}\psi(x_1) = \frac{-4\pi 10^{-9} e^{pt}}{\left[\frac{\sqrt{\beta^2 p + a^2}}{\mu a} + \tanh ag\right] a \cosh ag} \times \left\{\frac{I_r A_1}{2}[(p + j\omega)e^{j(ax_1+\omega t+\gamma)} + (p - j\omega)e^{-j(ax_1+\omega t+\gamma)}] + \frac{3}{2} B_1 \left[\cosh ag + \frac{\sqrt{\beta^2 p + a^2}}{\mu a} \sinh ag\right] \times \left[D(p + j\omega)e^{j(ax_1+\omega t)} + D'(p - j\omega)e^{-j(ax_1+\omega t)}\right]\right\} \quad (51)$$

(*Concluded on page 179*)

# Electrical Characteristics of Suspension-Insulator Units

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**Effects of humidity, corona, and mechanical stress on the electrical characteristics of porcelain and glass suspension-insulator units are shown in this paper. Moisture, alone and combined with corona, is found to produce surface deposits which cause hysteresis effects in the power, power factor, and capacitive characteristics, and mechanical stress is found to reduce the power, power factor, and capacitance. The effect of stress is reduced where soft metal is used in place of cement in assembling the unit.**

ALTHOUGH for a number of years the flashover and puncture characteristics of suspension-insulator units have been investigated extensively, very little study has been made of their power-loss, power-factor, and capacitance characteristics. The only published work of any importance is that of Draeger.[1] The extent and value of his measurements were limited, however, by the bridge facilities available to him at the time (1925). Moreover, he did not take into consideration the effect of humidity on the characteristics, which has been found by the authors to be the factor which, with corona, has the greatest effect on the electrical characteristics of the insulators. Furthermore, the authors have been able to carry the investigation much further than Draeger and to relate "corona hysteresis" to the combined effects of humidity, corona, and a microscopic surface deposit produced by corona.

The insulators tested were 10-inch porcelain disk-type suspension insulators supplied by the Locke Insulator Corporation, and a Pyrex 776, 10-inch glass disk-type suspension insulator supplied by the Corning Glass Works.

## Summary

1. The electric and dielectric circuits of a suspension-disk insulator consist of the porcelain and cement between cap and pin which is practically invariable, and the capacitance between the surfaces of the shell in series combinations with the surface resistance. This circuit is highly variable due to changes in surface resistance.

2. The surface resistance is a function of adsorbed moisture and decreases with increase in absolute humidity and increases with decrease in absolute humidity. The surface resistance also decreases with corona formation.

3. At any fixed voltage the electrical characteristics of the insulator vary with time. This is due to the change in surface resistance caused by Joule heating and to "island formation." The resistance may increase with time or it may decrease, depending on the part of the test cycle at which it is operating.

4. The electric and dielectric characteristics of the insulator are functions of the absolute humidity or of the absolute amount of moisture in the atmosphere.

5. Corona forms at lower voltage with increasing values of absolute humidity.

6. The power factor is practically a linear function of the absolute humidity.

7. Corona reacting with oxygen, nitrogen, and moisture of the atmosphere forms acidic compounds which deposit on the insulator surface, causing change in the surface resistance.

8. The combined action of the corona, acidic compounds, and the sputtering of the metal of the cap and pin form semipermanent conducting microscopic "island" deposits which cause a decrease in surface resistance. Such island deposits can be removed only by vigorous rubbing.

9. The moisture film on the insulator surface together with the island deposits causes a hysteresis effect in the electrical characteristics of the insulator.

10. The changes in surface resistance also vary the amount of shell capacitance connected between cap and pin. Hence the total insulator capacitance increases with decrease in surface resistance and *vice versa*.

11. The electric and dielectric characteristics of the insulator are not greatly affected directly by temperature, but are affected indirectly in that absolute humidity of air is a function of temperature.

12. Mechanical stress for the most part causes a decrease in the power factor and capacitance due to the compression of the cementing material. After such material has a permanent "set" further change is slight and with glass insulators the characteristics remain independent of further stress.

## Method of Measurement

The electrical characteristics were measured by means of the mutual-inductance type of high-voltage bridge developed and used in the high-voltage laboratories at Harvard University. The simplified diagram of connections of the bridge and the test insulator is shown in figure 1.

In order to facilitate the connection of the high-voltage lead and the low-voltage shielding, the insulator was tested in an inverted position. No differences in effects between this position and the upright one were noted.

The details of the bridge connections have already been published.[2] The shielding $S_2$ surrounding the low-voltage lead *ab* to the specimen is balanced to the

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1. For all numbered references see list at end of paper.

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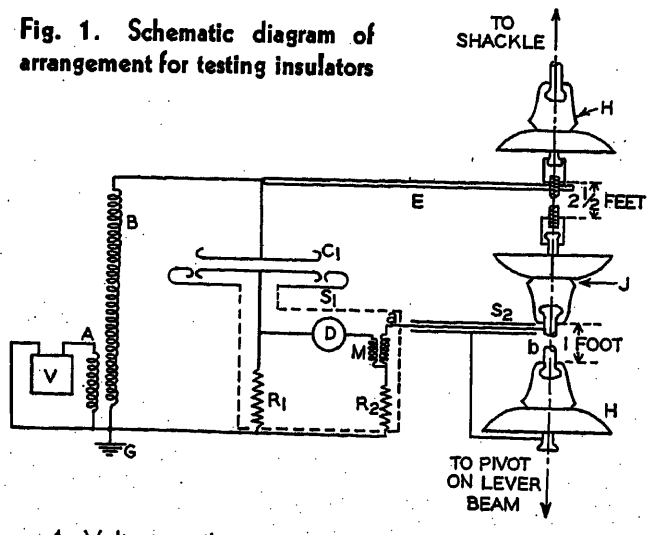
same potential as the lead *ab* so that capacitive effects between them are eliminated. The bridge is provided with an amplifier to give it the necessary sensitivity, and filters to eliminate harmonics from the circuit.[3]

## Equivalent Circuits of Disk Insulators

In figure 2*a* is shown the cross section of a typical insulator unit and the approximate electrical circuits. There is a capacitance $C$ of approximately 30 micro-microfarads between the cap and the pin. The dielectric is the porcelain, and the cement used to fasten the cap and pin in place. Such dielectrics obviously involve dielectric loss so that in the equivalent circuits of figures 4*b* and 4*c*, the capacitance $C$ is shown shunted by a resistance $R$ to simulate this loss. The dielectric characteristics of the porcelain and the cement remain practically constant under all conditions, although a slight increase in power factor with increase in voltage may be attributed to the ionization of occluded gases. The values of $C$ and $R$ may be changed slightly by mechanical stress.

The glazed porcelain shell may be considered as consisting of a number of capacitances $C'$ between the upper and lower surfaces. If the surface resistance were infinite, the capacitances $C'$ would have very little effect on the total insulator characteristics. These capacitances are, however, connected in the insulator circuit by the surface resistance $R'$ which is caused by moisture and other conducting deposits on the surface, as well as by corona which is also conducting. As will be shown later, the surface resistance $R'$ depends on the humidity and the voltage, and it has a very large effect on the insulator characteristics. Hence the effects of the shell capacitance depend on the surface resistance and they will vary with changes in the surface resistance.

**Fig. 1. Schematic diagram of arrangement for testing insulators**




*A*—Voltmeter coil
*B*—Step-up transformer secondary
$C_1$—Air capacitor
*D*—Detector
*E*—High-voltage lead, one inch in diameter
*G*—Ground
*H*—Insulators, mechanical strength, 25,000 pounds
*J*—Test specimen, mechanical strength 18,000 pounds
*M*—Mutual inductance
$R_1$, $R_2$—Series resistors
$S_1$, $S_2$—Shielding
*V*—Voltmeter

The equivalent circuit of the insulator shown in figure 2*a* is shown directly in *b*. The cap and pin capacitance $C$ is shunted by a resistance $R$ to simulate the dielectric losses. The capacitances $C'$ and the surface resistance $R'$ combine to form equivalent

*A*—Insulator cap
*B*—Corona
*C*—Main capacitance, 30 micro-microfarads
*R'*—Surface resistance
*D*—Insulator pin
$C_1$, $R_1$—Equivalent parallel circuit of insulator shell

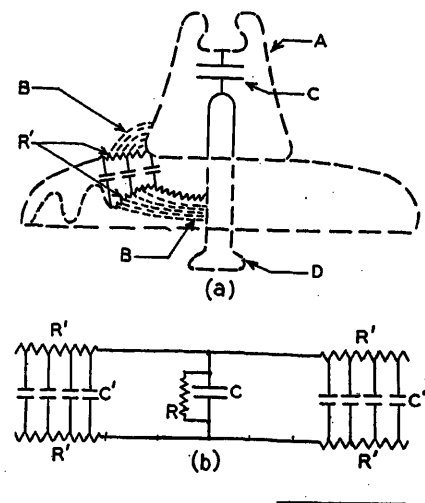



**Fig. 2. (a) Insulator with surface resistance, capacitance, and corona; (b) equivalent circuit of insulator with surface resistance; (c) total equivalent circuit of insulator**

T-circuits and this combination is connected in parallel with $C$ and $R$ to give the equivalent circuit of the entire insulator. The entire diagram of figure 2*b* may be simplified to that of *c* in which the over-all effect of the capacitances $C'$ and the surface resistance $R'$ for any one set of conditions are replaced by the capacitance $C_1$ and the resistance $R_1$. The variation of the surface resistance $R'$ with humidity, corona, and elapsed time of test for the most part accounts for the changes in the characteristics of the insulator.

## Time Lag

In making the measurements of power, power factor, and capacitance, it was found that very much higher values for these factors were obtained with decreasing values of voltage than with increasing values, thus giving a hysteresis effect. This effect is illustrated in figure 3 as well as in figures 4, 5, 6, and 7. It was also found that the hysteresis effect increased with absolute humidity, as is shown in figure 5.

Moreover, in making the measurements, it was found that the values of power, power factor, and capacitance for any definite voltage were not fixed, but varied with time. At low humidity and with increasing values of voltage, these factors increased with time. At high humidity and with increasing values of voltage, at low voltage, they decreased with time, but after corona formed they increased with time due to the surface deposits to be described later. These effects are illustrated in figures 3 and 4.

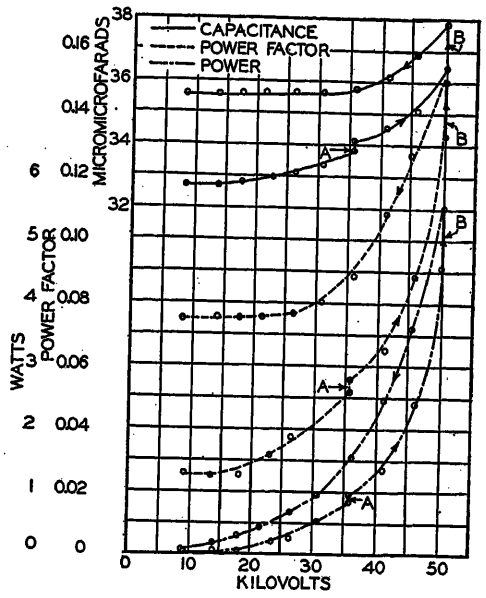



**Fig. 3. Characteristics of porcelain insulator, showing time lag and hysteresis effects at 60 cycles and 20 degrees centigrade**

*A*—Lapse of time of 10 minutes

*B*—Lapse of time of 2 hours

In figure 3 the increases in power, power factor, and capacitance for an interval of 10 minutes at 35 kv are shown. Also, the same effects are shown for a 2-hour interval at 50 kv, but the increases are much greater.

Careful study of this phenomenon showed that the values of power, power factor, and capacitance varied almost as does a direct current in an inductive circuit with resistance in series when a continuous voltage is suddenly switched across it, or when such a circuit is short-circuited. The change is at first rapid but the rate of change diminishes with time. It seemed that theoretically steady conditions would be reached only after infinite time. To reach the steady condition for each bridge balance would therefore require a prohibitively long time. Moreover, in order to interpret the phenomena, it is not necessary that the exact values corresponding to the ultimate steady state be obtained. Hence, in making the measurement it was decided to choose such values of time as would give from 85 to 90 per cent of the difference between the ultimate and initial readings.

The relationships among the characteristics obtained at the different values of time are shown in figure 4, *A* and *B* giving those for increasing values of voltage, and *C* and *D* giving those for decreasing values of voltage. In all the figures the characteristics *aa'* give the values of power factor which would be obtained if the measurement were made instantaneously. The characteristics *bb'* give the values of power factor which would be obtained if the measurement were made at infinite time. The characteristics *cc'* are those actually obtained and they lie at approximately 85 to 90 per cent of the distance from *aa'* to *bb'*. As will be shown later, these time-lag effects are due to the humidity of the atmosphere and to the accumulation of a deposit on the insulator surface.

It was found that the value of the time necessary to obtain curves *cc'* was not constant but varied with the voltage, the humidity, and the amount of corona formation. In a large measure, the time was determined by experience combined with watching the rate at which the bridge balance changed. The approximate values of time are as follows:

| Kilovolts Across Insulator | Elapsed Time Before Taking Reading, Minutes |
|---|---|
| 2 | 5 to 20 |
| 10 | 5 to 20 |
| 20 | 10 to 25 |
| 30 | 15 to 45 |
| 40 | 25 to 80 |
| 50 | 30 to 120 |

## Electrical Characteristics and Absolute Humidity

Early in the research it was found that the electrical characteristics of the insulators were, in a large measure, functions of the humidity. First it was attempted to relate the characteristics to the relative humidity, but there seemed to be no remote relationship, even, between them. Further investigations showed that the characteristics were closely related to both specific humidity and to absolute humidity. (Specific humidity is the actual amount of moisture per unit weight of dry air.) In this paper absolute humidity in grains of moisture per cubic foot of air is used (7,000 grains of moisture equal one pound).

In the authors' experimental work there were little means for controlling the humidity so that usually it was necessary to await natural changes in the laboratory. As a rule, high values of humidity occurred in summer and low values on cold winter days.

In figure 5 are shown the power-factor characteristics for a porcelain insulator with increasing and decreasing values of voltage for 3 different values of absolute humidity, $s = 2.6$, $s = 4.48$, and $s = 7.56$.

The very low value (2.6) was obtained on a cold,

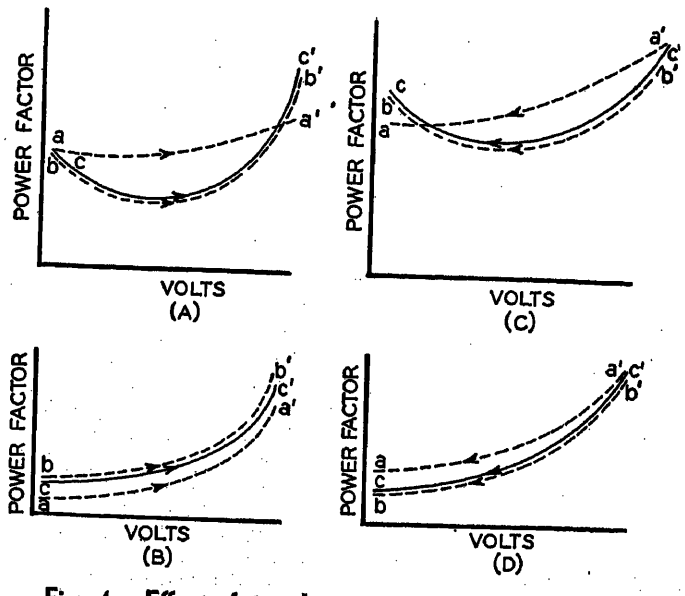



**Fig. 4. Effect of time lag on insulator characteristics**

*A*—High humidity, increasing voltage
*B*—Low humidity, increasing voltage
*C*—High humidity, decreasing voltage
*D*—Low humidity, decreasing voltage

dry winter day; the intermediate value (4.48) was obtained on a cool, autumn day, and the high value (7.56) was obtained during a hot, muggy day in July. Similarly, in figure 6 are shown the capacitance characteristics for the same insulator at these same 3 values of absolute humidity. In figure 7 is shown the power-factor characteristic of a glass insulator obtained at an absolute humidity of 4.7. It may be noted that with all the characteristics of figures 5, 6, and 7, the values for decreasing voltage are greater than for increasing voltage.

It will also be noted in figure 5 that with the low value of absolute humidity, $s = 2.6$, the power factor increases continuously with increase in voltage and decreases continuously with decrease in voltage. With the intermediate value of absolute humidity, $s = 4.48$, the power factor remains constant until 35 kv and then increases. This increase in power factor is caused by the corona which forms at approximately 35 kv. With the high value of absolute humidity, $s = 7.56$, the power factor first decreases rapidly with increase in voltage, reaches a minimum at approximately 25 kv, and then increases due to corona formation. The characteristic for descending values of voltage is similar, except that it lies above the first characteristic.

These characteristics are typical. With low values of absolute humidity, the power factor always increases with voltage, rising more rapidly after corona formation. With larger values of absolute humidity, the power factor at first decreases with increase in voltage until corona forms, when it increases. It is also found that with large values of absolute humidity the difference between the ascending and the descending characteristic increases (see figure 5). Corona forms at lower values of voltage with increasing values of absolute humidity. For example, in figure 5 corona formation begins at 34 kv when $s = 4.48$, and at 26 kv when $s = 7.56$ (also see figure 12).

## "Island" Deposits on Surface

It is well known that corona activates the air and causes the oxygen, nitrogen, and water vapor to combine and form weak nitric acid. This acid deposits on the insulator surface near the cap and pin to form initially conducting spots or small islands. The voltage gradient over the surface causes arcs to snap from island to island, vaporizing the deposits and scattering them over a wider area. At high voltages these arcs become longer and brighter and more explosive scattering of the vapors occurs. In the authors' opinion it is these arcs which in large measure cause radio interference.

These acidic islands are more or less conducting and it is in part due to their formation that the power factors, etc., increase with time.

Several factors led to the belief that, in addition to the acidic spots, a more or less permanent deposit must form on the insulator surface, but it was some time before this fact could be substantiated. After the voltage had initially been increased to its maximum value and then lowered, the power, power factor, and capacitance were greater than with increasing values of voltage, as is shown by the descending voltage characteristics, figures 5, 6, and 7. In subsequent tests these quantities always remained above their initial values, and, in fact, they increased continuously with continued application of voltage, particularly if the absolute humidity were large. However, if the surface were cleaned, vigorous wiping

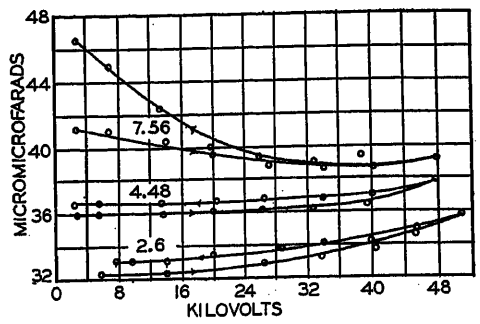



**Fig. 6. Capacitive characteristics of porcelain insulator at 3 values of absolute humidity**

Numbers on curves are humidities in grains of moisture per cubic foot of air

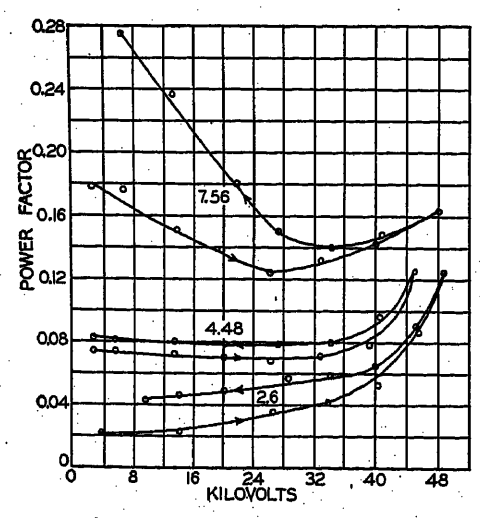



**Fig. 5. Power factor of porcelain insulator as a function of voltage at different absolute humidities**

Numbers on curves are absolute humidities in grains of moisture per cubic foot of air

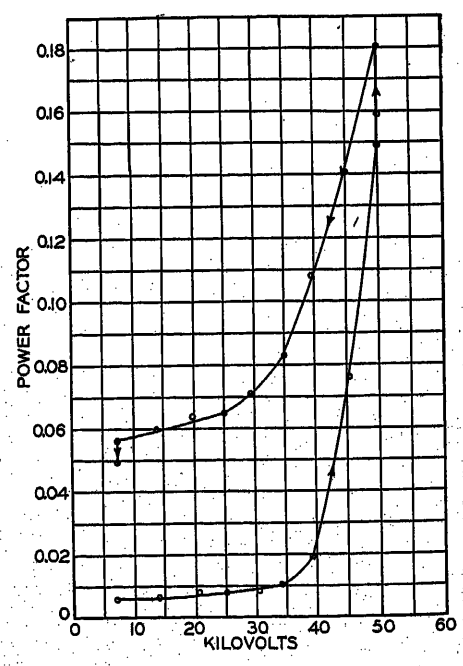



**Fig. 7. Power-factor characteristics of glass insulator at 60 cycles, 21.5 degrees centigrade, and 4.7 absolute humidity**

being necessary, the characteristics returned to the initial values.

Carefully polished surfaces of metals were then subjected to a corona discharge with moisture present and island formations could be readily seen under the microscope. (One of the authors has found that corona makes a very effective etching agent in micro-

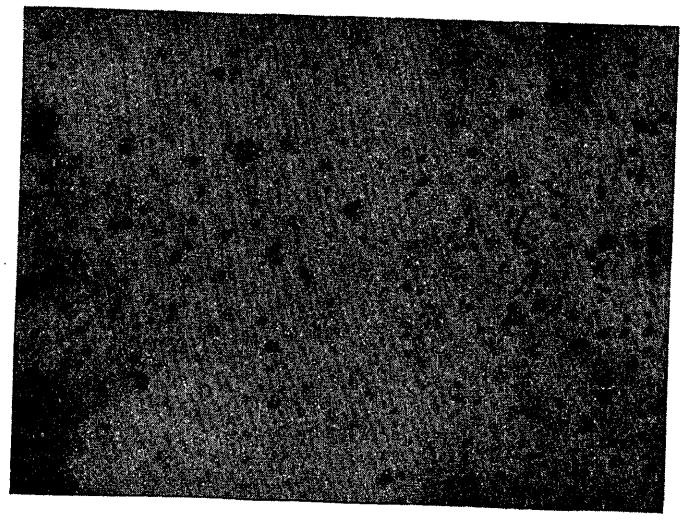


**Fig. 8. Microphotograph of deposit near pin on porcelain insulator caused by corona and moisture**

Magnification 120 diameters

photography.) Later, by means of a dark-field type of microscope, it became possible to detect the island deposits on porcelain, and a microphotograph taken near the pin is shown in figure 8. The examination of the surface is made difficult by the fact that microscopes are not adapted to bring to the objective the portions of the porcelain surface near the cap and pin, and thecurved surfaces make microphotography very difficult. Hence, it is necessary to break the porcelain without disturbing the deposits, and to select suitable pieces for examination. It is the island deposits such as are shown in figure 8 that cause the permanent changes in the insulator characteristics to which reference has already been made.

The authors have made several attempts to learn more about the nature of the deposit. It can be removed by wiping the surface vigorously and, as has already been stated, the characteristics of the insulator return to their initial values. The deposit is a very thin film consisting of microscopic islands, some of which are crystalline in form. The film is so thin and so difficult to remove that, so far, a chemical analysis has not been possible. The authors believe, however, that it consists of the nitric-acid deposit already discussed in combination with the metal of the cap or pin which has been deposited by the sputtering effect of the corona. This is substantiated by some experiments made on pieces of porcelain placed within a corona field, with moisture present. If a sheet of glass was interposed between the high-voltage electrode and the porcelain, no deposit occurred. If, however, moist air is interposed between the high-voltage metal electrode and the sur-

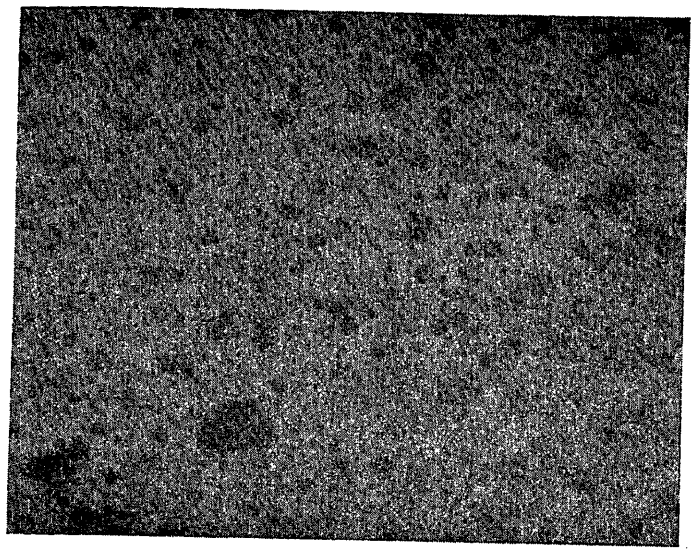


**Fig. 9. Microphotograph of deposit on glazed porcelain formed artificially by simulating natural conditions in the presence of corona and moisture**

Magnification 300 diameters

face of the porcelain, a deposit almost identical with that shown in figure 8 results. A microphotograph of this deposit is shown in figure 9. This seems to show that the deposit involves the metal of the electrodes. Further study of these deposits, with chemical, X-ray, and microscopic aid, is now in progress.

## Hysteresis in Power Factor Curves

With the preceding discussions of humidity, corona, and the surface deposits on the insulator surface, it now becomes possible to analyze the corona hysteresis characteristics.

Consider, for example, the characteristic for $s = 7.56$ in figure 5. With increasing values of voltage the power factor decreases. Due to the humidity an adsorbed film of moisture has accumulated on the surface of the insulator, accounting for the resistance $R'$ in figures 2*a* and 2*b*. At the lower values of voltage, if the voltage is brought to any particular value and held constant, the power factor will diminish, that is, the characteristic tends to go from $aa'$ to $bb'$ in figure 4*A*. This is due to the joulean heating effect ($I^2R'$) on the insulator surface which vaporizes some of the moisture and hence increases $R'$ (figure 2, *a* and *b*). This will continue until a steady state is reached, that is, until a balance is reached between the moisture removed by heat and that which is steadily being deposited from the humid atmosphere. With increasing voltage, the surface heating effect is increased, and more moisture is driven from the insulator surface. This increases the value of $R'$ (figure 2*b*) and the power factor again diminishes with time. This effect continues until corona forms.

Corona itself is an energy loss and will accordingly of itself increase the power factor. Moreover, it is conducting in character and causes the surface resistance $R'$ to decrease (figure 2, *a* and *b*). Up to a certain point a decrease in $R'$ increases the power fac-

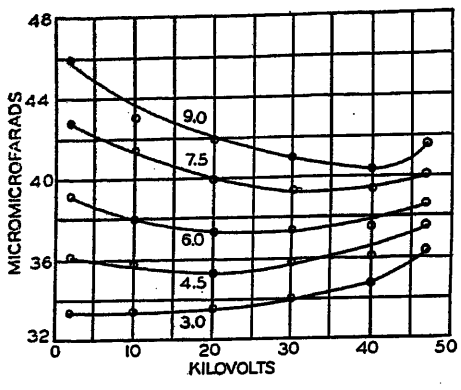
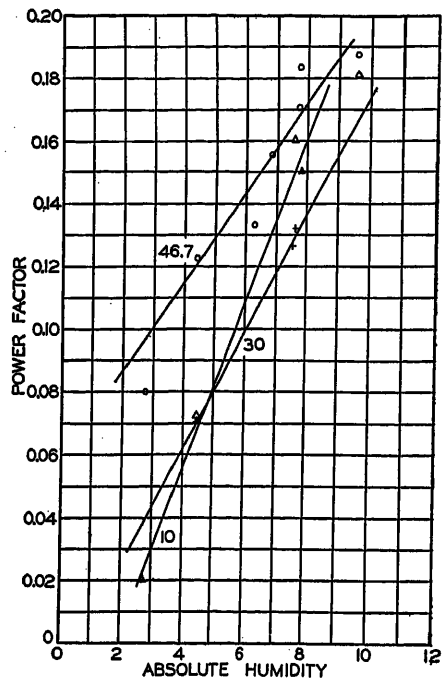



**Fig. 10 (left). Capacitance of porcelain insulator as a function of voltage at different absolute humidities; interpolated data from increasing voltage**

Numbers on curves are absolute humidities in grains of moisture per cubic foot

**Fig. 11 (right). Power factor of porcelain insulator as a linear function of absolute humidity at constant voltage; data from increasing voltage**

Numbers on curves are potentials in kilovolts




tor. Corona thus accounts for the increase in power factor which occurs at the higher values of voltage.

With low values of absolute humidity, the adsorbed surface moisture is so small that it has very little and at times negligible effect on the power and power factor. As the voltage is raised with very low absolute humidities, a slight increase in power factor occurs as is shown by the characteristic, $s = 2.6$, in figure 5. This undoubtedly is due to corona formation occurring in the pores of the porcelain and cement and in any small voids that may exist between cap and pin. With a higher value of absolute humidity, $s = 4.48$ (figure 5), the value of power factor remains substantially constant until corona forms. This undoubtedly occurs because the effects of humidity, which cause a decrease in power factor, are being balanced with the corona formation in the voids, which causes an increase in power factor.

With decreasing voltage the power-factor characteristics lie above those for increasing voltage as has already been stated. This is due primarily to the conducting surface deposits resulting from the combined action of corona and moisture. As the voltage decreases, the corona formation itself decreases and the resulting power factor decreases. A point will, however, be reached when corona ceases and the characteristic will reach a minimum (see characteristic $s = 7.56$, figure 5). With further decrease in voltage, and hence in surface heating, moisture will again deposit on the insulator surface and the power factor will now increase. As the voltage becomes less, less heat is evolved on the insulator surface, more moisture deposits, and the power factor continues to increase with diminishing values of voltage.

With low values of humidity the effect of surface loss is negligible so that the rise in power factor with diminishing voltage does not occur as is shown by the characteristics for $s = 4.48$ and $s = 2.6$ in figure 5.

## Capacitance Characteristics

A study of $a$ and $b$ in figure 2 shows that the total capacitance of the insulator consists of the sum of the capacitance $C$ of the head of the insulator and the capacitances $C'$ between the conducting surfaces of the shell. The effectiveness of the capacitances $C'$, however, depends on the value of the surface resistance $R'$. With $R'$ infinite, the capacitances $C'$ have negligible effect on the total capacitance of the insulator. The effect of $C'$ increases as $R'$ diminishes and the maximum effect of $C'$ occurs when $R'$ is zero. Hence the value of the total capacitance $C$ of the insulator depends on the conductance of the film of surface moisture.

With low values of absolute humidity, the capacitance changes little with voltage. There is a steady rise in capacitance with voltage, as is shown by the 2 characteristics at $s = 2.6$ and $s = 4.48$ in figure 6. This rise is undoubtedly due to corona formation in the voids in the porcelain and cement between cap and pin. There is but slight rise in capacitance after corona formation at the edges of the cap and the pin. This is because the corona probably does not extend sufficiently far out from the cap and the pin to include much of the capacitance $C'$ of the shell.

The effect of the adsorbed surface moisture is well illustrated by the characteristic for $s = 7.56$. At first the capacitance dimin-

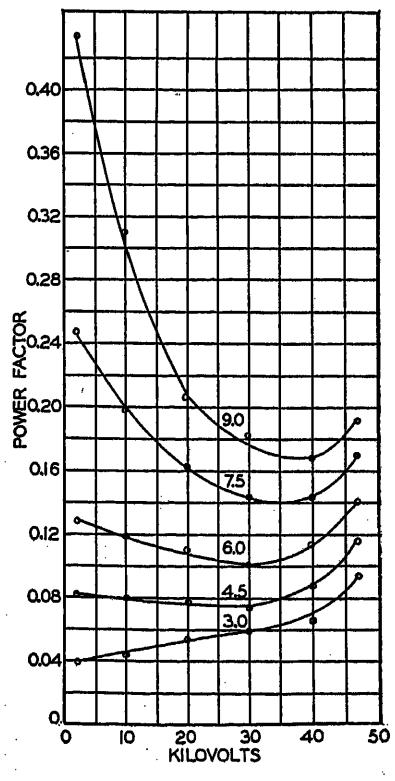



**Fig. 12. Power factor of porcelain insulator as a function of voltage at different absolute humidities; interpolated data from increasing voltage**

Numbers on curves are absolute humidities in grains of moisture per cubic foot of air

ishes with increasing voltage due to the increasing surface resistance $R'$. When corona forms the capacitance increases slightly due to reduction in surface resistance by corona and island deposits. With diminishing voltage the capacitance increases due to the combined effect of returning adsorbed surface moisture and the permanent island deposits. Hence the total capacitance of a disk insulator is a function of the deposit and the adsorbed moisture on the surface, and of the corona.

In figure 10 is shown a complete family of capacitance-kilovolt characteristics with increasing values of voltage for 5 different values of absolute humidity. These characteristics further illustrate the analysis of the relationship of capacitance to absolute humidity. That is, at low values of absolute humidity, the changes in capacitance are small; at large values, they are considerable.

## Power Factor and Absolute Humidity

It is found that if the values of power factor for constant voltage be plotted as functions of absolute humidity, the best representative characteristics are

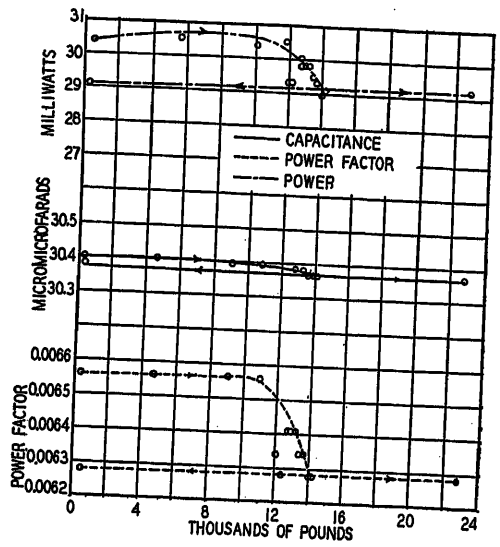



**Fig. 13. Electrical characteristics of glass insulator as functions of mechanical stress at 60 cycles, 21.5 degrees centigrade, and 30 kv**

linear. Three such characteristics for 10, 30, and 46.7 kv are shown in figure 11. For the sake of clearness, similar characteristics for other values of voltage are omitted.

If the data for the characteristics of power factor versus absolute humidity such as are given in figure 11 are replotted, with power factors as functions of kilovolts at constant values of absolute humidity, characteristics similar to those of figure 12 are obtained. These characteristics are similar to those of figures 3 and 5 except that they include more values of absolute humidity. A study of these curves shows that with increasing voltage the rise due to corona formation at the edges of cap and pin begins at lower values of voltage with increasing values of absolute humidity. With decreasing voltage the reverse is true.

In the foregoing relationships, the effect of temperature has not been mentioned. The authors' studies showed no explicit relationship of any of the characteristics to temperature over the annual range of atmospheric temperature variation. Over extreme ranges of temperature Draeger[1] shows a relationship. However, it must be remembered that absolute humidity is a function of the temperature. Hence indirectly, temperature does affect the electrical characteristics of suspension disks.

## Electrical-Mechanical Characteristics[1]

In order to study the effects of mechanical stress on the electrical characteristics, the suspension disk was so mounted that mechanical stress could be applied and measured simultaneously with the high-voltage electrical measurements. It was anticipated that any dislocation of the cap or pin by mechanical stress would affect the electrical characteristics of the insulator. The stress was applied by means of a large automobile jack acting through a lever with a 5 to 1 ratio. With this arrangement, stresses as high as 40,000 pounds could be applied.

The stress was measured by means of an extensometer. A steel rod $1\frac{1}{4}$ inches in diameter for 10-inch length was connected in series with the insulator. It was necessary to choose a diameter which would give an elongation sufficiently great for measurement and yet permit the steel to retain perfect elasticity and not be stressed beyond the yield point.[5] The ends of the rod were reduced to $\frac{3}{4}$ inch diameter to adapt them to the special fittings. The elongation of only

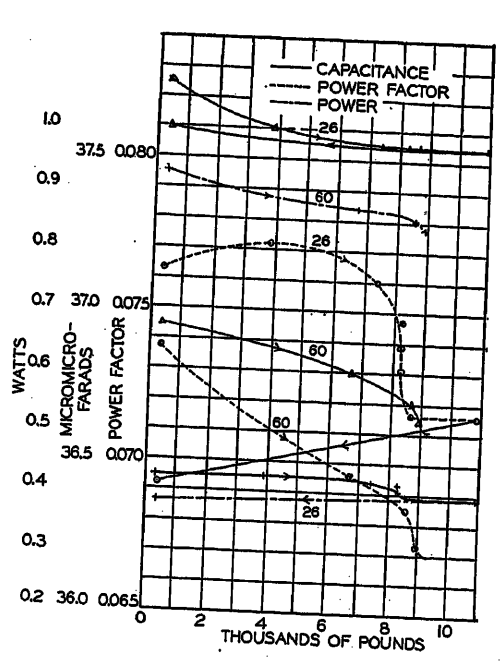



**Fig. 14. Electrical characteristics of porcelain insulator as functions of mechanical stress at constant frequencies of 26 and 60 cycles, 19 degrees centigrade, 30 kv, and 4.3 absolute humidity**

Numbers on curves are frequencies in cycles per second

3 inches of the rod at the center was measured. The extra length of 10 inches is necessary in order to insure stress equalization over the cross sections near the center. The elongation was measured by means of a combination of mirrors, knife edges, and telescopes. The elongation of the rod was magnified $10^6$ times.

The effects of mechanical stress on power, power factor, and capacitance for the glass insulator are shown in figure 13. For an applied potential of 30 kv until a stress of 12,000 pounds is reached, little or

no effect on the characteristics occurs. Then all 3 quantities show a small decrease. (The quantities in figure 13 are plotted to a large scale.) The change in the power and the power factor is approximately 4 or 5 per cent and the change in the capacitance is extremely small. The stress is then carried to 23,000 pounds. All these quantities remain constant up to this value of stress. They also remain constant as the stress is carried back to zero.

Similarly, in figure 14 are shown the effects of stress on the porcelain insulator. The characteristics are obtained at 30 kv and at the 2 frequencies, 26 and 60 cycles. The stress at 60 cycles was not carried back to zero because of the insulator's failure. It may be noted that although the effects of stress are in general similar to those for glass, yet the characteristics are not so simple. They tend to have a steady drop before the critical stress of 8,500 pounds is reached, when they drop rapidly. Moreover, after the application of the critical stress, the quantities, except the power at 26 cycles, do not remain constant as with glass. This would be expected. With glass the pin is held by a soft metal. With application of stress the metal would be pressed more firmly against the glass and little change in conductive relationships of this metal to the glass would be expected. On the contrary, with the porcelain insulator the cement used to fasten the cap and pin is an imperfect dielectric probably containing moisture. Under mechanical stress its dielectric properties would be expected to change considerably. The effect of stress appears to diminish the power, power factor, and capacitance, undoubtedly because of changes in the geometrical relationships between cap and pin.

The authors feel that the results of this research may assist in the obtaining of a better understanding of insulator performance and design, as well as of radio interference resulting from surface discharge.

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## Sealed-Off Ignitrons for Welding Control

(*Continued from page 40*)

The welding of large pieces, particularly when done rapidly with automatic machinery, usually requires the use of water-cooled tubes. There are few resistance-welding machines in use today requiring currents higher than these tubes are able to control.

## Advantages of Sealed-Off Ignitrons

The sealed-off ignitron tube provides the following attractive features for welding control. No other device offers all of these advantages:

1. Tubes have no moving parts and so require little or no attention throughout their normal life. They are designed for long life. As compared with mechanical devices for rapidly opening and closing high current circuits, maintenance expense is low.

2. Tubes provide flexibility, short timing, and accuracy of control otherwise unobtainable. This reduces surface heating, thus minimizing deformation and oxidation of work and lengthening electrode life. They permit welding of metals or alloys which were previously difficult if not impossible to weld.

3. Ignitron tubes, because of their ability to pass very high peak currents, are connected directly in the primary circuit of the welding transformer.

4. Ignitron tubes, particularly the metal models, are not fragile and so do not require extreme care in handling. They may be safely installed by unskilled workmen.

5. Sealed-off ignitrons are replaceable units. Tube failure results in only the few minutes shutdown necessary to accomplish replacement. When welding equipment is one link in a continuous production line, the avoidance of long forced shutdowns may result in sizeable savings.

6. Sealed-off ignitrons are small in size, comparatively, and, with the small amount of auxiliary apparatus they require, save valuable space in high production shops.

At higher currents the longer total life of the more completely demountable and repairable continuously pumped tanks weigh in their favor. The capacity above which tanks might be preferred is dependent upon the ultimate life of the sealed-off tubes, the cost of development of larger sealed-off sizes, and the manufacturing cost of those developed. When higher power is needed it may be desirable as an alternative to develop ignitrons of approximately present current ratings but capable of operating at higher voltages.

Two or three years ago these ignitron tubes were in the developmental stage and were used in a few commercial applications.[8] Today there are many equipments located in key positions of large volume production lines producing more consistent welds at higher speed than is practical with other types of control.

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# Short-Time Spark-Over of Gaps

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ASSOCIATE AIEE

**In this paper data are presented on spark-over values of rod gaps, insulators, bushings, sphere gaps, and solid insulation for a range of spark-over times of approximately from 0.2 to 4 microseconds. The problems of accurate measurement that are involved are also discussed, and a shielded resistance voltage divider is described.**

DURING the last few years considerable progress has been made in impulse testing technique.[1,2] The results obtained in different laboratories on the spark-over of sphere and rod gaps with the standard 1.5 x 40 wave where spark-over occurs after the crest of the wave agree well and have permitted standardization of such spark-over curves.

There has been little data published on spark-over values of gaps and insulation at very short time lags (less than 2 microseconds).[3,4] These data become important when insulation co-ordination is considered. A given gap might protect a piece of insulation when a 1.5x40 wave of low amplitude is applied to the combination, such that spark-over takes place after the crest of the wave, but the insulation might fail if a wave of much higher voltage or steeper front is applied. Therefore, to enable satisfactory co-ordination of various insulating structures it is important to know the behavior of gaps and insulation for the steepest waves expected on transmission lines.

The greatest rate of voltage rise of traveling waves due to lightning is not definitely known. However, from some oscillograms obtained in field investigations it is quite safe to assume that 1,000 kv per microseconds or more is a rate of voltage rise, which can occur quite frequently at least at the point where lightning strikes a line. If a rate of 1,000 kv per microseconds is assumed, this means, for instance, a spark-over at 300 kv at 0.3 microseconds.

The problems concerning the accuracy of the impulse measurements when high spark-over voltage and short spark-over time are involved are discussed in part I of the paper. Definitions of rate of voltage rise and of time to spark-over are discussed since they are important for comparison of results obtained in different laboratories. In part II of the paper, results of tests on rod gaps, insulators, bushings, sphere gaps, and solid insulation covering a range of spark-over time of approximately 0.2 to 4 microseconds, are presented.

## I. Impulse Testing Technique

### The Voltage Divider

The resistance type of divider has been found to be an ideal tool for the reduction of high impulse voltages to true images of low enough amplitudes, which permit recording with a cathode ray oscillograph, when tests are made to determine the minimum spark-over of gaps with the standard 1.5x40 wave. The resistance can be measured conveniently and the true ratio between oscillograms and actual spark-over voltage can be established with certainty.

For the standard wave the distributed constants of the divider such as its inductance, capacitances to ground, and capacitance between successive turns of the non-inductively wound cards, are of negligible importance. However, the presence of the distributed constants changes the apparent ratio of the divider when high potentials with spark-over occurring at short times are to be measured. For instance, a 10,000-ohm divider, which is used in the range between 200 kv and 1,000 kv slants a rectangular front to about a 0.4-microsecond front and a $^1/_2$-microsecond front to about $^3/_4$-microsecond front in certain positions of the divider with respect to a ground plane. Consequently the breakdown voltage of a sphere gap might be recorded much too low as shown on figure 1*a*, which was taken with a $6^1/_4$-centimeter gap illuminated both by a mercury quartz lamp and a spark from a gap. Although the gap did not spark every time (see full wave on same figure), the amplitude of the recorded spark-over voltage was only $^1/_2$ the amplitude of the full wave. When the waves of figure 1*b* are considered, however, it is evident that the spark-over actually occurred after the crest is reached and the disturbing result in figure 1*a* is due only to the distortion caused by the divider. In the appendix equations are given showing the distortion caused by the different distributed constants of the divider and also some curves pertaining to some particular case illustrating their separate effect.

When examining the effect of the various distributed constants on the distortion, it was found, that the main offender was the capacitance to ground which together with the resistance of the divider slants the wave front. Therefore for equal capacitance to ground the distortion will be greater as the resistance of the divider increases. In the above test, this capacitance had been equally distributed by placing the divider about 6 feet above and parallel with the ground plane. In usual practice such a divider will be moved around in the laboratory, to place it in the optimum position with respect to the test

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1. For all numbered references see list at

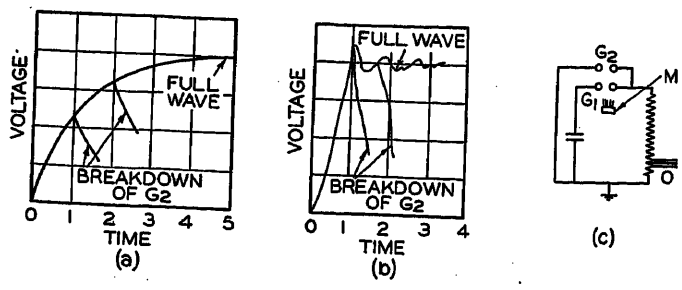



**Fig. 1. Comparative tests with ordinary and shielded resistance divider**

*a*—Measured wave front with ordinary divider
*b*—Measured wave front with shielded divider
*c*—Test circuit
$G_1$, $G_2$—6¼-centimeter spheres
*M*—Mercury-arc lamp
*O*—Oscillograph

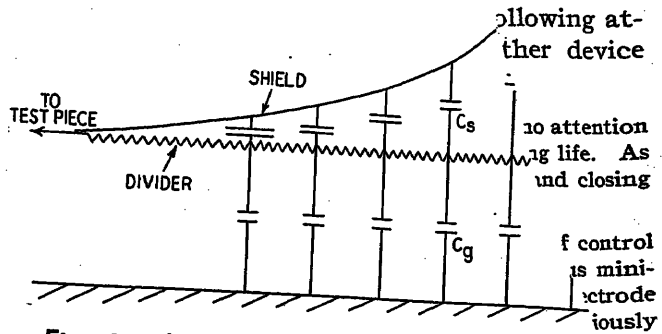



**Fig. 2. Schematic diagram of shielded resi divider**

$C_s$—Capacitance from shield to divider
$C_g$—Capacitance from divider to ground

piece and the effect of the capacitance to ground will be greater or smaller depending on any particular case.

Another source of error obtained with any divider at tion rapid changes of voltage is the presence of the rapidly againanging fields produced from the impulse generator proper, from the connecting lines, sphere gaps, etc., each changing at a somewhat different rate but all contributing a part to the distortion of the field around the divider.

Therefore, 3 conditions are imposed in eliminating the distortion:

1. The effect of the capacitance to ground must be compensated.
2. A change in position of the divider must not change the compensation.
3. The influence of external fields should be kept as small as possible.

To eliminate the effect of the capacitance to ground a method similar to that used in shielded winding transformers[5] has been employed. This method is shown diagrammatically in figure 2. The shield is shaped in such a manner, that by means of capacitance $C_s$ it supplies just the right amount of current through capacitance $C_g$ to ground, which is required to maintain the voltage $e$ at an amplitude equal to the ratio of resistances at that point. Such a divider also will meet condition 2 by fixing the ground plane permanently to the divider. However, condition 3 cannot be met very readily without going to a very large grounded shield above the divider, which the available space in the laboratory usually would not permit.

To meet all 3 of the conditions a different type of divider was developed which is shown in figure 3. In this divider a center cylindrical electrode serves as the line shield. The tank serves as the ground plane as well as the shield against external fields. The resistor is placed in the field between the line and ground shield in such a way that equal parts of resistances are placed on equipotential lines of correct potential differences. The divider as shown can be used up to 700 kv for minimum breakdown voltage tests on a 1.5x40 wave and up to 2,000 kv on front of the wave tests. In addition to the shielding, the distortion effect has been minimized by keeping the di resistance low—7,000 ohms. The tank is filled wit to avoid forming of corona. The minimum ratio of divider is 100 to 1, since the surge impedance of the de cable of 100-ft. length, which is used to transmit the sur to the oscillograph plates, equals 70 ohms. This ratio can be increased to approximately 1,400 to 1 by placing a required low resistance parallel to the cable at the divider end of the cable.

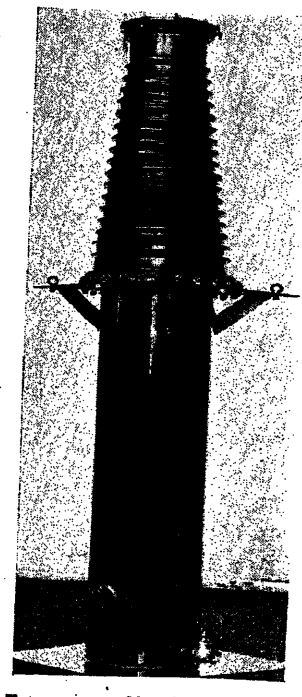


**Fig. 3. Shielded oil-immersed divider**

## The Impulse Circuit

For testing with high rates of voltage rise, it is very important, that the divider is connected as closely to the test piece as possible, to avoid reflections of connecting lines and also to avoid measuring the inductive drop on long connecting lines from the steep wave fronts. One factor which produces distortion on the front as well as on the tail of chopped waves is the position of the test piece in the generator discharge circuit, figure 4*a*. The inherent inductance of the circuit is divided into 3 parts; the inductance of the impulse generator proper $L_t$, the inductance of the line to the test piece $L_L$, and the inductance of the ground return $L_g$. The effect of these inductances is twofold:

1. On the front of the waves, the rate of rise is influenced by the apparent addition of a superimposed oscillation. This is due to the fact, that at the initial moment, when the impulse generator discharges, the voltages in the circuit distribute according to the inductances. Depending then on the ratio of $L_g$ to the total inductance in the circuit $L_t + L_L + L_g$ the amplitude of this initial inductive kick will be large or small. This inductive effect will have largely disappeared at the time the gap breaks down, provided

the breakdown occurs between 50 per cent and 100 per cent of the wave crest.

2. After spark-over of the test piece the load capacitance is short circuited by the low resistance of the arc and the discharge circuit changes practically into a $L$, $R$, $C$ circuit with an oscillatory discharge with a time constant approximately proportional to $LC$. In the extreme case then the breakdown voltage would be of sinusoidal form of long time constant (8 to 10 microseconds) while the true time constant of the gap breakdown is of the order of a fraction of a microsecond.

To avoid the above discrepancies it is desirable to keep $L_g$ as small as possible by connecting the grounded end of the test piece to the generator through short leads,

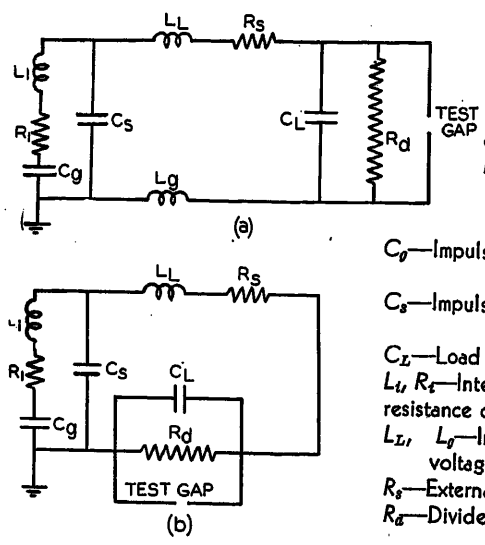



**Fig. 4. Impulse-generator discharge circuit**

*a*—Usual connection
*b*—Preferred connection

$C_g$—Impulse generator capacitance
$C_s$—Impulse generator stray capacitance
$C_L$—Load capacitance
$L_i$, $R_i$—Internal inductance and resistance of impulse generator
$L_L$, $L_g$—Inductance of high voltage and ground leads
$R_s$—External series resistance
$R_d$—Divider resistance

figure 4*b*. The actual position of true ground with respect to the generator is then not so important as long as discharge currents do not flow through the ground straps. It can be seen from figure 4*a*, that traveling waves of considerable amplitude would be set up in the divider cable sheath, if the cable sheath were connected to the grounded side of the test piece, while in case of figure 4*b*, the cable can be connected at that point without complications.

## Effect of Circuit Constants on the Spark-Over on the Front of Waves

The control of wave fronts depends on the inductance and resistance in series with the discharge circuit, on the generator stray capacitance to ground and the capacitance of the test piece or any additional load capacitance. Usually the inductance inherent to the circuit is fixed and it is more convenient to control fronts by choosing the proper values of load capacitances and series resistances. For tests on minimum spark-over especially of air gaps, it is quite immaterial whether a relatively large resistance or a large load capacitance is chosen except that the resistance must be large enough to prevent superimposed oscillation. For breakdown on the front of waves, somewhat different results are obtained using the same time constant $RC$ but using either high $R$ or high $C$.

Figure 5 shows a typical wave front, with breakdown at $t_1$ and $t_1'$. Breakdown at $t_1'$ would occur with large resistance, (for instance, 2,000 ohms) and at $t_1$ with the small resistance, (for instance 400 ohms). The difference between the 2 waves is due to the voltage drop caused across the resistance by the relatively large charging and especially streamer currents[6] through the gap shortly before breakdown. Naturally the larger the resistance the greater will be the drop and the more will the voltage wave depart from that natural to the circuit. It is evident that the spark-over voltages would be quite different in the 2 tests although the rate of voltage rise as determined by conventional methods, is practically the same for the 2 waves. Therefore if plotted on a curve showing rate of rise against breakdown voltage, a considerable spread of test points would be observed. The importance of this phenomenon with respect to evaluation of results will be discussed later.

With respect to the maximum rate of rise and maximum voltage, that can be obtained from an impulse generator, curves of figure 6 are prepared. The generator has a rating of 2,500 kv at a discharge capacitance of 0.011 microfarads and an inherent inductance of 120 microhenries including leads.

It was desired to determine whether the generator was of sufficient size to test transformers with steep fronts of

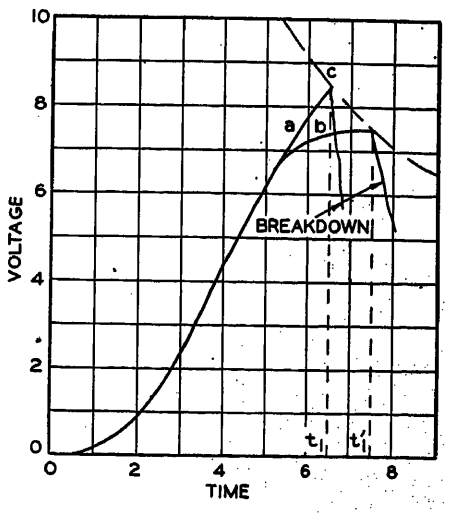



**Fig. 5 (left). Change of wave shape due to change in circuit constants**

*a*—$RC$ = constant; $R$ small, $C$ large
*b*—$RC$ = constant; $R$ large, $C$ small
*c*—Volt-time curve

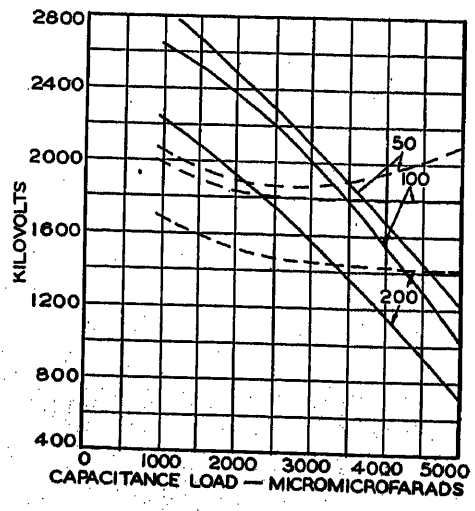
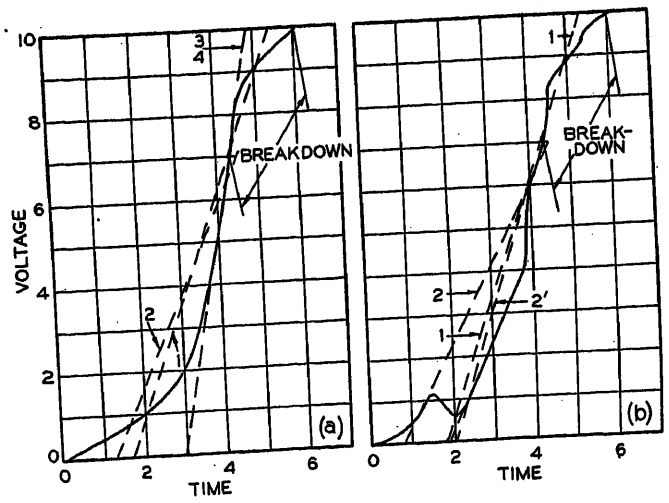



**Fig. 6 (right). Rate of rise and maximum spark-over voltages obtainable with a 2,500-kv impulse generator as a function of series resistance and capacitance load**

Solid lines—Kilovolts per microsecond
Dashed lines—Kilovolts crest
Numbers on curves are series resistances in ohms




Rate of Rise

1. 10/3.8 = 2.6 units
2. 7/3.2 = 2.2 units
3. 10/1.9 = 5.3 units
4. 7/1.4 = 5.0 units

Rate of Rise

1. 10/3.7 = 2.7 units
2. 7/3.7 = 1.9 units
2′. 7/2.3 = 3 units

**Fig. 7. Comparison of definitions of rate of voltage rise**

the order of 1,000 kv per microsecond. A transformer can be represented by a capacitance equal to its impulse capacitance when chopped waves of short duration are applied. The impulse capacitance of transformers ranges from approximately 300 to 2,500 micromicrofarads.

Tests were made with the electrical transient analyzer.[7] The analyzer represents an ideal tool for such purposes and eliminates a large amount of routine labor in evaluating the equations. In the curves of figure 6 the rate of rise is calculated by using the crest voltage as measured with the analyzer and dividing it by the time interval from zero to crest. The maximum rate of rise obtainable is therefore greater than indicated on the curves of figure 6. It can be seen from figure 6, that in the range of load capacitances from 300 to 2,000 micromicrofarads, rates of rise between 1,000 and 2,800 kv per microsecond can be obtained with maximum voltages of approximately 2,000 kv. These values are sufficiently high to permit spark-over of test gaps parallel to transformers with spacings up to 70 inches at 1,000 kv per microsecond voltage rise. For tests on transformers of higher voltage ratings, a larger impulse generator is available. It should of course, be realized, that the constants to be chosen for the wave front test would not at all be suitable for testing on the tail of the wave. For instance, when using $R_2 = 50$, $C_2 = 5{,}000$, a high-frequency oscillation results which is superimposed on the wave front. However, it is just this superimposed oscillation which produces the wave front of 1,200 kv per microsecond rise. Since the test is required to be made on the front of the wave, only the first rise of the wave will be applied to the gap. It is, therefore, immaterial whether a 1.5x40 wave is used for testing a gap with steep wave fronts as long as the rate of voltage rise follows the specification. The use of 1.5x40 waves for tests on the front of the wave would limit the spark-over tests to relatively small gap spacings or else would require an impulse generator of uneconomical proportions.

## Definition of Breakdown Voltage, Time to Breakdown, and Rate of Voltage Rise

If impulse generators contained resistances and capacitances only, it would be an easy matter strictly to define terms determining the time to breakdown, and the rate of voltage rise on wave fronts, However, throughout the impulse discharge circuit, especially of the high-voltage impulse generators, inductance of sometimes considerable value is distributed. These inductances, together with the generator capacitance and capacitances to ground, such as stray capacitances and load capacitance, produce oscillations on the wave front and the waves do not have strictly exponential characteristics. While these phenomena are not disturbing when testing with 1.5x40 waves for minimum spark-over of gaps, they tend to magnify the difficulties of exact definition, and comparison of results of different investigators is difficult unless the same procedure is used for evaluating the oscillograms.

Two main groups of definitions are used at present, both of which practically ignore the time to breakdown but rather use the rate of voltage rise to record results of tests of spark-over voltages of a gap. The rate of voltage rise is defined as:

(*A*) A line drawn through 2 points with an amplitude of 10 per cent and 90 per cent of the crest voltage intersects the zero line and a line through the maximum voltage parallel to the zero axis.

(*B*) A tangent drawn to the steepest part of the front intersects the zero line and a line through the maximum voltage parallel to the zero axis.

In both cases division of the maximum voltage by the time interval between the 2 intersection points gives the rate of voltage rise.

Method *A* has the advantage of a clearer definition since in most cases, it is quite a simple problem to define the 10 per cent and 90 per cent point and the 2 intersection points, while it is generally extremely difficult to determine a tangent. Both methods however, have slight inconsistencies as follows:

Figure 7*a* shows a wave front without superimposed oscillations. The relative rate of rise is indicated for 4 conditions:

1. Spark-over at 10 units of voltage, method *A*, 2.6 units of rate of voltage rise.
2. Spark-over at 7 units of voltage, method *A*, 2.2 units of rate of voltage rise.
3. Spark-over at 10 units of voltage, method *B*, 5.3 units of rate of voltage rise.
4. Spark-over at 7 units of voltage, method *B*, 5.0 units of rate of voltage rise.

The resulting rates of rise show considerable difference although for about 50 per cent the rate of rise of the 2 waves is identical. The relative rate of rise for the wave breaking down at 7 units of voltage is even less than that for the 10 unit breakdown when obtained with method *A*.

The method of $B$ would indicate a rate of rise twice as large as that of $A$. Further actual wave fronts are often of a form as shown on figure 7*b*, because optimum test conditions cannot be obtained. The method $A$ would practically give the same rates of rise as that in figure 7*a*, while it would be very difficult to use method $B$. From the above discussion it appears that the use of the rate of voltage rise to determine spark-over voltages is at least confusing if used with any of the above definitions.

From comparative tests such as mentioned in connection with figure 5, it appears that the maximum rate of rise as defined above is relatively unimportant, while the crest voltage and the time to spark-over seem to be quite definitely related. For instance, spark-over voltages obtained with the same time constant $RC$ but large and small series resistance $R$ lie on a smooth curve when plotted against time to spark-over but when plotted against rate of voltage rise (by standard definition) a considerable spread is observed.

From these considerations, it was found to be an advantage to use the average rate of rise as the factor which determines the breakdown. Average rate of rise is obtained by dividing crest voltage by the time to spark-over. The wave zero under this definition would be defined as the point of intersection with the zero axis of a line drawn through the 10 per cent and 90 per cent points of crest voltage.

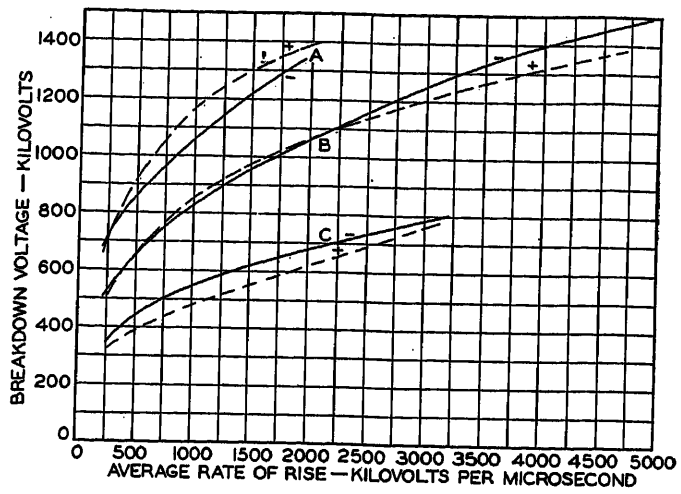



**Fig. 9. Variation of spark-over voltage with steepness of applied wave corrected for standard conditions**

Solid curves negative polarity, dashed curves positive polarity
*A*—30-inch rod gap *B*—20-inch rod gap
C—10-inch rod gap

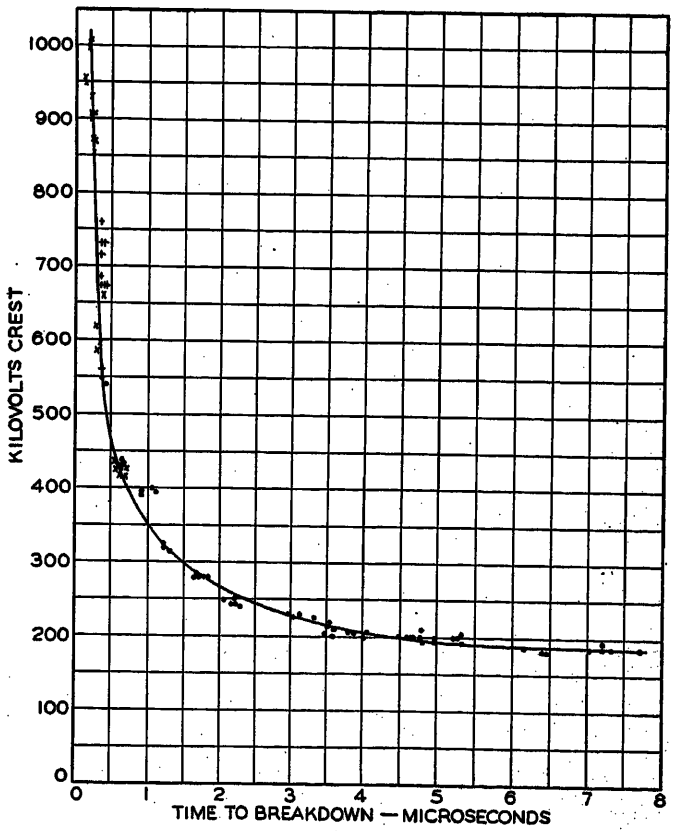



**Fig. 8. Volt-time curve of a 10-inch rod gap: $^1/_2$-inch square rods**

· 2,000 ohms series resistance
+ 1,500 ohms series resistance
× 0 ohms series resistance
1.5x40-microsecond wave for tests with 2,000 ohms series resistance, positive polarity

Necessary discrimination has to be used when due to enforced testing conditions the front of a wave is not smooth but has for instance the shape of figure 7*b*. At the spark-over at 7 voltage units, the 10 per cent point should not be chosen at the first rise in voltage, but on the zero extension of the following voltage rise as shown by line 2′.

## II. Results of Breakdown Tests

### Accuracy of Test Results

Tests of breakdown on the front of waves are conducted in the following manner. Beginning at minimum spark-over of the gap for a 1.5x40 wave the charging voltage of the impulse generator is raised in 10 per cent steps. For each charging voltage usually 3 arc-overs are recorded by oscillograms. As the voltage is raised higher the losses in the series resistance due to streamer currents become greater than the increase in voltage. At this point the series resistance is lowered or removed completely which changes the wave front accordingly. The oscillograms are then analyzed for spark-over voltage and the time to spark-over. Figure 8 is included to show what accuracy can be expected from a single random calibration point. It is evident that down to 0.4 microsecond the spread of values is of the order of 10 per cent and usually less. This spread is partly due to variations in gap spark-over, partly to errors in scaling of oscillograms, partly to the error inherent to the divider and oscillograph. For breakdown times of less than 0.4 microsecond the error becomes greater. Here the greatest error is due to the scaling of the oscillograms. Usually the time to spark-over is the greater source of error, although for these fast times the sweep is chosen such that 1 microsecond represents 40 to 60 millimeters on the time axis of the oscillogram. Even

at these fast sweeps an error in displacing the line for 10/90 per cent by 2 millimeters at both ends amounts in an error in time to breakdown of about 0.1 microsecond.

The errors, real and apparent, due to variations in gap spark-over and the scaling of oscillograms can be practically eliminated by comparing a large number of oscillograms, and curves such as shown on figure 8 can be drawn with a fair degree of accuracy even to such short times as 0.2 microsecond.

It should be noted that portions of this curve were obtained with different values of series resistance which partly overlap. The continuity of the curve is not disturbed, although the relative slope of wave fronts for different values of resistance is quite different.

## Spark-Over Curves of Gaps

The results of tests on 10, 20, and 30-inch rod gaps are shown on figure 9 for positive and negative polarity. These curves were drawn by using the average curves obtained as outlined above. The kilovolts per microsecond values were calculated by using crest voltage and time to breakdown as explained earlier in the paper. The curves level somewhat at the high rates of rise and appear to approach some straight line characteristic. The left-hand portion of figure 8 seems to substantiate this. Here the voltage rises almost abruptly while the time to breakdown hardly changes. A difference of about 10 per cent is indicated between positive and negative breakdown voltages.

To compare gaps of different size and different character it is an advantage to use some common basis for comparison. As a characteristic curve the overvoltage-time to spark-over curve is considered. Overvoltage is defined as the voltage required to spark over a gap in excess of the minimum impulse spark-over voltage, for instance due to a 1.5x40 wave, at a spark-over time less than the minimum impulse spark-over time. Such curves

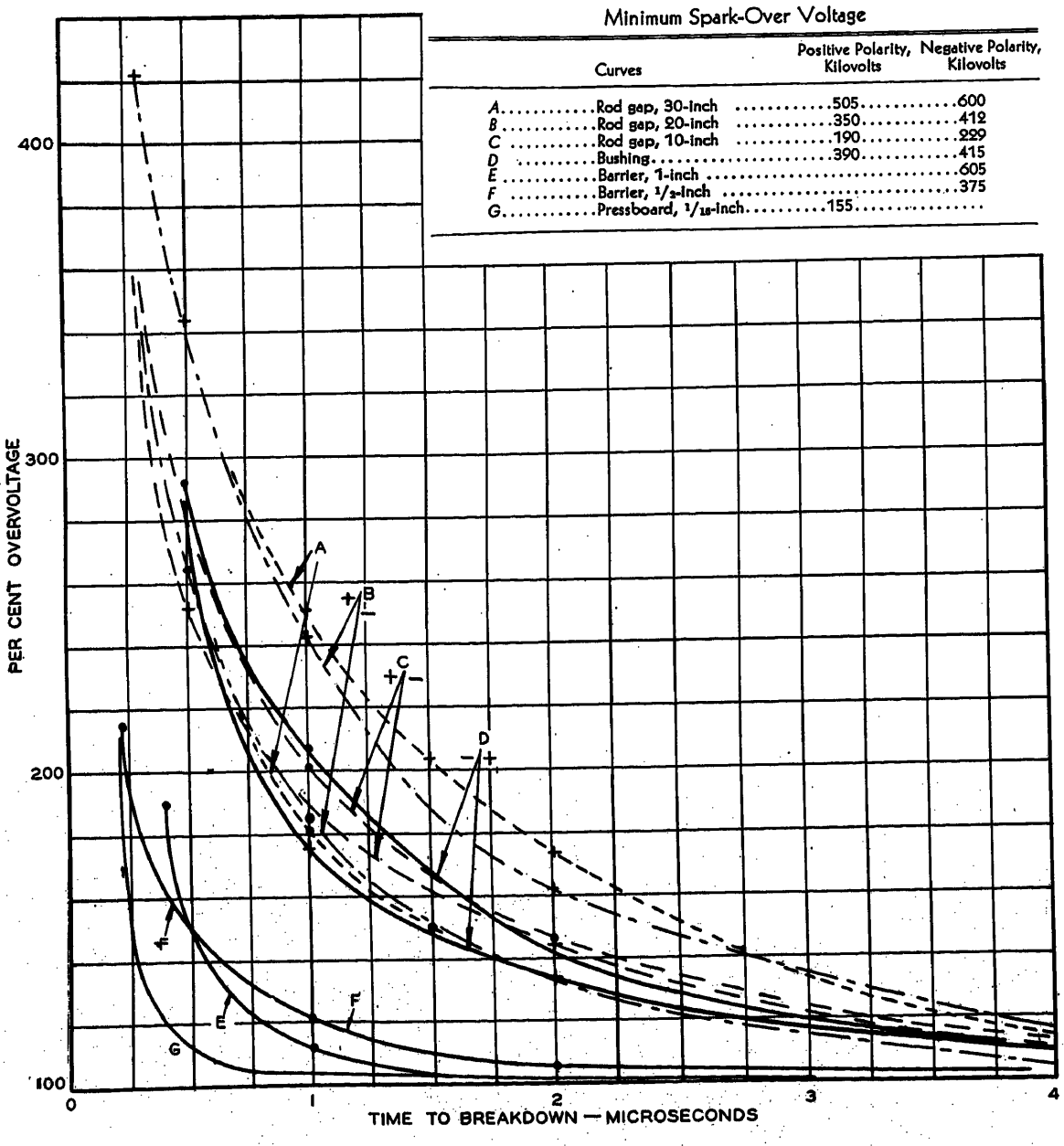



**Fig. 10. Overvoltage curves of rod gaps, bushings, and barriers**

Test electrodes of barriers are 4-inch round disks with square edges. Barriers consist of 3 oil ducts of 1/4 of total spacing each and 2 pressboard sheets 1/8 of total spacing each

Rod gap of 1/2-inch square rods

+ indicates positive polarity, • indicates negative polarity

10-inch and 20-inch gap. The insulator curves represent the average values for 1, 2, and 3 units of suspension insulators and the breakdown values for the $^1/_2$-inch and 1-inch barrier are averaged. The circles indicate the overvoltage values of a 50-centimeter sphere gap at 34.25-centimeter (68 per cent) spacing at negative polarity.

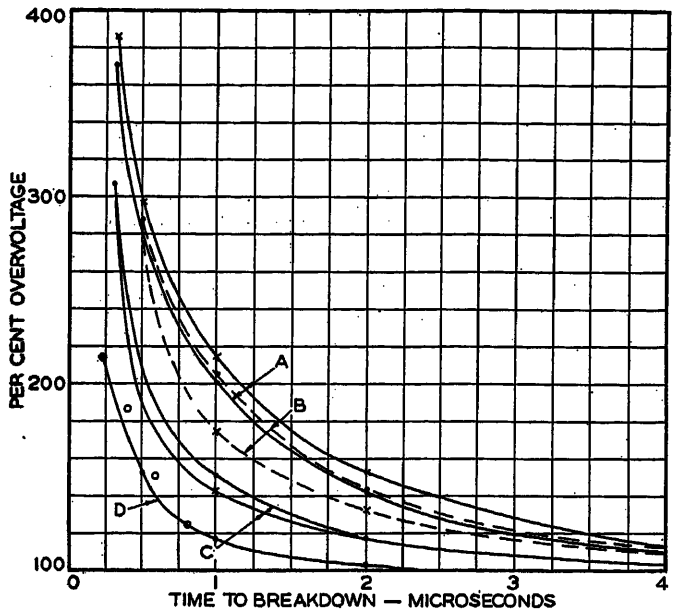



**Fig. 13. Comparison of overvoltage characteristics of different types of gaps**

*A*—Rod gap, average values of 10-inch and 20-inch gaps
*B*—Bushing
*C*—Insulator, average values of 1, 2, and 3 suspension insulators
*D*—Solid and oil, average of $^1/_2$-inch and 1-inch barriers
Circles show voltage of a 50-centimeter diameter sphere gap spaced 34.25 centimeters
+ indicates positive polarity, • indicates negative polarity

Wherever possible the rod gap tests were made with the gap mounted according to standard specifications of the National Electrical Manufacturers Association, $H = (1.3\,S + 4'') \pm 10$ per cent where $H$ is the height of the gap above ground plane and $S$ is the spacing of the gap. However, the relative characteristics of pedestal insulators and rod gaps is such that the rod gap will not protect the pedestal at very short times to spark-over. In such cases the number of pedestal insulators was increased. Figure 14 has been prepared to show the breakdown characteristics for 2 pedestal insulators giving the specified height of the rod gap above the ground plane for a 20-inch rod gap. It shows that the curves for rod gap and pedestal insulators cross at 1 microsecond for the positive wave and approach at $^1/_2$ microsecond for a negative wave, which indicates that either may arc. It appears desirable to modify the NEMA rules for the condition of tests on the front of waves.

The above gaps with exception of the solid and barrier type represent strictly non-uniform fields. Contrary to this a sphere gap is considered to have a fairly uniform field. Figure 15 is included to show the spark-over characteristics of such a gap, when spark-over occurs at a short time. A 25-centimeter gap was chosen as representative for the larger gaps. It is evident that the sphere gap requires considerable overvoltage to spark-over at short time. The overvoltage values are shown in table I.

**Table I—Overvoltage Values of 25-Centimeter Sphere Gap, Positive Polarity**

| Time to Breakdown, Microseconds | Gap Spacing in Per Cent of Sphere Diameter | | |
|---|---|---|---|
| | 16 | 32 | 76 |
| 1 | 113 | 115 | 109 |
| 0.5 | 154 | 140 | 137 |
| 0.2 | 191 | 155 | |

The table shows that overvoltage values decrease as the gap spacing is increased.

Incidentally the crosses on these curves indicate tests made with artificial irradiation from a mercury arc light spaced 18 inches from sphere center with 60 watts input.

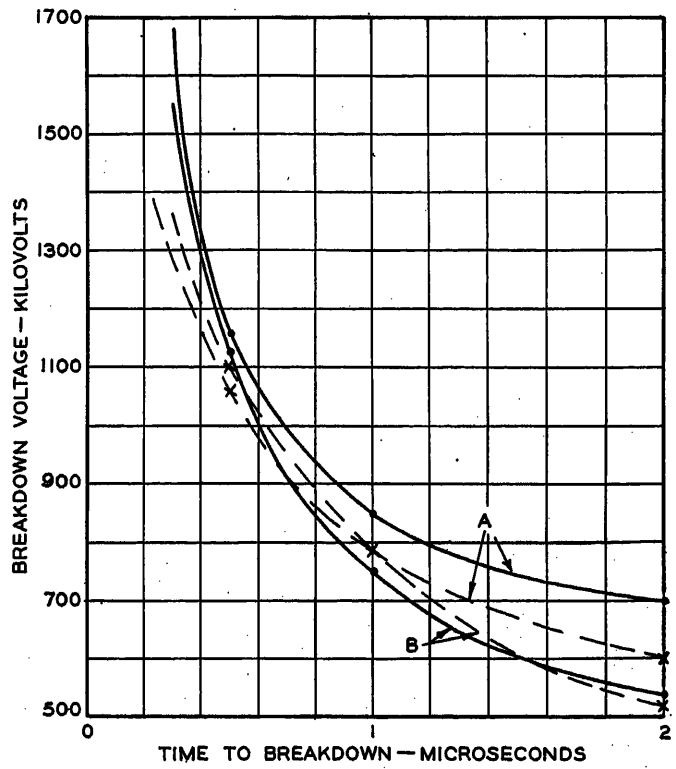



**Fig. 14. Volt-time characteristics of 2 pedestal insulators (A) and a 20-inch rod gap (B). The pedestal represents the standard mounting for this size gap**

+ indicates positive polarity, • indicates negative polarity

The effect of this ionization appears to be negligible for large gaps at relatively large spacings. From these curves it appears that for spark-over time of 1 microsecond or more the sphere gap indicates spark-over at the same voltage irrespective of voltage application.

For times shorter than 1 microsecond the established values of sphere gap spark-over do not apply. The over-voltage-time to spark-over characteristics for different spacings of the same gap are not the same. This requires a complete short time spark-over calibration for a number of spacings on each size sphere, if the sphere is to be used for measuring short time spark-over. Fortunately the oscillograph in connection with a proper divider has become a reliable instrument which can be used with confidence as a voltage measuring device when the sphere gap is not applicable. Figure 16 shows some representative oscillograms of spark-over of rod gaps

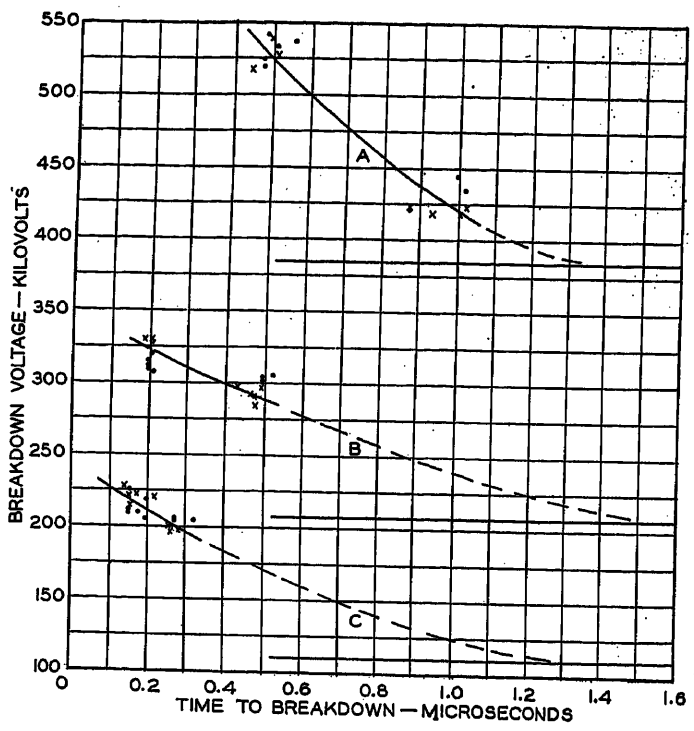



**Fig. 15. Spark-over voltage of a 25-centimeter sphere, at positive polarity**

Horizontal lines *M* are minimum breakdown voltages

*A*—19-centimeter spacing *B*—8-centimeter spacing
*C*—4-centimeter spacing

without and with transformer load and a sphere gap spark-over.

## Summary


1. A shielded resistance divider is described which incorporates the desirable features of the ordinary resistance divider and by means of shielding eliminates distortion inherent to such dividers on application of fast wave fronts.

2. The over-all accuracy of measurements of waves at short times is approximately 10 per cent or better for spark-over times of 0.4 microsecond or more, 15 per cent to 20 per cent for shorter times. This applies for individual test points. For a more accurate determination a series of 3 to 5 breakdowns can be used under identical condition of test circuits with a probable accuracy of better than 10 per cent.

3. The curves presented show that the relative short time spark-over voltages are highest for gaps with non-uniform field such as rod gaps, bushings, pedestal, and suspension insulators in the order named, figure 13. The gaps with more nearly uniform field such as

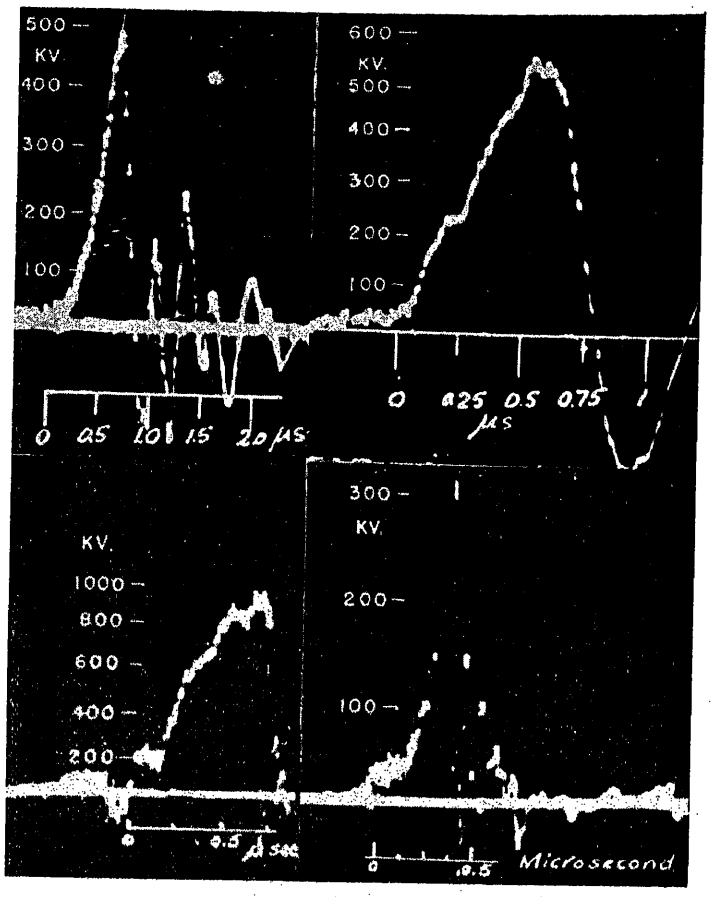




**Fig. 16. Oscillograms of front of wave spark-over**

*A*—1/2-inch square rod gap, 10-inch spacing. Rate of rise 850 kv per microsecond; crest 475 kv; negative polarity

*B*—25-centimeter sphere gap, 19-centimeter spacing. Rate of rise 950 kv per microsecond; crest 551 kv; positive polarity

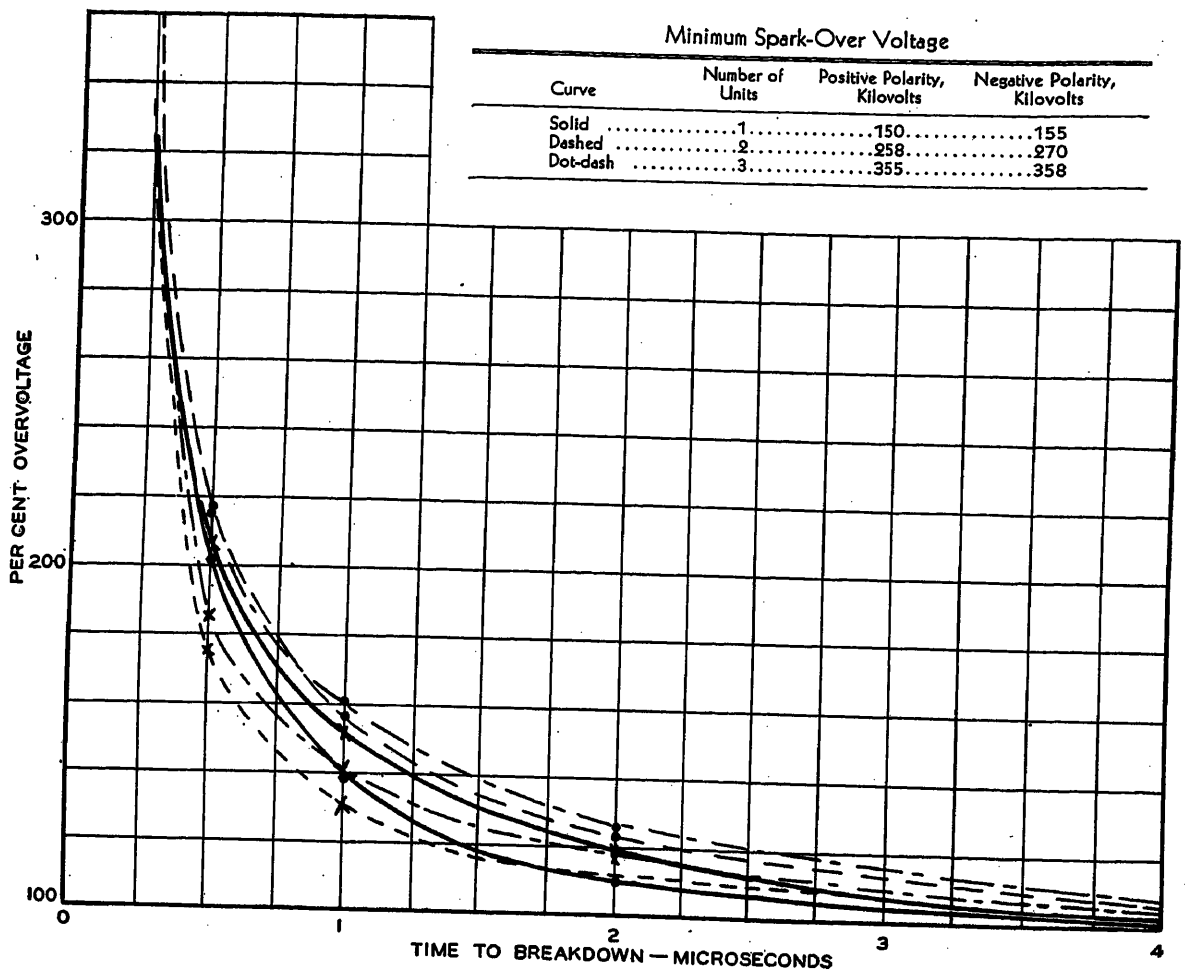
*C*—1/2-inch square rod gap, 20-inch spacing. Rate of rise 1,300 kv per microsecond; crest 913 kv; transformer load; negative polarity

*D*—1/2-inch square rod gap, 3-inch spacing. Rate of rise 1,330 kv per microsecond; crest 300 kv; transformer load, negative polarity


sphere gaps and the 4-inch disks used in tests with solid insulation show relatively high overvoltages but they occur at considerably shorter times than those of gaps with non-uniform fields.

4. Although a large number of volt-time curves has been made, a considerable amount of additional tests are required to complete the experiments, on which co-ordination can be perfected for the fastest rates of rise of natural lightning waves. Experience in the latter field is very restricted. However, rates of rise of 1,000 kv per microsecond and higher can be expected at least at the point of lightning contact. Further data are needed to enable a better understanding of requirements.

5. Impulse breakdown tests on front of waves can be made with similar ease as those on the tail of waves. The limits of accuracy, however, should be more liberal to allow for the greater spread in breakdown voltages of gaps when subjected to high rates of voltage rise.




Minimum Spark-Over Voltage

| Curve | Number of Units | Positive Polarity, Kilovolts | Negative Polarity, Kilovolts |
|---|---|---|---|
| Solid | 1 | 150 | 155 |
| Dashed | 2 | 258 | 270 |
| Dot-dash | 3 | 355 | 358 |

**Fig. 11. Overvoltage curves of suspension insulators**

Spacing 5¾ inches; diameter 10 inches

+ indicates positive polarity; • indicates negative polarity

show at a glance the relative time to breakdown characteristics of the different types of gaps.

To increase the usefulness of overvoltage-time to spark-over curves the minimum spark-over voltage is noted below the figures. To obtain kilovolt values from the curves, it is necessary only to multiply the minimum spark-over voltage times the per cent overvoltage and to divide by 100.

The curves of figure 10 show the overvoltage-time to spark-over characteristics for rod gaps, bushings, solid insulation, and combinations of solid and oil insulation. It should be noted that the electrodes used for tests on solid insulation are 4-inch round disks with square edges, which produce a somewhat uniform field. It is evident that the overvoltage values of rods and bushings are considerably higher than those of the solid insulation. Part of this difference can be attributed to the difference in electrostatic field.

In figure 11 the curves for suspension insulators are shown. It is surprising that the overvoltage curves have such a small spread and an increase of overvoltage with increase in string length is hardly indicated. On the contrary the curves for pedestal insulators, figure 12, show larger differences in characteristic shape and a high increase in overvoltage as the number of insulators is increased, especially for positive polarity.

Figure 13 shows a summary of the previous curves. The curves for rod gaps correspond to the average of the

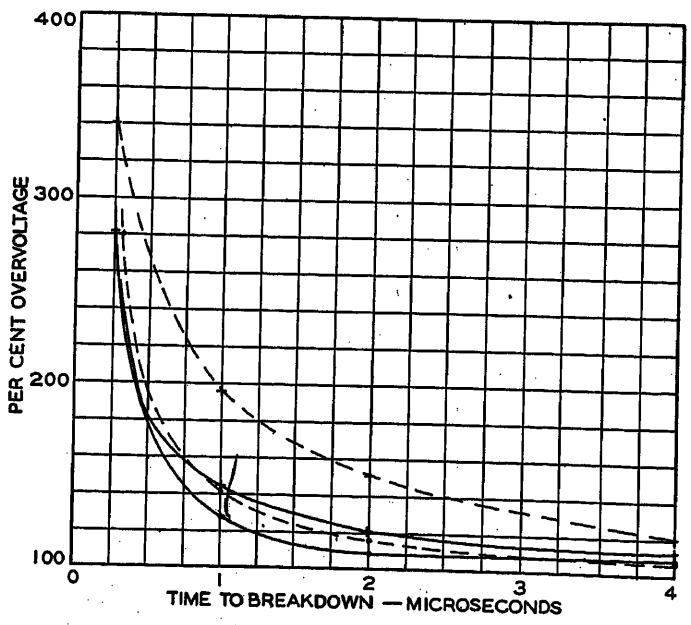



**Fig. 12. Overvoltage curves of pedestal insulators**

Spacing 14½ inches; diameter 17 inches

+ indicates positive polarity; • indicates negative polarity

Minimum Spark-Over Voltage

| Curve | Number of Units | Positive Polarity, Kilovolts | Negative Polarity, Kilovolts |
|---|---|---|---|
| Solid | 1 | 240 | 300 |
| Dashed | 2 | 400 | 600 |

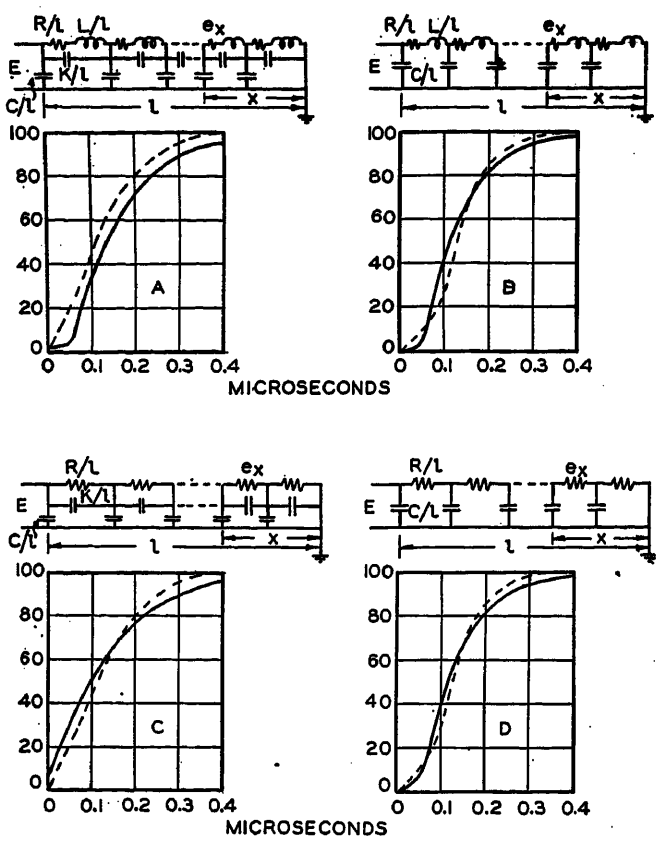



**Fig. 17. Comparative wave shapes obtained with ordinary resistance divider and equivalent circuits**

Solid curves from calculations; dashed curves from tests

For conditions *A* and *C*; *K'* has been added externally to the divider

Inherent constants—$R = 10{,}200$ ohms; $C = 81 \times 10^{-12}F$; $L = 34 \times 10^{-6}h$; $K = 3 \times 10^{-12}F$

## Appendix

To study the behavior of a resistance divider, the divider was placed horizontally 6 feet above ground. Under this condition an extremely steep wave was applied to the divider and the response was measured at the grounded end. Since the effect of the series capacitance $K$ is beneficial, such series capacitance was externally applied to the divider (condition *A* and *C*, figure 17). However, it was found that the amount of series capacitance which could reasonably be connected to the divider was not nearly sufficient to benefit the transmission of the wave.

The equations for the 4 possible combinations of divider constants were solved and the results plotted together with the test results. From a comparison of tested and calculated waves, it appears that the calculations ignoring the inductive component of the divider (conditions *C* and *D*, figure 17) show as good agreement between test and calculation as those with the inductance included. It appears therefore that for simplicity of calculations the circuit *D* of figure 17 can be considered as being representative of the resistance divider circuit.

The equations for the voltage $e$ at a point $x$ to ground of the divider for the 4 conditions are:

A. $$\frac{e_x}{E} = x + \epsilon^{-at}\sum_1^\infty \frac{2}{\pi s}\sin \pi s x \quad \cos \pi s \frac{\alpha^2}{\alpha^2 + \pi^2 s^2}\left(\cos b_s t + \frac{\alpha}{b_s}\sin b_s t\right)$$

when

$$\frac{\pi^2 s^2}{LK(\alpha^2+\pi^2 s^2)} > a^2$$

$$\frac{e_x}{E} = x + \sum_1^\infty \frac{\sin \pi s x}{s\pi} \cos \pi s \frac{\alpha^2}{\alpha^2+\pi^2 s^2}\left\{\left(1+\frac{a}{\omega_s}\right)\epsilon^{-(a-\omega_s)t} + \left(1-\frac{a}{\omega_s}\right)\epsilon^{-(a+\omega_s)t}\right\}$$

when

$$\frac{\pi^2 s^2}{LK(\alpha^2+\pi^2 s^2)} < a^2$$

$$a = \frac{R}{2L}; \quad b_s = \sqrt{\frac{\pi^2 s^2}{LK(\alpha^2+h^2 s^2)} - a^2}; \quad \omega = jb_s; \quad \alpha^2 = \frac{c}{K}; \quad l = 1$$

B. $$\frac{e_x}{E} = x + \epsilon^{-at}\sum_1^\infty \frac{2}{\pi s}\sin \pi\, sx \cos \pi s\left[\cos b_s t + \frac{a}{b_s}\sin b_s t\right]$$

when

$$\frac{\pi^2 s^2}{LC} > a^2$$

$$\frac{e_x}{E} = x + \sum_1^\infty \frac{\sin \pi\, sx}{\pi s}\cos \pi s\left\{\left(1+\frac{a}{\omega_s}\right)\epsilon^{-(a-\omega_s)t} + \left(1-\frac{a}{\omega_s}\right)\epsilon^{-(a+\omega_s)t}\right\}$$

when

$$\frac{\pi^2 s^2}{LC} < a^2$$

$$a = \frac{R}{2L}; \quad b_s = \sqrt{\frac{\pi^2 s^2}{LC} - a^2}; \quad \omega_s = jb_s; \quad \alpha^2 = \infty; \quad l = 1$$

C. $$\frac{e_x}{E} = x + \sum_1^\infty \epsilon^{-at}\frac{\alpha^2}{\alpha^2+\pi^2 s^2}\frac{2}{\pi s}\sin \pi\, s\, x \cos \pi\, s$$

$$a = \frac{\pi^2 s^2}{RK(\alpha^2+\pi^2 s^2)}; \quad \alpha^2 = \frac{K}{C}; \quad l = 1$$

D. $$\frac{e_x}{E} = x + \sum_1^\infty \epsilon^{-at}\frac{2}{\pi s}\sin \pi\, sx \cos \pi\, s$$

$$a = \frac{\pi^2 s^2}{RC}; \quad l = 1$$

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# A Single-Element Polyphase Directional Relay

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**Increased speed because of reduced inertia and greater torque is obtained from the polyphase directional relay described in this paper. A single cup-like moving element is used in place of multiple disks as used heretofore, the polyphase function being obtained by the use of multiple poles.**

THE IMPORTANCE of polyphase directional relays in relay protective arrangements is generally recognized today.

The first polyphase directional relays consisted of 2 or 3 single-phase elements connected to a common shaft. These single-phase elements were almost identical to existing forms of meters, namely, induction-disk watt-hour meters and indicating wattmeters. During the evolution of these devices, many improvements were made, some following the advances in meter design, and others being the result of problems met only in the protective relay field.

Notwithstanding these improvements, it became increasingly apparent that a relay with higher speed and greater torque was necessary for many applications. Furthermore, such a relay would be convenient even for those applications not requiring high speed, providing it involved no added expense.

## Improved Single-Phase Directional Relay

Improvements in the speed of single-phase and polyphase induction-disk relays have been limited by inherent high disk inertia and low torque efficiency. These limitations are largely overcome in the induction cylinder or cup relay recently developed. A single-phase power directional element of this design is shown in figure 1.

It consists of a stator with 8 laminated salients projecting inward and arranged symmetrically around a central magnetic core. The salients are fitted with alternate current and potential coils. In the annular air gap between the stator and central core is the cylindrical part of the cup-like induction rotor. The central core is fixed to the stator frame. The cup alone turns. The combination of the smaller rotor inertia and the greater efficiency of this design greatly increases the speed.

For some time, polyphase directional relays of this type of construction have been built using 3 elements having 3 rotors mounted on a single shaft.

## Single-Unit 3-Phase Directional Element

Engineers have long considered the economy of using one directional unit to perform the polyphase function. In fact, methods utilizing potential and current switching have been in use for some time, mainly in other countries. These, however, have the disadvantage of being complicated by auxiliary switching relays, in addition to the time lost in performing the switching function.

The multiple-pole induction-cylinder relay makes it possible, as will be shown, to combine the polyphase function of 3 elements in a single element without the use of auxiliary switching. This has resulted in a large reduction in size and weight, together with low inertia and high speed, as illustrated in table I.

The relay operating element is similar to the element shown in figure 1, but a magnetic return path is provided for each salient.

The production of torque is like that in the induction-disk directional relay and the unit may be considered to be a number of directional magnets acting upon the same rotor.

Referring to figure 2, each coil produces rotor currents which react with the flux of each other coil to produce torque. The torque of adjacent pairs of salients is large, relative to that of other pairs. For example, the torque produced by combination 1 and 3 is approximately 15 per cent of the torque produced by combination 1 and 2, while that produced by combination 1 and 4 is about 2 per cent, a negligible amount. The torques of alternate salients (*e. g.*, 1 and 3 or 2 and 4) being appreciable, the connections are so arranged that these torques balance out substantially to zero; an adjustment being provided in addition, for more accurate balance of the current torques.

**Table I—Comparison of Types of 3-Phase Relays**

| | Two-Disk Relay (Per Cent) | Three-Cup Relay (Per Cent) | One-Cup Relay (Per Cent) |
|---|---|---|---|
| Size | 100 | 100 | 50 |
| Weight | 100 | 100 | 50 |
| Torque per watt input | 100 | 190 | 156 |
| Inertia of moving element | 100 | 17 | 6.6 |
| Speed (equal input) | 100 | 330 | 480 |
| Speed (rated input) | 100 | 330 | 280 |

Thus, in analyzing the action of the relay, it is necessary to consider only the adjacent combinations.

Although the same performance characteristics of all the usual connections (quadrature, etc.) are possible, the connections shown in figure 2 appear to be the most suitable. Considering the interaction of adjacent combinations, $I_a$ acts with $E_B$ and with $E_A$. Since $E_B$ and $E_A$ are on opposite sides of $I_a$, combination 1–2 is of opposite sign to combination 2–3. Assuming the reaction of each

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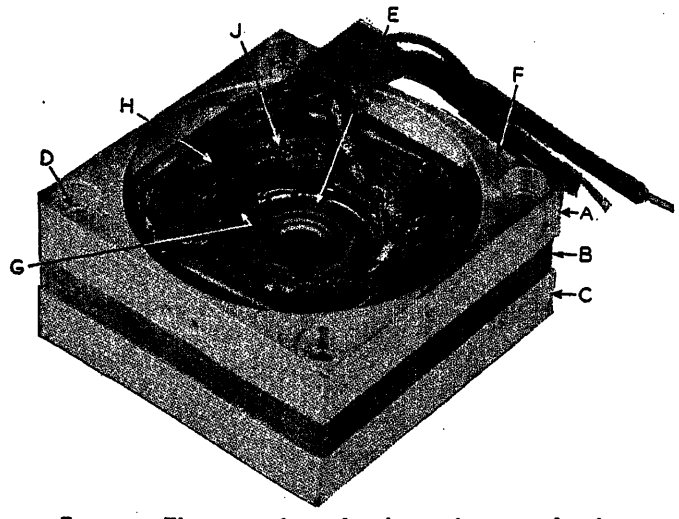



**Fig. 1. Element of single-phase directional relay**

*A*—Upper stator casting
*B*—Laminations
*C*—Lower stator casting
*D*—Rivets which fasten parts *A*, *B*, and *C* together
*E*—Central core (laminated iron) fixed to part *C*
*F*—Notch to facilitate disassembly
*G*—Air gap in which rotor cup turns
*H*—Position for current coils
*J*—Position for potential coils

current coil with the counterclockwise potential coil as positive, and with the clockwise potential coil as negative, the total input (watts and reactive volt-amperes) to the relay will be[1]

$$P_R + jQ_R = (E_B - E_A)\bar{I}_a + (-E_A - E_B)\bar{I}_b + (E_A - E_C)\bar{I}_c + (E_A + E_C)\bar{I}_b$$

With the above power quantities supplied to the relay, it will have average torque proportional to

$$(|E_1|)(|I_1|)\cos(\phi_1 - 60 + \theta) + (|E_2|)(|I_2|)\cos(\phi_2 + 60 + \theta) \quad \text{(appendix I}A\text{)}$$

The corresponding equation for the torque of the standard quadrature connection of the usual type of induction-disk relay is

$$(|E_1|)(|I_1|)\cos(\phi_1 - 90 + \theta) + (|E_2|)(|I_2|)\cos(\phi_2 + 90 + \theta) \quad \text{(appendix II}A\text{)}$$

It may be seen that there is agreement between the 2 connections, except for 30 degrees in both the positive- and negative-phase-sequence terms.

With the connections of figure 2, there is a difference of 30 degrees in phase angle between a 3-phase fault and a dead phase-to-phase fault; maximum torque being at the more lagging angle in the phase-to-phase condition (appendix I*B*).

This characteristic is desirable because a 3-phase fault, from the relay point of view, is likely to be nearer unity power factor than is a phase-to-phase fault. This is because the phase angle at the relay during a 3-phase fault depends only on the impedance (line and arc) from the relay to the fault, whereas, during a phase-to-phase fault,

1. For numbered references see end of paper.

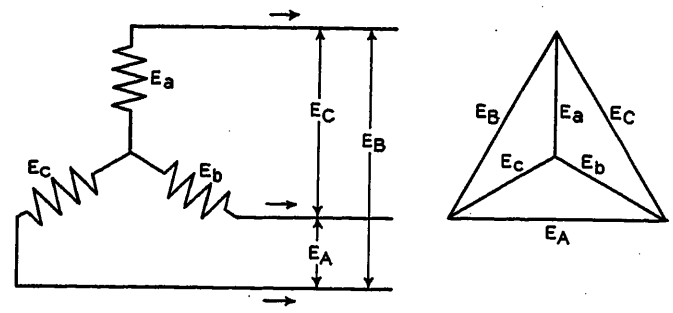



**Fig. 2a (right). Diagram illustrating relay connection**

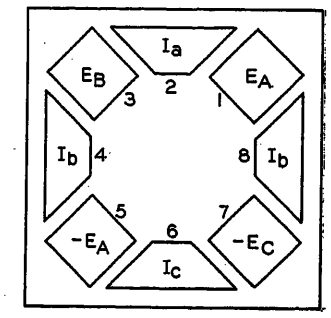



**Fig. 2b (above). Diagrams of current and voltage relations**

the phase angle depends on the impedance back to and including the generator as well as the impedance to the fault (appendix III). This inherent 30 degree shift is advantageous for another reason, namely, less resistance is required in the potential circuit than with the quadrature connection in order to obtain the same 3-phase phase-angle characteristics. The loss is therefore less.

## Quadrature and Other Connections

It is possible to obtain the performance characteristics of the well-known quadrature connection in several ways; 2 ways are illustrated in figure 3. Figure 3*a* utilizes phase-to-neutral voltages, the neutral being either ground or an artificial neutral formed by a common connection of the potential coils. Figure 3*b* uses a delta voltage on each potential coil. Appendix IV shows how each of these connections is equivalent to the quadrature connection.

It is also possible to obtain the equivalent of the adjacent connections by changing the cyclic order of either the voltages or currents of figure 3.

### Relays Using the 3-Phase Element in Combination With Other Elements

The element described in the preceding is, of course, a plain directional relay. On the same shaft have been added certain other elements of like construction in order to modify the characteristics. For example, it is often advantageous to prevent a directional relay from operating except during fault conditions. For this purpose, a voltage restraining element has been added. This type of relay is shown in figure 4.

Although a plain directional relay will often take care of ground faults as well as phase faults, it is necessary to add ground-fault protection when the torque caused by ground-fault voltage and current is less than that caused by load current, or when generation is present at one end only. To meet this requirement a strong ground-fault

element may be added to the 3-phase element, this combination being sufficient for almost any relay location.

The addition of a voltage-restraining element to the 3-phase directional and ground directional elements has resulted in an entirely new combination. A relay of this type is shown in figure 5.

The successful use of the induction-cup element for the applications described above gives encouragement for the development of other forms of polyphase high-speed relays having a higher torque-to-input ratio and lower inertia of the moving parts.

## Nomenclature

$P_R$ = total power applied to relay
$Q_R$ = total reactive volt-amperes applied to relay
$I$ = current vector as a complex quantity (of the form $a + jb$)
$\bar{I}$ = conjugate of $I(a - jb)$
$|I|$ = absolute value of the vector $I(\sqrt{a^2 + b^2})$
$E$ = voltage vector as a complex quantity
$a$ = operator which rotates a vector 120 degrees in the counter-clockwise direction
$\alpha_1$ = angle by which the vector $E_1$ leads a reference line
$\beta_1$ = angle by which the vector $I_1$ leads a reference line
$\phi_1$ = $\alpha_1 - \beta_1$ = angle by which $I_1$ lags $E_1$
$\alpha_2$ = angle by which the vector $E_2$ leads a reference line
$\beta_2$ = angle by which the vector $I_2$ leads a reference line
$\phi_2$ = $\alpha_2 - \beta_2$ = angle by which $I_2$ lags $E_2$
$\theta$ = angle of lead (current leading voltage) at which maximum torque of a pair of adjacent salients occurs
$Z_1$ = positive-phase-sequence impedance of the generator
$Z_2$ = negative-phase-sequence impedance of the generator
$Z_L$ = positive- and negative-phase-sequence line impedance
$R$ = phase-to-neutral arc resistance
$K$ = relay torque constant per pair of adjacent salients

Subscripts $a$, $b$, $c$, $A$, $B$, $C$ are defined by figure 2$b$.
Subscripts 1, 2, and 0 denote positive, negative, and zero phase sequence, respectively.

## Appendix IA

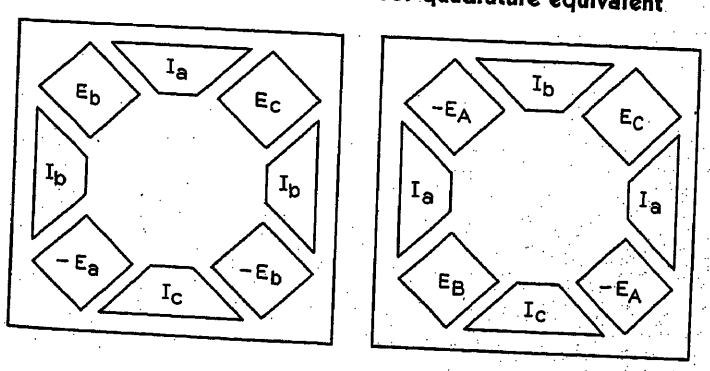
Connections according to figure 2.
The total input to the relay is[1]

$$P_R + jQ_R = (E_B - E_A)\bar{I}_a + (\underline{-E_A} - E_B)\bar{I}_b + (-E_C + E_A)\bar{I}_c + \underline{(E_A + E_C)}\bar{I}_b$$

The underlined terms cancel, leaving

$$P_R + jQ_R = E_B\bar{I}_a - E_A\bar{I}_a + E_C\bar{I}_b - E_B\bar{I}_b + E_A\bar{I}_c - E_C\bar{I}_c$$

**Fig. 3. Relay connections for quadrature equivalent**




These power quantities can be expressed in terms of symmetrical components as follows:

$$E_B\bar{I}_a = (E_a - E_c)\bar{I}_a = E_0 + E_1 + E_2 - E_0 - aE_1 - a^2E_2)(\bar{I}_0 + \bar{I}_1 + \bar{I}_2)$$
$$= (1 - a)E_1\bar{I}_0 + (1 - a)E_1\bar{I}_1 + (1 - a)E_1\bar{I}_2 + (1 - a^2)E_2\bar{I}_0 + (1 - a^2)E_2\bar{I}_1 + (1 - a^2)E_2\bar{I}_2$$

The following table gives the coefficients of all of the sequence voltage-current products.

| Relay Quantities | $E_1\bar{I}_1$ | $E_1\bar{I}_2$ | $E_1\bar{I}_0$ | $E_2\bar{I}_1$ | $E_2\bar{I}_2$ | $E_2\bar{I}_0$ | $E_0\bar{I}_1$ | $E_0\bar{I}_2$ | $E_0\bar{I}_0$ |
|---|---|---|---|---|---|---|---|---|---|
| $E_B\bar{I}_a$ | $1 - a$ | $1 - a$ | $1 - a$ | $1 - a^2$ | $1 - a^2$ | $1 - a^2$ | 0 | 0 | 0 |
| $-E_A\bar{I}_a$ | $a^2 - a$ | $a^2 - a$ | $a - a^2$ | $a - a^2$ | $a - a^2$ | $a - a^2$ | 0 | 0 | 0 |
| $E_C\bar{I}_b$ | $1 - a$ | $a - a^2$ | $a^2 - 1$ | $a^2 - a$ | $1 - a^2$ | $a - 1$ | 0 | 0 | 0 |
| $-E_B\bar{I}_b$ | $a^2 - a$ | $1 - a^2$ | $a - 1$ | $1 - a$ | $a - a^2$ | $a^2 - 1$ | 0 | 0 | 0 |
| $E_A\bar{I}_c$ | $1 - a$ | $a^2 - 1$ | $a - a^2$ | $a - 1$ | $1 - a^2$ | $a^2 - a$ | 0 | 0 | 0 |
| $-E_C\bar{I}_c$ | $a^2 - a$ | $a - 1$ | $1 - a^2$ | $a^2 - 1$ | $a - a^2$ | $1 - a$ | 0 | 0 | 0 |
| Total | $3 - 6a + 3a^2$ | 0 | 0 | 0 | $3 + 3a - 6a^2$ | 0 | 0 | 0 | 0 |
| Total | $-9a$ | 0 | 0 | 0 | $-9a^2$ | 0 | 0 | 0 | 0 |

$$P_R + jQ_R = -9aE_1\bar{I}_1 - 9a^2E_2\bar{I}_2$$
but $a = \epsilon^{j120}$ $\quad a^2 = \epsilon^{j240}$
$E_1 = |E_1|\,\epsilon^{j\alpha_1}$ $\quad E_2 = |E_2|\,\epsilon^{j\alpha_2}$
$I_1 = |I_1|\,\epsilon^{-j\beta_1}$ $\quad \bar{I}_2 = |I_2|\,\epsilon^{-j\beta_2}$

(Note: Angles are in degrees.)

Therefore:

$$P_R + jQ_R = -9(|E_1|)(|I_1|)\epsilon^{j(\alpha_1 - \beta_1 + 120)} - 9(|E_2|)(|I_2|)\epsilon^{j(\alpha_2 - \beta_2 + 240)}$$
$$= 9(|E_1|)(|I_1|)\epsilon^{j(\alpha_1 - \beta_1 - 60)} + 9(|E_2|)(|I_2|)\epsilon^{j(\alpha_2 - \beta_2 + 60)}$$
$$P_R + jQ_R = 9(|E_1|)(|I_1|)[\cos(\alpha_1 - \beta_1 - 60) + j\sin(\alpha_1 - \beta_1 - 60)] + 9(|E_2|)(|I_2|)[\cos(\alpha_2 - \beta_2 + 60) + j\sin(\alpha_2 - \beta_2 + 60)]$$
$$= (|E_1|)(|I_1|)[\cos(\phi_1 - 60) + j\sin(\phi_1 - 60)] + 9(|E_2|)(|I_2|)[\cos(\phi_2 + 60) + j\sin(\phi_2 + 60)]$$

This is the total input to the relay in terms of symmetrical components. It is seen that the input consists of a positive-phase-sequence term with a voltage $E_1$, a current $I_1$, and an angle between $E_1$ and $I_1$ equal to $(\phi_1 - 60)$ and a similar negative-phase-sequence term with an angle $(\phi_2 + 60)$.

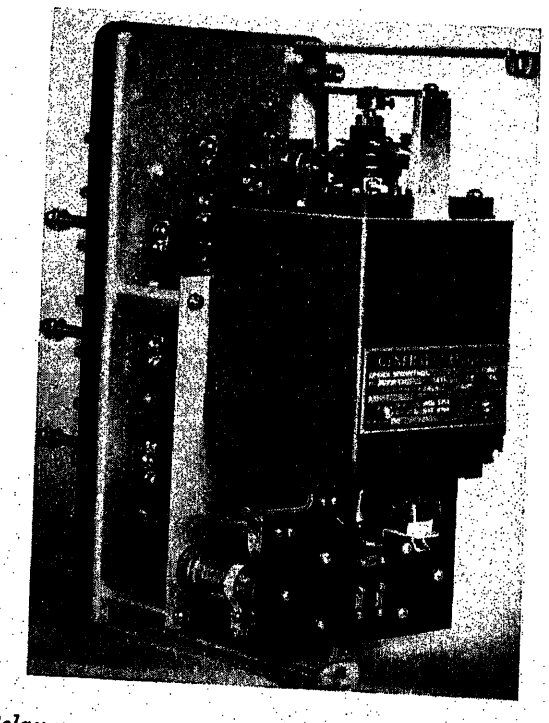


**Fig. 4. Three-phase directional relay with voltage restraint**

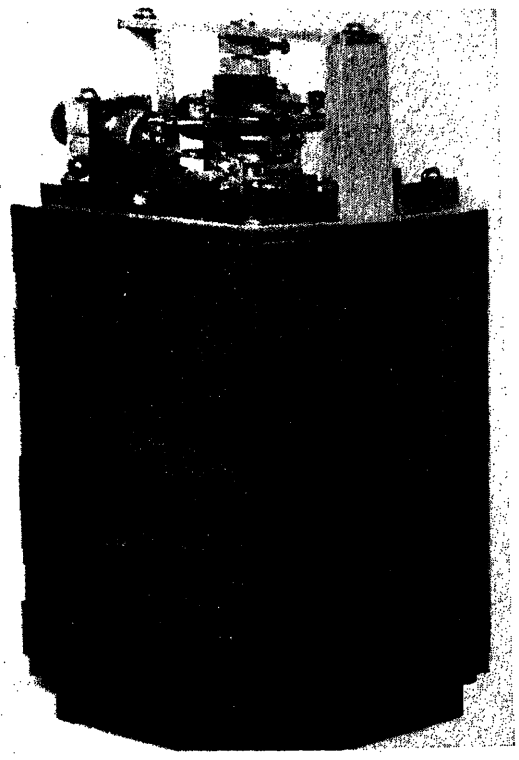


**Fig. 5. Three-phase and ground directional relay with voltage restraint**

On the basis of a pair of adjacent salients, the relay has average torque proportional to $(|E|)(|I|)\cos(\phi + \theta)$ where

$\phi$ = the angle by which the current lags the voltage
$\theta$ = the angle of lead (current leading voltage) at which maximum torque occurs

Thus, with the above input, the relay will have torque equal to

$$9K[(|E_1|)(|I_1|)\cos(\phi_1 - 60 + \theta) + (|E_2|)(|I_2|)\cos(\phi_2 + 60 + \theta)]$$

where $K$ is the relay torque constant per pair of adjacent salients.

## Appendix IB

Connections according to figure 2.

### Relay Torque During 3-Phase Fault

$$\text{Torque} = 9K(|E_1|)(|I_1|)\cos(\phi_1 - 60 + \theta)$$

Maximum torque is when $\phi_1 + \theta - 60 = 0$, that is, when $\phi_1 + \theta = 60$ (see figure 6)

### Relay Torque During Dead Phase-to-Phase Fault

Assuming $|E_1| = |E_2|$, $|I_1| = |I_2|$, and $\phi_2 = \phi_1 + 180$

$$\text{Torque} = 9K[(|E_1|)(|I_1|)\cos(\phi_1 - 60 + \theta) + (|E_1|)(|I_1|)\cos(\phi_1 + 180 + 60 + \theta)]$$

$$= 9K(|E_1|)(|I_1|)[\cos(\phi_1 - 60 + \theta) + \cos(\phi_1 + 240 + \theta)]$$

$$= 9\sqrt{3}K(|E_1|)(|I_1|)\cos(\phi_1 - 90 + \theta)$$

Maximum torque occurs when $\phi_1 - 90 + \theta = 0$
that is, when $\phi_1 + \theta = 90$ degrees (See figure 7)

## Appendix IIA

### Quadrature Connection

With the quadrature connection, $E_A$ operates with $-I_a$, $E_B$ with $-I_b$, and $E_C$ with $-I_c$.

The total input to the relay is

$$P_R + jQ_R = -E_A\bar{I}_a - E_B\bar{I}_b - E_C\bar{I}_c$$

| Relay Quantities | $E_1I_1$ | $E_1I_2$ | $E_1I_0$ | $E_2I_1$ | $E_2I_2$ | $E_2I_0$ | $E_0I_1$ | $E_0I_2$ | $E_0I_0$ |
|---|---|---|---|---|---|---|---|---|---|
| $-E_A\bar{I}_a$ | $a^2 - a$ | $a^2 - a$ | $a^2 - a$ | $a - a^2$ | $a - a^2$ | $a - a^2$ | 0 | 0 | 0 |
| $-E_B\bar{I}_b$ | $a^2 - a$ | $1 - a^2$ | $a - 1$ | $1 - a$ | $a - a^2$ | $a^2 - 1$ | 0 | 0 | 0 |
| $-E_C\bar{I}_c$ | $a^2 - a$ | $a - 1$ | $1 - a^2$ | $a^2 - 1$ | $a - a^2$ | $1 - a$ | 0 | 0 | 0 |
| Total | $3a^2 - 3a$ | 0 | 0 | 0 | $3a - 3a^2$ | 0 | 0 | 0 | 0 |

$$P_R + jQ_R = 3(a^2 - a)E_1\bar{I}_1 + 3(a - a^2)E_2\bar{I}_2$$
$$= -3\sqrt{3}\,jE_1\bar{I}_1 + 3\sqrt{3}\,jE_2\bar{I}_2$$
$$= 3\sqrt{3}(|E_1|)(|I_1|)e^{j(\alpha_1 - \beta_1 - 90)} + 3\sqrt{3}(|E_2|)(|I_2|)e^{j(\alpha_2 - \beta_2 + 90)}$$
$$= 3\sqrt{3}(|E_1|)(|I_1|)[\cos(\alpha_1 - \beta_1 - 90) + j\sin(\alpha_1 - \beta_1 - 90)] + 3\sqrt{3}(|E_2|)(|I_2|) \times [\cos(\alpha_2 - \beta_2 + 90) + j\sin(\alpha_2 - \beta_2 + 90)]$$

which is the total input to the relay in terms of symmetrical components and the relay torque is

$$3\sqrt{3}K[(|E_1|)(|I_1|)\cos(\phi_1 - 90 + \theta) + (|E_2|)(|I_2|)\cos(\phi_2 + 90 + \theta)]$$

## Appendix IIB

### Quadrature Connection

RELAY TORQUE DURING 3-PHASE FAULT

$$\text{Torque} = 3\sqrt{3}K(|E_1|)(|I_1|)\cos(\phi_1 - 90 + \theta)$$

Maximum torque is when $\phi_1 - 90 + \theta = 0$ that is, when $\phi_1 + \theta = 90$ (See figure 7)

RELAY TORQUE DURING DEAD PHASE-TO-PHASE FAULT

Assuming $|E_1| = |E_2|$, $|I_1| = |I_2|$, and $\phi_2 = \phi_1 + 180$

$$\text{Torque} = 3\sqrt{3}K[(|E_1|)(|I_1|)\cos(\phi_1 - 90 + \theta) + (|E_1|)(|I_1|)\cos(\phi_1 + 180 + 90 + \theta)]$$
$$= 6\sqrt{3}K(|E_1|)(|I_1|)\cos(\phi_1 - 90 + \theta)$$

Maximum torque is when $\phi_1 - 90 + \theta = 0$ that is, when $\phi_1 + \theta = 90$ (See figure 7)

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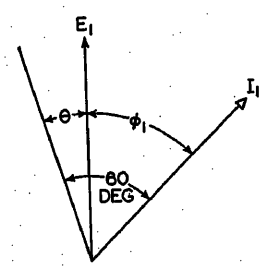



**Fig. 6. Phase angle for maximum torque**

Three-phase fault; connections according to figure 2

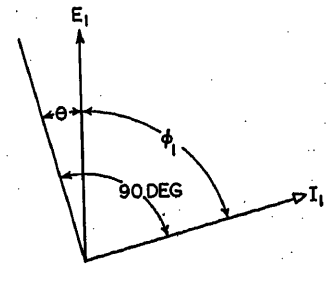



**Fig. 7. Phase angle for maximum torque**

Dead phase-to-phase fault; connections according to figure 2 or quadrature connections

# Ultrahigh-Speed Reclosing of High-Voltage Transmission Lines

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**Reclosure of circuit breakers following a fault on a high-voltage transmission line with a minimum of delay in order that synchronous load will not fall out of step is described in this paper. Apparatus that performs a complete operation in approximately 20 cycles on a 60-cycle system may be used to obtain a high degree of service continuity from a single-circuit transmission line.**

HIGH-SPEED reclosing of high-voltage transmission lines has been practiced for a number of years and has been described previously.[1] This method of reclosing has sometimes been termed "instantaneous reclosing." The term "instantaneous" obviously admits of no latitude. It has always, however, been broadly interpreted. As applied to reclosing of high-voltage circuits, as heretofore practiced, it is obviously a misnomer because the time involved has always been appreciable, running into a considerable fraction of a second. In this paper the authors have given the name of ultrahigh-speed reclosing to a reclosing operation at the maximum speed physical phenomena, particularly arc deionization, will permit. So far as is known, this is the first time that high-voltage transmission circuits have been set up to reclose on that basis.

## Background of the Problem

The experience back of high-speed reclosing and ultrahigh-speed reclosure is considerable. It has accumulated with the vast extension of transmission networks in the United States and with the experience in interruptions to service, particularly to industrial service, as a result of voltage surges or dips occurring on systems. The basic reason for these voltage dips was generally found to be the long time taken to clear faults occurring on the system. Going back 10 years, these times were frequently of the order of from 3 to 4 seconds. This long duration of reduced voltage, coupled with the fact that many of the industrial control systems were using extensively instantaneous undervoltage devices (instantaneous in this case involving times of from 5 to 10 cycles in the terms of a 60-cycle system) gave serious interruptions in section after section of the United States where transmission service was extensively substituted for rather short-feed localized generation service. The remedy adopted for these difficulties was two-fold. First, a reduction in time of relay action, and second, extensive work in the introduction of time delay undervoltage protection in connection with the control systems. The detailed methods for handling the problem in the latter fashion have again been described elsewhere.[2] All of these solutions, however, had definite limitations, first because many types of motor drives are fundamentally not susceptible to time-delay undervoltage protection as a cure and, second, there is always the problem of complete loss of service where a single line is utilized to take care of the supply into an area or station. One of these difficulties has lately been taken care of by extremely fast clearing of faults. Thus, in recent practice with the use of one-cycle carrier relaying it has been possible, even by using nothing more than a standard 8-cycle breaker, to get a maximum time clearing under all conditions of 0.15 second (9 cycles) and under these conditions the disturbance is not of sufficiently long duration to cause synchronous motor drives to drop out of step. However, there is still the problem of the single line which even with such rapid clearing of faults, of necessity, has to have a service interruption when the line is faulty. It is this particular problem that the authors and their associates had in mind and set themselves to solve in the development described herein.

In a measure this development is an outgrowth of the work done on high-speed breakers and high-speed relaying. Each of these particular developments has previously been described.[3,4,5,6] The problem posed was the attainment of a breaker reclosure so quickly that the net effect on load would be as if no interruption had taken place and no load would be lost. It is apparent that as regards lightning the same result could be obtained by the use of expulsion deionizing gaps. However, although considerable work in that direction has been carried out and some of it has been described,[7] it is a fact that the experience with gaps is still rather limited. Further, the gap has the disadvantage that it will not take care of anything but lightning difficulties and there are other difficulties besides lightning that may cause momentary flashovers which can be cleared and re-established by sufficiently fast reclosure. Besides, since there must be circuit breakers on the line in any event, if these circuit breakers by a special reclosing provision can approach the service standard of a line with both breakers and expulsion gaps, a considerable economic advantage is possible.

From all this it was apparent that a thorough exploration of the possibilities of ultrarapid reclosure by circuit breakers was in order. An examination of the problem

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1. For all numbered references see list at end of paper.

indicated that the following were essential parts of the solution to the problem:

1. Relaying must be provided which will locate the fault and communicate the trip impulse to all breakers involved in the shortest possible time and, if possible, in a time not exceeding one cycle.

2. Reclosing mechanisms must be provided which will open and reclose the breakers in a total time somewhere between 0.25 and 0.50 second, or a total time of somewhere between 15 and 30 cycles, with the chances very great of need in the direction of the smaller as against the larger of the 2 intervals.

3. The circuit breaker must extinguish the arc in the least possible time and in a period possibly not to exceed 5 or 6 cycles.

4. The actual arc causing the service interruption must not restrike when voltage is restored.

Some of these parts of the complete solution were already available or the facts with regard to the phenomena involved definitely known. Thus, it was definitely known that standard breakers could be obtained to operate in a period not to exceed 8 cycles, and special breakers in a period not over 3 cycles.[4] Again it was definitely known and experience had been previously obtained with a relay system functioning in a period not exceeding one cycle. However, the problem of getting a mechanism applicable to a standard breaker that would reclose in a period of from 7 to 8 cycles, or a total period from initiation of fault of 15 cycles, definitely had not been solved. Again, although the action of the arc upon re-establishment of potential had been previously explored[8] by others, insufficient and inconclusive data was available for complete guidance to a satisfactory solution of the problem presented. Nevertheless, it was decided that the period had arrived when it was necessary and desirable to attempt to bring to a solution this particular problem, taking advantage of what was available, and developing or exploring those parts that were unavailable from an equipment standpoint or unknown from a fundamental theoretical standpoint. This paper describes the developments thus made, the investigations both in the laboratory and in the field, and the performance of a system of rapid circuit interruption and ultrahigh-speed reclosing.

## Carrier Current Relaying System

Choice of relay equipment was determined by the desirability of high-speed operation combined with nearly simultaneous energization of the trip circuits of the breakers at each terminal. Carrier-current relaying is the only practical system which provides high-speed operation for any fault at any location on the circuit being protected.[9] When it came to a decision as to the type of carrier to be employed, one was confronted with the fact that as a matter of plain arithmetic a one-cycle system was almost essential. Thus, if 6 cycles is allowed for arcing and 8 cycles is permitted for reclosure after the arc has been extinguished, the total time available for relaying, if the total time of 15 cycles is to be adhered to, is only one cycle. It was obvious that if a larger amount of time was satisfactory for reclosure, some leeway was available in the relaying time but the one-cycle system, if practically available, was ideally suited for this problem.

The one-cycle relaying system utilized here has been previously described[5,6] as can be seen by reference to such previous data. The trip circuit is normally held open by the receiver relays and it is closed only by the dropping out of these relays when no carrier signal is received. Since the relays controlling the trip circuits at both ends are simultaneously de-energized by the stoppage of the carrier signal, the actual closing of the trip circuits will occur at nearly the same instant.

Because of the importance that the relaying plays in the entire scheme, it may be pertinent to review the salient parts of the relay scheme, their function and performance. Figure 1 shows the fundamental scheme and involves in essence the following equipment:

1. *Receiver Relay.* This is a polarized relay having a field winding and an operating winding arranged to be energized either from the local battery circuit or from the received carrier signal. The relay

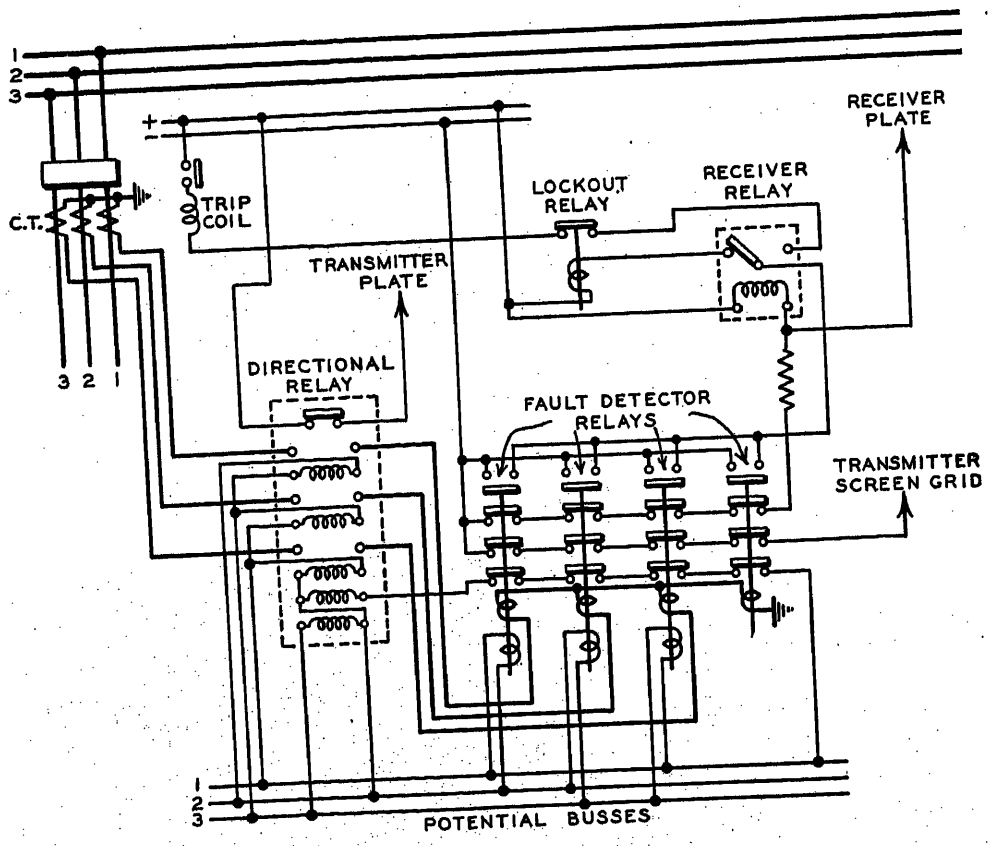



**Fig. 1. High-speed carrier-current relay circuit**

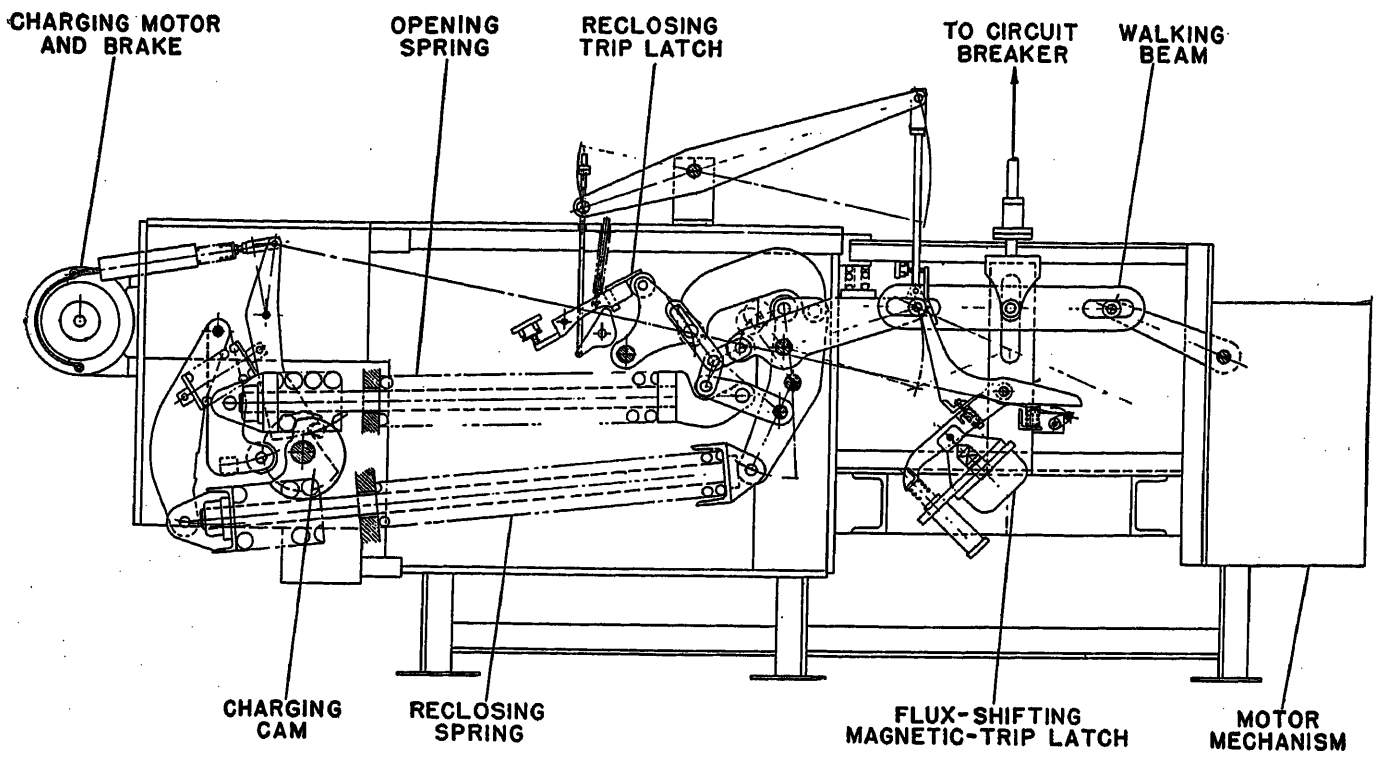



**Fig. 2. Schematic diagram of ultrahigh-speed reclosing mechanism for oil circuit breakers**

will close its tripping contacts when de-energized and hold the tripping contacts open normally when excited from the battery circuit and during fault conditions when excited from the received carrier signal. The relay will close its lockout contacts when energized and hold them closed normally when excited from the battery circuit and during fault conditions when excited from the received carrier signal.

2. *Fault Detecting Elements.* Three for phase faults, these being of the impedance type, that is, having a current operating winding and a voltage restraining winding, and one for ground faults having only a current winding. All of these fault detectors were equipped with 4 independent contacts for performing the following functions:

*a.* A circuit-opening contact for starting carrier by the removal of the grid bias.

*b.* A circuit-opening contact for disconnecting the receiver relay coil from the local battery supply.

*c.* A circuit-opening contact for removing voltage restraint from the directional relay.

*d.* A circuit-closing contact which is in series with the receiver relay contact and the tripping circuit.

3. *Directional Relay.* This is the polyphase type, having voltage restraint. This relay is of the new induction cup type, giving it greater speed than was obtainable with previous types of power directional relays.

4. *Lockout Relay.* This is a time-delay circuit-opening and circuit-closing auxiliary relay of the plunger bellows type which is adjusted to give a time delay of 5 cycles in opening or closing its contacts.

The sequence of operation is comparatively simple and may be described briefly as follows: Under normal conditions the directional-relay contacts are held closed by voltage restraint, applying plate voltage to the transmitter but the transmitter does not operate because of the normally closed contacts of the fault-detector relays which apply a negative bias to the screen grid of the transmitter. Further, the receiver-relay contacts are held open by the closed contacts of the fault-detector relays energizing the receiver-relay coil from the station battery. In case of an internal fault the directional relays will operate to stop the transmission of carrier at both ends of the line. When the carrier from both ends has been stopped then the receiver relays are de-energized and they both drop out, completing the trip circuits. The receiver relay operates in an average time of 0.35 cycle. The directional relay opens its contacts in an average time of 0.40 cycle so that the fundamental fastest time possible is approximately 0.75 cycle. Some variations on either side of that value are obviously possible. On an external fault one of the directional relays on the end where power is flowing from the line into the bus will permit the carrier signal to be maintained, thereby preventing tripping. The function of the lockout relay is to open the trip 5 cycles after the circuit-closing contacts of the fault detector have closed to prevent false tripping on a through fault as the result of sudden reversals of power flow and also to prevent tripping in case of system instability.

## Tripping and Reclosing Mechanisms and Circuit-Breaker Operation

Most standard mechanisms require about 0.5 second to close the circuit breaker. Reclosing mechanisms have been made providing an over-all time of this order by connecting 2 mechanisms together through a walking beam. One of the 2 mechanisms is at all times at rest with its latch reset. When tripped the circuit breaker opens until the energized mechanism builds up enough force to overcome the opening springs and momentum.

It was obviously necessary in this case to secure a much

higher speed than was obtainable in this way. Accordingly, a spring-charged mechanism was designed to take the place of one standard mechanism in the teamed arrangement. This mechanism is shown schematically in figure 2. A standard motor mechanism operates on one end of the main walking beam to the center of which the circuit-breaker linkage is attached. For ordinary switching operations and for the second opening should a flashover re-establish or repeat, this mechanism functions in a normal manner. The spring mechanism of the stored-energy type has 2 sets of springs; one set to reinforce the breaker opening springs, the other set to close. This mechanism when charged performs an opening and closing operation, its normal position being closed.

The spring mechanism has a high-speed latch of the flux-shifting type which operates with the opening springs to give a contact parting time of from 2.5 to 3.5 cycles. After the contacts have moved 8 inches a link attached to the opening mechanism trips the auxiliary opening springs and releases the closing springs. These then reclose the breaker. Figures 3 and 4 are views of the mechanism and an ultrahigh-speed breaker installation, respectively, which give an excellent idea of the size.

During the reclosing stroke the tripping circuit is transferred to the motor mechanism so that a permanent fault will be tripped off at once. As adjusted for test, one of these mechanisms gave an over-all time from initial trip impulse to contact make of 15 cycles. It proved rather difficult to hold this fine adjustment throughout so that the service record aimed at was much nearer 18 cycles. A typical calculated travel record is shown in figure 5. It may be noticed first that the total time from the instant of energization of the trip coil is 16 cycles: taking relay time at one cycle, this gives a total time from initiation of fault of 17 cycles. Second, the mechanism once started on a tripping cycle is definitely set for reclosure upon the completion of 8 inches of stroke without waiting for arc extinction. This definitely meant that the circuit breaker had to be reliable to the point where it would extinguish the arc on the completion of the allowed stroke, that is, 8 inches, with enough to spare for the tripping relays to reset. As will be brought out later, this was accomplished in general very successfully.

## Basic Ideas Underlying Ultrahigh-Speed Reclosing

As previously pointed out, one of the essential parts of the solution of the problem of ultrarapid reclosing was the necessity for the actual arc causing the service interruption not to restrike when voltage is restored. The usual fault against which protection is sought is a lightning stroke. The circuit in this case cannot be re-energized until the ionization produced by the stroke has been dissipated enough that the restored voltage may be withstood. This time was investigated in both field and laboratory tests. Griscom and Torok[8] have made a series of such tests, varying the current from 800 to 1,500 amperes and the voltage from 66 kv to 130 kv with the spacing of electrodes from 12 inches to 93 inches. They concluded that:

1. The restriking of arcs is a random phenomenon.

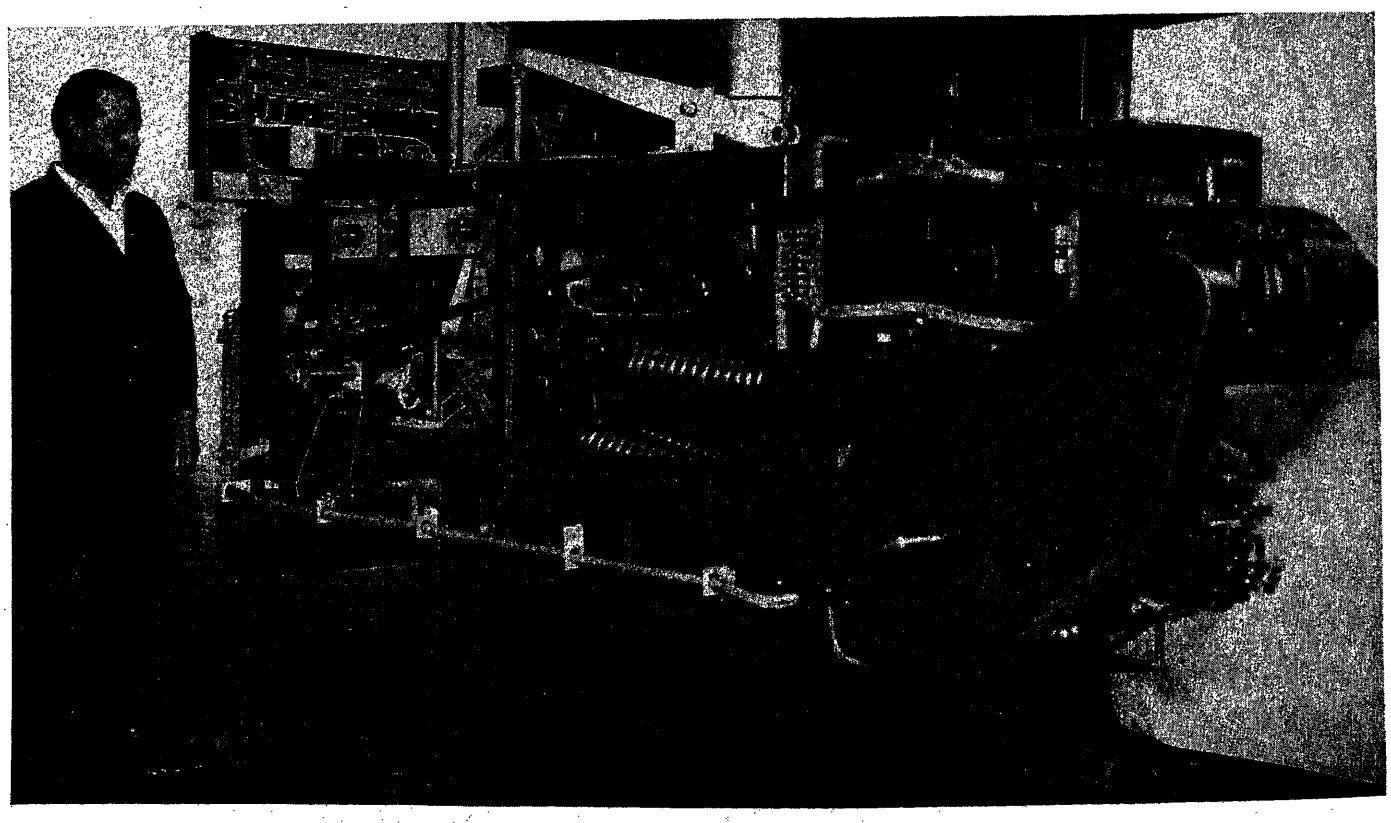


**Fig. 3. Ultrahigh-speed circuit-breaker reclosing mechanism**

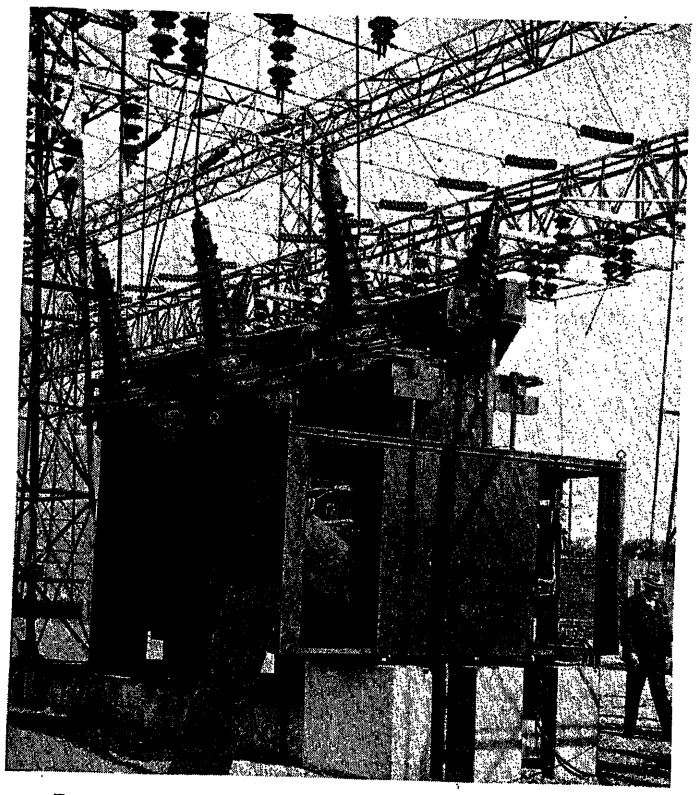


**Fig. 4. A 132-kv installation of the ultrahigh-speed reclosing breaker**

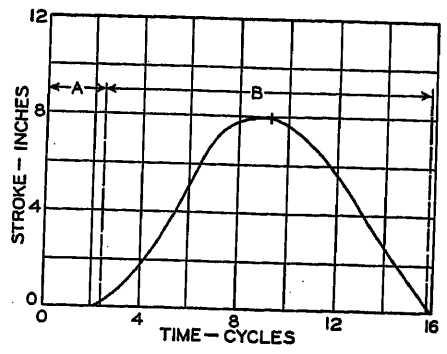



**Fig. 5. Travel record of ultra-high-speed mechanism**

*A*—Trip impulse of 2.4 cycles until contacts part

*B*—Contacts part to make 8-inch stroke during 13.4 cycles

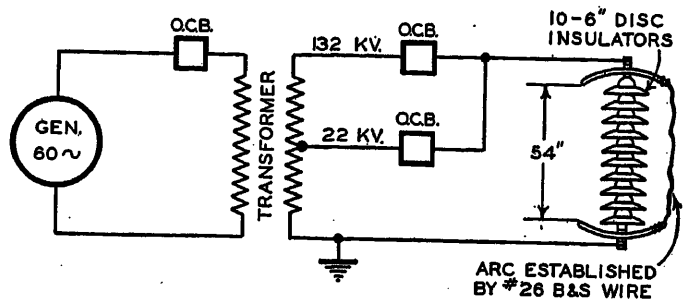



**Fig. 6. Circuit used for laboratory tests**

2. The probability of restrike increases with operating voltage for spacings ordinarily used.

3. The probability of restriking is only slightly affected by large variations in current.

4. For a given recovery voltage above a certain spacing, the probability of restriking is but slightly affected by the spacing of electrodes; below this value, spacing plays an important part.

The restriking times found by Griscom and Torok vary from about $1^1/_2$ cycles at 66 kv to a little over 3 cycles at 130 kv. The authors made some preliminary tests in 1935, under conditions similar to those used by Griscom and Torok but with currents of the order of 5,000 amperes, from which a probable restriking time of nearly 5 cycles resulted. These tests seemed to indicate that insufficient current range had been used in the earlier tests. Several other variables seemed to require attention, including velocity of wind, duration of arcing, and position of gap. In addition to these, the weatherman's part in the picture had to be determined. What would be the practical effect of multiple strokes of lightning? Would field experience show a larger or smaller proportion of successful reclosures than obtained in fair weather tests? It was decided to undertake additional tests along 3 lines:

1. Additional laboratory tests to further clarify the effects of voltage, current, distance between electrodes, wind, arc duration, etc.

2. Staged field tests to cross check against laboratory tests and determine the operation of high-speed reclosure under practical field conditions.

3. An extended field-operation test to determine from experience the service improvement possible with high-speed reclosure.

## Laboratory Tests

The method employed in the laboratory tests is indicated in figure 6. A fine-wire fuse is suspended between the ends of an insulator string, arcing horns, or other electrodes. The arc is drawn by closing a 20-kv circuit through this fuse. The fuse is quickly vaporized. The 20-kv circuit is then opened and after a time another circuit of higher voltage is closed. Some 300 tests have been made from which some conclusions seem justified, while others are in doubt. Figure 7 is a chart and table I is a summary of all the tests made. On the chart, crosses indicate a restrike and circles an absence of restrike. A line is drawn from the cross representing the longest restriking time to the circle representing the shortest non-restriking time. The center of this line should represent 50 per cent probability of restriking.

Any conclusions drawn are subject to modification as more experimental evidence becomes available.

In the meantime, the data on the chart and table may be examined to determine different tendencies. As a matter of probabilities, one may conclude that:

1. Restriking times are longer with a high-current arc.

2. Restriking times are longer the longer the arc is sustained.

3. Restriking times are longer in still air.

4. Moderate changes in electrode form, spacing, and location of arc are not important although a wider range might disclose differences as in 1, 2, and 3.

5. Restriking times vary from $2^1/_2$ to 12 cycles.

The line of development which would give a minimum

## Table I—Summary of Laboratory Tests on Effect of Various Changes on Restriking Time on String of Suspension Insulators

| Conditions of Test | | | | | | | | Restriking Time, Cycles | | | | | | | | | | | | | | | | Conclusions |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Voltage, Kilovolts | Current, Amperes | Rain | Number of 5½-in. Insulator Units | Arcing Rings | Wind Velocity, Miles per Hour | Faults to Lee or Wind of String | Initial Fault Duration, Cycles | 800 Amperes Low | 800 Amperes High | 800 Amperes Mean | 6,000 Amperes Low | 6,000 Amperes High | 6,000 Amperes Mean | Difference Low | Difference High | Difference Mean | Number of Tests Geometric Mean | Weighted Difference Low | Weighted Difference High | Weighted Difference Mean | |
| 80 | | No | 12 | Yes | 20–30 | Lee | 8 | 2.0 | 5.0 | 3.5 | 5.3 | 5.6 | 5.4 | 3.3 | 0.6 | 1.9 | 19 | 63 | 11 | 36 | On the average approximately 2¼ cycles or 50 per cent more dead time is required at 6,000 amperes than at 800 amperes |
| 80 | | No | 12 | No | 10–15 | Lee | 8 | 4.0 | 4.6 | 4.3 | 4.4 | 4.6 | 4.5 | 0.4 | 0.0 | 0.2 | 13 | 5 | 0 | 3 | |
| 80 | | No | 12 | Yes | 0– 5 | Lee | 8 | 5.8 | 6.4 | 6.1 | 6.8 | 9.4 | 8.1 | 1.0 | 3.0 | 2.0 | 9.5 | 10 | 29 | 19 | |
| 80 | | No | 12 | No | 0– 5 | Lee | 8 | 4.3 | | | 6.8 | 11.9 | 9.3 | 2.5 | | | 10 | 25 | | | |
| 80 | | No | 9 | Yes | 0– 5 | Lee | 8 | 2.7 | 7.1 | 4.9 | 9.0 | 9.9 | 9.4 | 6.3 | 2.8 | 4.5 | 15.5 | 98 | 43 | 69 | |
| 80 | | No | 12 | Yes | 0– 5 | Lee | 2 | 4.6 | 5.6 | 5.1 | 5.3 | 6.2 | 5.8 | 0.7 | 0.6 | 0.7 | 9.8 | 7 | 2 | 4 | |
| 80 | | No | 12 | Yes | 0– 5 | Lee | 8 | 6.0 | 7.0 | 6.5 | 9.5 | 10.0 | 9.8 | 3.5 | 3.0 | 3.3 | 14.5 | 50 | 43 | 47 | |
| 80 | | Yes | 12 | No | 0– 5 | Lee | 8 | | | | | | | | | | 91.3 | 81.3 | 81.3 | 258 | 130 | 178 | |
| | | | | | | | | | | | | | | | | | Weighted average difference | | | 2.8 | 1.6 | 2.2 | |

| | | | | | | | | 0–5 Miles per Hour Low | 0–5 Miles per Hour High | 0–5 Miles per Hour Mean | 5–10 Miles per Hour Low | 5–10 Miles per Hour High | 5–10 Miles per Hour Mean | 10–15 Miles per Hour Low | 10–15 Miles per Hour High | 10–15 Miles per Hour Mean | 20–30 Miles per Hour Low | 20–30 Miles per Hour High | 20–30 Miles per Hour Mean | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 80 | 6,000 | No | 12 | Yes | | Lee | 8 | 6.8 | 9.4 | 8.1 | | | | 8.6 | 9.2 | 8.7 | 5.3 | 5.6 | 5.4 | Effect of wind velocity negligible below 10 miles per hour without arcing rings and 15 miles per hour with arcing rings<br>Between 10 and 15 miles per hour, it allows a reduction in dead time of about 2.0 cycles without arcing rings<br>Between 20 and 30 miles per hour, it allows a reduction in dead time of about 2.5 cycles even with arcing rings |
| 80 | 6,000 | No | 12 | No | | Lee | 8 | 6.8 | 11.9 | 9.3 | | | | 4.4 | 4.6 | 4.5 | | | | |
| 80 | 800 | No | 12 | Yes | | Lee | 8 | 5.8 | 6.4 | 6.1 | | | | | | | 2.0 | 5.0 | 3.5 | |
| 80 | 800 | No | 12 | No | | Lee | 8 | 4.3 | | | 4.0 | 4.2 | 4.1 | 4.0 | 4.6 | 4.3 | | | | |
| 80 | 800 | No | 9 | Yes | | Lee | 8 | 2.7 | 7.1 | 4.9 | | | | 6.7 | 7.2 | 6.9 | | | | |
| 80 | 800 | No | 12 | No | | Wind | 8 | 4.7 | 6.1 | 5.4 | 7.5 | 7.7 | 7.6 | 2.9 | 5.5 | 4.2 | | | | |

| | | | | | | | | 2 Cycles Low | 2 Cycles High | 2 Cycles Mean | 8 Cycles Low | 8 Cycles High | 8 Cycles Mean | 30 Cycles Low | 30 Cycles High | 30 Cycles Mean | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 80 | 6,000 | No | 12 | Yes | 0– 5 | Lee | | 5.3 | 6.2 | 5.8 | 6.8 | 9.4 | 8.1 | 9.3 | 9.7 | 9.5 | At 6,000 amperes, 2 cycles less dead time is required for 2-cycle initial fault duration than for 8 cycles<br>Between 8 and 30 cycles, the loss is only one cycle<br>At 800 amperes, the difference is reduced only one cycle between 2- and 8-cycle initial fault duration |
| 80 | 800 | No | 12 | Yes | 0– 5 | Lee | | 4.6 | 5.6 | 5.1 | 5.8 | 6.4 | 6.1 | | | | |

| | | | | | | | | Arcing Rings Low | Arcing Rings High | Arcing Rings Mean | No Arcing Rings Low | No Arcing Rings High | No Arcing Rings Mean | Difference Low | Difference High | Difference Mean | Number of Tests Geometric Mean | Weighted Difference Low | Weighted Difference High | Weighted Difference Mean | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 80 | 6,000 | No | 12 | | 10–15 | Lee | 8 | 8.6 | 9.2 | 8.9 | 4.4 | 4.6 | 4.5 | 4.2 | 4.6 | 4.4 | 12 | 50 | 55 | 53 | Wind velocity between 10 and 15 miles per hour showed a decrease in necessary dead time of 4½ cycles when arcing rings were removed. Wind velocity less than 5 miles per hour shows no appreciable effect of the presence or absence of arcing rings |
| 80 | 6,000 | No | 12 | | 0– 5 | Lee | 8 | 6.8 | 9.4 | 8.1 | 6.8 | 11.8 | 9.3 | 0.0 | −2.4 | −1.2 | 13 | 0 | −31 | −16 | |
| 80 | 800 | No | 12 | | 0– 5 | Lee | 8 | 5.8 | 6.4 | 6.1 | 4.3 | | | 1.5 | | | 8 | 12 | | | |
| 80 | 800 | No | 9 | | 0– 5 | Lee | 8 | 2.7 | 7.1 | 4.9 | 3.4 | 6.4 | 4.9 | −0.7 | +0.7 | 0 | 20.5 | −14 | +14 | 0 | |
| | | | | | | | | | | | | | | | | | 53.5 | 45.5 | 45.5 | 48 | 38 | 37 | |
| | | | | | | | | | | | | | | | | | Weighted average difference | | | 0.9 | 0.8 | 0.8 | |

| | | | | | | | | Lee Low | Lee High | Lee Mean | Windward Low | Windward High | Windward Mean | Difference Low | Difference High | Difference Mean | Number of Tests Geometric Mean | Weighted Difference Low | Weighted Difference High | Weighted Difference Mean | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 80 | 800 | No | 12 | No | 10–15 | | 8 | 4.0 | 4.6 | 4.3 | 2.9 | 5.5 | 4.2 | −1.1 | +0.9 | −0.1 | 11.5 | −13 | +10 | −1 | Necessary dead time is about 1½ cycles less on the lee than on the windward side of the string |
| 80 | 800 | No | 12 | No | 5–10 | | 8 | 4.0 | 4.2 | 4.1 | 7.5 | 7.7 | 7.6 | 3.5 | 3.5 | 3.5 | 8.5 | 30 | 30 | 30 | |
| 80 | 800 | No | 12 | No | 0– 5 | | 8 | 4.3 | | | 4.7 | 6.2 | 5.4 | 0.4 | | | 5.5 | 2 | | | |
| | | | | | | | | | | | | | | | | | 25.5 | 20 | 20 | 19 | 40 | 29 | |
| | | | | | | | | | | | | | | | | | Weighted average difference | | | 0.7 | +2 | +1 | |

| | | | | | | | | 12 Units Low | 12 Units High | 12 Units Mean | 9 Units Low | 9 Units High | 9 Units Mean | Difference Low | Difference High | Difference Mean | Number of Tests Geometric Mean | Weighted Difference Low | Weighted Difference High | Weighted Difference Mean | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 80 | 6,000 | No | | Yes | 0– 5 | Lee | 8 | 6.8 | 9.4 | 8.1 | 9.0 | 9.9 | 9.4 | 2.2 | 0.5 | 1.3 | 10.4 | 23 | 5 | 14 | Within the limits investigated, the number of insulator units makes no difference in the necessary dead time |
| 80 | 800 | No | | Yes | 0– 5 | Lee | 8 | 5.8 | 6.4 | 6.1 | 3.7 | 7.1 | 4.9 | −3.1 | +0.7 | −1.2 | 14 | −43 | 10 | −17 | |
| 80 | 800 | No | | No | 0– 5 | Lee | 8 | 4.3 | | | 3.4 | 6.4 | 4.9 | | | | 11 | | | | |

| | | | | | | | | No Rain Low | No Rain High | No Rain Mean | Rain Low | Rain High | Rain Mean | Number of Tests Geometric Mean | Weighted Difference Low | Weighted Difference High | Weighted Difference Mean | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 80 | 6,000 | | 12 | No | 0– 5 | Lee | 8 | 6.8 | 11.9 | 8.3 | 9.5 | 10.0 | 9.7 | 16.5 | 31 | 23 | 28 | Presence of rain appears to increase the necessary dead time about 1½ cycles |
| 80 | 800 | | 12 | No | 0– 5 | Lee | 8 | 4.3 | | | 6.0 | 7.0 | 6.5 | 11.5 | 39 | 17 | 28 | |
| | | | | | | | | | | | | | | 28 | 70 | 40 | 56 | |
| | | | | | | | | | | | | | | Weighted average difference | 2.5 | 1.4 | 2.0 | |

outage time should combine high-speed tripping to give short fault duration with high-speed reclosing.

If reclosing is to be at a long enough interval to give little probability of a restrike, voltage must not be applied to the line for about 12 cycles after the arc has been interrupted. With an 8 cycle breaker this gives 20 cycles for the over-all reclosure time. At the other extreme, reclosure after $2^1/_2$ cycles will be successful sometimes. If a flashover is caused by multiple lightning strokes, some reclosures longer than 20 cycles over-all may still be followed by restriking. For that reason, the final limits will not have been determined until after a considerable period of experience under actual service conditions.

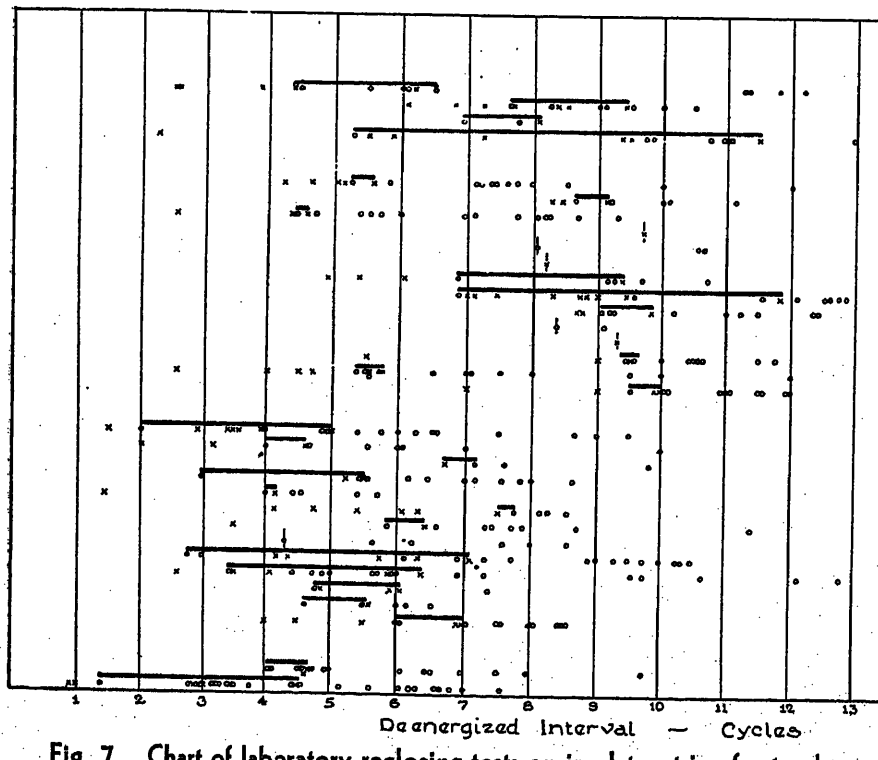
## Field Tests

The actual installation of ultrahigh-speed reclosing breakers was made on the 59.2-mile 132-kv line between the Fort Wayne, Ind., station of the Indiana & Michigan Electric Company and the Deer Creek (Marion) station of the Indiana General Service Company. High-speed reclosing mechanisms of the type described herein were installed on the breakers at both stations. One-cycle carrier-current relaying was employed on the line for fast and simultaneous tripping of breakers at both ends of the line. Automatic high-speed oscillographs were installed at both stations to determine the performance of the breakers under actual operating conditions. As a preliminary to long-time test operation, a series of complete tests was made on May 17, 1936, and another on June 14, 1936, the object being not only to test thoroughly the performance of the assembled equipment but to ascertain, if possible, the likelihood of successful performance under actual operating conditions and the actual time to be used as the reclosure interval for such long time tests.

In all, 35 reclosure tests were made. A tabulated summation of 20 of these tests is indicated in table II.

Tests 1 to 4 illustrate the normal performance of the breakers and relays for an internal phase-to-ground fault. The carrier-current relays operated within from 0.70 to 1.00 cycle after the inception of the fault to energize the trip circuits of the circuit breakers. The line was completely de-energized from 5.3 to 7.2 cycles later and remained so for a period of from 10.7 to 12.0 cycles before being re-energized. The total time from the initiation of the fault until the reclosing of the last breaker was from 21.0 to 21.8 cycles. On all of these tests the line was re-energized without restriking of the arc.

Tests 5 to 7 show the performance for internal phase-to-phase faults not involving ground. Here it will be noted that in 2 of the tests the arc was restruck after the line was energized. The line was de-energized for periods of from 11.5 to 14.1 cycles, and the test where the line was de-energized for 14.1 cycles was the only case where the arc did not restrike after energization of the line.




| Test Group No. | No. Tests | Rain | No. 5¾ Ins Units | Arcing Rings | Wind Vel Mi/Hr | Fuse on Lee or Wind Side of String | Approx Duration Init Fault Cycles | Approx Current Init Fault Amperes | Reest. Voltage KV |
|---|---|---|---|---|---|---|---|---|---|
| 1 | 16 | No | 10 | Yes | ϕ | ϕ | 4-7 | 200-2000 | 132 |
| 2 | 14 | No | 16 | Yes | 0-5 | Wind | 8 | 1500 | 132 |
| 3 | 3 | No | 16* | Yes | 5-10 | Wind | 8 | 1500 | 132 |
| 4 | 16 | No | 18* | Yes | 0-5 | Wind | 8 | 1000 | 136† |
| 5 | 17 | No | 12 | Yes | 20-30 | Lee | 8 | 6000 | 80 |
| 6 | 8 | No | 12 | Yes | 10-15 | Lee | 8 | 6000 | 80 |
| 7 | 17 | No | 12 | No | 10-15 | Lee | 8 | 6000 | 80 |
| 8 | 1 | No | 9 | No | 10-15 | Wind | 8 | 6000 | 80 |
| 9 | 3 | No | 9 | No | 5-10 | Lee | 8 | 6000 | 80 |
| 10 | 1 | No | 9 | No | 5-10 | Wind | 8 | 6000 | 80 |
| 11 | 9 | No | 12 | Yes | 0-5 | Lee | 8 | 6000 | 80 |
| 12 | 17 | No | 12 | No | 0-5 | Lee | 8 | 6000 | 80 |
| 13 | 12 | No | 9 | Yes | 0-5 | Lee | 8 | 6000 | 80 |
| 14 | 2 | No | 9 | No | 0-5 | Lee | 8 | 6000 | 80 |
| 15 | 1 | No | 9 | No | 0-5 | Wind | 8 | 6000 | 80 |
| 16 | 12 | No | 12 | Yes | 0-5 | Lee | 30 | 6000 | 80 |
| 17 | 18 | No | 12 | Yes | 0-5 | Lee | 2 | 6000 | 80 |
| 18 | 14 | Yes | 12 | No | 0-5 | Wind | 8 | 6000 | 80 |
| 19 | 21 | No | 12 | Yes | 20-30 | Lee | 8 | 800 | 80 |
| 20 | 10 | No | 12 | No | 10-15 | Lee | 8 | 800 | 80 |
| 21 | 4 | No | 9 | Yes | 10-15 | Lee | 8 | 800 | 80 |
| 22 | 13 | No | 12 | No | 10-15 | Wind | 8 | 800 | 80 |
| 23 | 7 | No | 12 | No | 5-10 | Lee | 8 | 800 | 80 |
| 24 | 10 | No | 12 | No | 5-10 | Wind | 8 | 800 | 80 |
| 25 | 10 | No | 12 | Yes | 0-5 | Lee | 8 | 800 | 80 |
| 26 | 6 | No | 12 | No | 0-5 | Lee | 8 | 800 | 80 |
| 27 | 20 | No | 9 | Yes | 0-5 | Lee | 8 | 800 | 80 |
| 28 | 21 | No | 9 | No | 0-5 | Lee | 8 | 800 | 80 |
| 29 | 5 | No | 12 | No | 0-5 | Wind | 8 | 800 | 80 |
| 30 | 6 | No | 12 | Yes | 0-5 | Lee | 2 | 800 | 80 |
| 31 | 15 | Yes | 12 | No | 0-5 | Lee | 8 | 800 | 80 |
| 32 | 16 | No | 4 | No | 10-15 | Wind | 8 | 6000 | 20 |
| 33 | 27 | No | 4 | No | 0-5 | Wind | 8 | 800 | 20 |

**Fig. 7. Chart of laboratory reclosing tests on insulator string for tendency to restrike versus de-energized interval**

Crosses indicate arc re-establishment; circles indicate no arc re-establishment

* Insulator string suspended horizontally

† Supplied by 2 transformers at 120 degrees, each supplying 80 kv, common point grounded

§ Wind velocity not recorded; believed to be about 15 miles per hour

Position of fuse wire changed from test to test

**Table II—Summary of Field Tests on 132-Kv Ultrahigh-Speed Reclosing Oil Circuit Breakers, Fort Wayne-Deer Creek Line, May 17 and June 14, 1936**

| Test Number | Date | Time* | Type of Fault | Line Dead Time, Cycles | Fault Arc Restruck | Primary Amperes | Relay Time | Breaker Clearing Time | Breaker Reclosing Time | Total Time | Breaker to Interrupt | Breaker to Reclose | Breaker Retripped | Remarks |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | **Deer Creek** | | | | | | | | |
| | | | | | | **Time, Cycles** | | | | **Travel, Inches** | | | | |
| 1 | 6/14/36 | 8:34 | $\phi$1 to Grd. | 11.8 | No | 275 | 1.00 | 7.2 | 19.0 | 20.0 | 6.25 | 9.25 | No | |
| 2 | 6/14/36 | 8:54 | $\phi$1 to Grd. | 12.0 | No | 270 | 0.96 | 6.55 | 18.55 | 19.5 | 6.25 | 9.25 | No | |
| 3 | 6/14/36 | 9:07 | $\phi$1 to Grd. | 12.0 | No | 270 | 0.95 | 6.35 | 18.35 | 19.3 | 6.25 | 9.25 | No | |
| 4 | 5/17/36 | 9:40 | $\phi$1 to Grd. | 10.7 | No | 300 | 1.00 | 5.3 | 16.0 | 17.0 | 5.0 | 7.0 | No | |
| 5 | 5/17/36 | 2:36 | $\phi$1 to $\phi$3 | 14.1 | No | 740 | 0.90 | 6.8 | 20.9 | 21.8 | 6.0 | 8.0 | No | |
| 6 | 6/14/36 | 12:10 | $\phi$1 to $\phi$3 | 13.9 | Yes | 750 | 0.70 | 6.4 | 20.3 | 21.0 | 6.25 | 10.5 | Yes | |
| 7 | 6/14/36 | 11:30 | $\phi$1 to $\phi$3 | 11.5 | Yes | 750 | 0.70 | 5.4 | 18.6 | 19.3 | 5.25 | 10.0 | Yes | |
| 8 | 6/14/36 | 2:10 | $\phi$1 to $\phi$3 to Grd. | 13.3 | No | 750 | 0.90 | 6.4 | 19.7 | 20.6 | 6.25 | 10.5 | No | |
| 9 | 5/17/36 | 1:33 | $\phi$1 to Grd. | 7.4 | No | 290 | 0.70 | 5.3 | 15.9 | 16.6 | 4.5 | 7.0 | No | |
| 10 | 5/17/36 | 6:30 | $\phi$1 to Grd. | 6.2 | No | 300 | 0.90 | 6.1 | 15.8 | 16.7 | 4.5 | 8.0 | No | |
| 11 | 5/17/36 | 6:40 | $\phi$1 to Grd. | 5.5 | No | 290 | 0.85 | 6.15 | 16.05 | 16.9 | 5.0 | 7.0 | No | |
| 12 | 5/17/36 | 7:09 | $\phi$1 to Grd. | 5.5 | Yes | 270 | 1.00 | 5.3 | 15.5 | 16.5 | 4.5 | 7.0 | Yes | |
| 13 | 5/17/36 | 6:57 | $\phi$1 to Grd. | 3.6 | Yes | 280 | 0.90 | 5.8 | 14.9 | 15.8 | 4.5 | 7.0 | Yes | |
| 14 | 6/14/36 | 10:31 | $\phi$1 to Grd. | 10.2 | No | 250 | 1.05 | 8.35 | 18.55 | 19.6 | 7.0 | 9.25 | No | |
| 15 | 6/14/36 | 10:44 | $\phi$1 to Grd. | 11.5 | No | 230 | 1.20 | 6.9 | 18.4 | 19.6 | 6.25 | 9.25 | No | |
| 16 | 6/14/36 | 12:24 | $\phi$1 to Grd. | 11.6 | No | 230 | 1.10 | 6.9 | 18.5 | 19.6 | 6.25 | 9.25 | No | |
| 17 | 6/14/36 | 5:31 | $\phi$1 to Grd. | 11.7 | No | 210 | 0.70 | 7.2 | 18.9 | 19.6 | 7.0 | 9.25 | No | |
| 18 | 6/14/36 | 4:10 | $\phi$1 to Grd. | 11.8 | No | 250 | 1.33 | 6.3 | 18.1 | 19.4 | 6.25 | 9.25 | No | |
| 19 | 6/14/36 | 4:50 | $\phi$1 to Grd. | 11.4 | No | 250 | 0.70 | 6.9 | 18.3 | 19.0 | 6.25 | 9.25 | No | |
| 20 | 6/14/36 | 5:08 | $\phi$1 to Grd. | 12.5 | No | 290 | 0.70 | 6.3 | 18.8 | 19.5 | 6.25 | 9.25 | No | |
| | | | | | | **Fort Wayne** | | | | | | | | |
| | | | | | | **Time, Cycles** | | | | **Travel, Inches** | | | | |
| 1 | 6/14/36 | 8:34 | $\phi$1 to Grd. | 11.8 | No | 690 | 0.90 | 5.4 | 20.9 | 21.8 | 5.75 | 11.5 | No | |
| 2 | 6/14/36 | 8:54 | $\phi$1 to Grd. | 12.0 | No | 745 | 0.90 | 5.1 | 20.2 | 21.1 | 4.75 | 10.0 | No | |
| 3 | 6/14/36 | 9:07 | $\phi$1 to Grd. | 12.0 | No | 745 | 0.70 | 5.2 | 20.8 | 21.5 | 4.75 | 10.0 | No | |
| 4 | 5/17/36 | 9:40 | $\phi$1 to Grd. | 10.7 | No | 800 | 0.80 | 4.8 | 20.2 | 21.0 | 6.0 | 11.5 | No | |
| 5 | 5/17/36 | 2:36 | $\phi$1 to $\phi$3 | 14.1 | No | 510 | 0.80 | 5.0 | 21.3 | 22.1 | 6.0 | 13.0 | No | |
| 6 | 6/14/36 | 12:10 | $\phi$1 to $\phi$3 | 13.9 | Yes | 520 | 0.70 | 5.45 | 22.5 | 23.2 | 5.75 | 11.5 | Yes | |
| 7 | 6/14/36 | 11:30 | $\phi$1 to $\phi$3 | 11.5 | Yes | 520 | 0.70 | 7.45 | 23.5 | 24.2 | 5.75 | 11.5 | Yes | |
| 8 | 6/14/36 | 2:10 | $\phi$1 to $\phi$3 to Grd. | 13.3 | No | 760 | 0.90 | 5.0 | 21.2 | 22.1 | 5.75 | 12.75 | No | |
| 9 | 5/17/36 | 1:33 | $\phi$1 to Grd. | 7.4 | No | 880 | 0.75 | 8.75 | 23.75 | 24.5 | 6.0 | 13.0 | No | |
| 10 | 5/17/36 | 6:30 | $\phi$1 to Grd. | 6.2 | No | 980 | 0.70 | 9.9 | 24.8 | 25.5 | 6.0 | 11.5 | No | |
| 11 | 5/17/36 | 6:40 | $\phi$1 to Grd. | 5.5 | No | 890 | 0.70 | 10.3 | 25.8 | 26.5 | 6.0 | 11.5 | No | |
| 12 | 5/17/36 | 7:09 | $\phi$1 to Grd. | 5.5 | Yes | 840 | 0.70 | 9.9 | 25.5 | 26.2 | 6.0 | 11.0 | Yes | |
| 13 | 5/17/36 | 6:57 | $\phi$1 to Grd. | 3.6 | Yes | 840 | 0.70 | 11.0 | 27.2 | 27.9 | 6.0 | 10.0 | No | |
| 14 | 6/14/36 | 10:31 | $\phi$1 to Grd. | 10.2 | No | 625 | 0.70 | 5.5 | 21.6 | 22.3 | 5.75 | 11.5 | No | |
| 15 | 6/14/36 | 10:44 | $\phi$1 to Grd. | 11.5 | No | 830 | 1.00 | 6.0 | 21.2 | 22.2 | 5.75 | 12.75 | No | |
| 16 | 6/14/36 | 12:24 | $\phi$1 to Grd. | 11.6 | No | 750 | 1.00 | 6.8 | 21.3 | 22.3 | 5.75 | 12.75 | No | |
| 17 | 6/14/36 | 5:31 | $\phi$1 to Grd. | 11.7 | No | 850 | 1.00 | 6.7 | 20.6 | 21.6 | 7.25 | 11.5 | Yes | |
| 18 | 6/14/36 | 4:10 | $\phi$1 to Grd. | 11.8 | No | 1,060 | 1.00 | 5.3 | 20.1 | 21.1 | 5.75 | 10.0 | No | |
| 19 | 6/14/36 | 4:50 | $\phi$1 to Grd. | 11.4 | No | 1,110 | 1.00 | 5.8 | 20.0 | 21.0 | 5.75 | 11.5 | No | |
| 20 | 6/14/36 | 5:08 | $\phi$1 to Grd. | 12.5 | No | 1,060 | 1.00 | 6.1 | 19.9 | 20.9 | 5.75 | 10.0 | No | |

| | |
|---|---|
| 1 | Tripping delayed 3 cycles at Deer Creek |
| 2 | Tripping delayed 4 cycles at Deer Creek |
| 3 | Tripping delayed 5 cycles at Deer Creek |
| 4 | Tripping delayed 5 cycles at Deer Creek |
| 5 | Tripping delayed 6 cycles at Deer Creek |
| 6 | Systems out of parallel; 9,000 kw over line |
| 7 | Systems out of parallel; 28,000 kw over line |
| 8 | Systems out of parallel; 28,000 kw over line |
| 9 | Systems out of parallel; 40,000 kw over line |
| 10 | Systems out of parallel; 0 kw over line |
| 11 | Systems out of parallel; 9,000 kw over line |
| 12 | Systems out of parallel; 10,000 kw over line |

* Light face indicates time a.m.; bold face indicates time p.m.

In test 8 an internal phase-to-phase-to-ground fault was applied. Here the line was de-energized for 13.3 cycles and the line was re-energized without the arc restriking.

Tests 9 to 13 were made to determine the minimum time that the line could be de-energized on an internal phase-to-ground fault without the arc restriking upon energization of the line. This was accomplished by intentionally delaying the tripping time of the breaker at Deer Creek station by inserting a time-delay auxiliary relay in the trip circuit. It may be noted that the minimum time the line had to be de-energized averaged approximately 6.0 cycles in order to prevent the arc restriking. In test 13, voltage was reapplied a second time when the breaker at Deer Creek station finally reclosed. The dead time in the second interval was only 2.0 cycles.

Tests 14 to 20 were made to determine the performance of the reclosing equipments on a single tie line between 2 systems (not otherwise connected in parallel) with varying amounts of load transfer over the tie line. The system arrangement used on these tests represented a single 132-kv tie line approximately 340 miles long between the 2 generating stations.

With load transfers up to 28,000 kw over the tie line, the breakers and relays performed satisfactorily to hold the 2 systems in synchronism upon reclosure. With load transfer up to 40,000 kw over the tie line, the breakers reclosed satisfactorily at both terminals of the tie line but the operation of the relays retripped the breakers. Figure 6 shows 3 oscillograms taken at Fort Wayne station for tests 4, 7, and 15, respectively. The top oscillogram is for test 4 from which it will be noted that the directional relay contacts opened after 0.50 cycle, that blocking was removed in 0.60 cycle, and trip circuit energized in 1.0 cycle after the inception of the short circuit. Fault current was 300 amperes, primary current, and was interrupted in a total time of 6.3 cycles. The breaker contacts reclosed in 17 cycles, total time, or 16 cycles after the trip circuit was energized, as indicated by the oscillations in the current element. The point where the breaker contacts reclose can also be determined from the top oscillograph element which is attached to a travel recorder and gives the mechanical position of the breaker contacts throughout the operation.

The middle oscillogram is for test 7, which was a phase-to-phase short circuit in which the arc restruck. The relay operating time was somewhat faster in this case, the directional-relay contacts opening in 0.4 cycle, blocking being removed in 0.5 cycle, and the

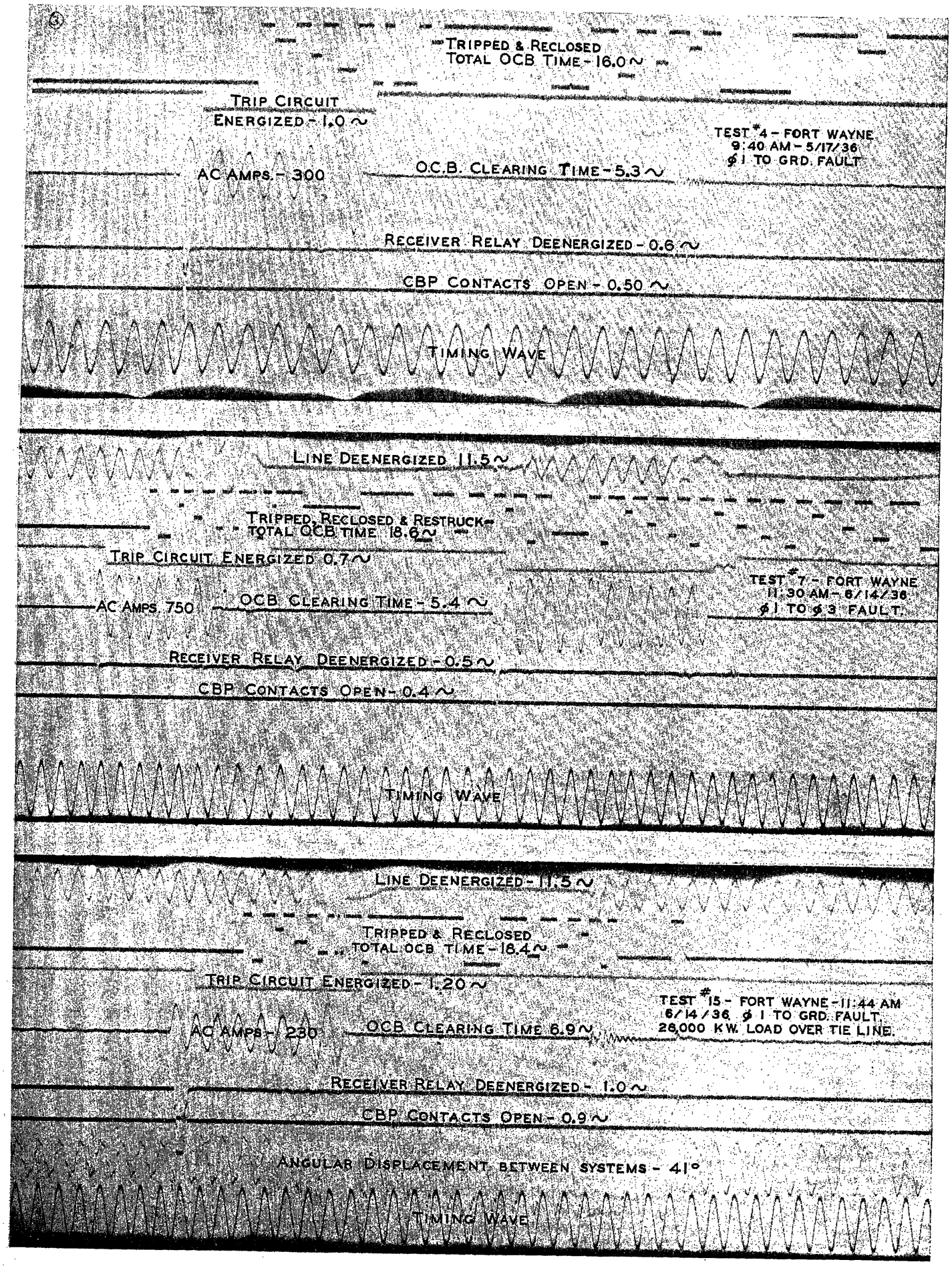



**Fig. 8. Oscillograms of field tests**

trip circuit energized in 0.7 cycle. Fault current was 750 primary amperes and was finally interrupted in a total time of 7.7 cycles. The breaker contacts reclosed in 19.3 cycles and this time the arc was re-established. In this case the top element of the oscillograph was connected to a potential transformer on the line and hence shows directly the total time the line was de-energized, which was 11.6 cycles.

The bottom oscillogram is for test 15. This was a single phase-to-ground fault with the systems out of parallel during the time the line was open. The relay operating time was 0.9 cycle for the directional relay contacts to open, 1.0 cycle for the blocking to cease, and 1.2 cycles before the trip circuit was finally energized. This slower relay time was probably due to the low fault current, which was only 230 primary amperes at the beginning of the fault. The fault current was interrupted in 8.1 cycles and the breaker reclosed 19.6 cycles after the fault began. The line was de-energized for 11.5 cycles. The angular displacement between the 2 systems was 41 degrees at the instant they reclosed. This was measured by connecting an element of the oscillograph so as to measure the vector difference between the voltages of phases one on the 2 systems. The oscillograph element measuring fault current measured ground current and hence does not show the original load current or the in-rush of current which occurred when the line was reclosed.

## Field Experience

Since the installation of the ultrahigh-speed reclosing equipments on the Fort Wayne-Deer Creek line in May 1936, there have been 4 lightning flashovers on this line. In all 4 cases, the flashover occurred between phase 3 and ground. The average time that the line was de-energized was 13.0 cycles. In 3 cases the breakers at both ends of the line tripped and reclosed within a total time of 22.0 cycles without the arc restriking. In one case, the breakers failed to stay in after reclosing because the arc restruck, which is believed to have been caused by a multiple lightning stroke. Figure 9 shows an oscillogram taken at Deer Creek station for a flashover from phase 3 to ground caused by lightning that occurred at 8:59 a.m. on August 28, 1936. The fault current was 1,165 amperes, primary current, and was interrupted in total time of 6.0 cycles. The breaker contacts reclosed in 22.5 cycles total time or 21.5 cycles after the trip circuit was energized. The line was de-energized for a period of 12.5 cycles. From the elements measuring the 3 phase-to-phase bus voltages, it may be seen that the fault was a flashover from phase 3 to ground.

## Future Possible Applications

It is, of course, extremely difficult, nor is it well within the province of a paper of this sort, to predict the course a development of this type will take. Even more difficult is the problem of indicating with so little experience available the possible immediate application. One thing, however, is certain, on lines forming part of extensive transmission networks and particularly where loads of appreciable magnitude are carried, if lightning is at all a factor it ought to be found economically extremely attractive to equip the 2 ends of any lines of that sort with mechanisms of the type described to make possible ultra-rapid reclosing on any lightning outage. As a matter of fact, on the power system with which one of the authors is associated, 2 such lines in addition to the one described are now being so equipped.

The application of ultrahigh-speed reclosing, the authors believe, may eventually make possible in some instances a reduction in the investment in transmission lines now required to give uninterrupted service to large industrial loads. That is, the duplicate line may, with the further development of this idea, give way to the single line with the possibility of giving as good service with the single line as can be given with the multiple feeds now used.

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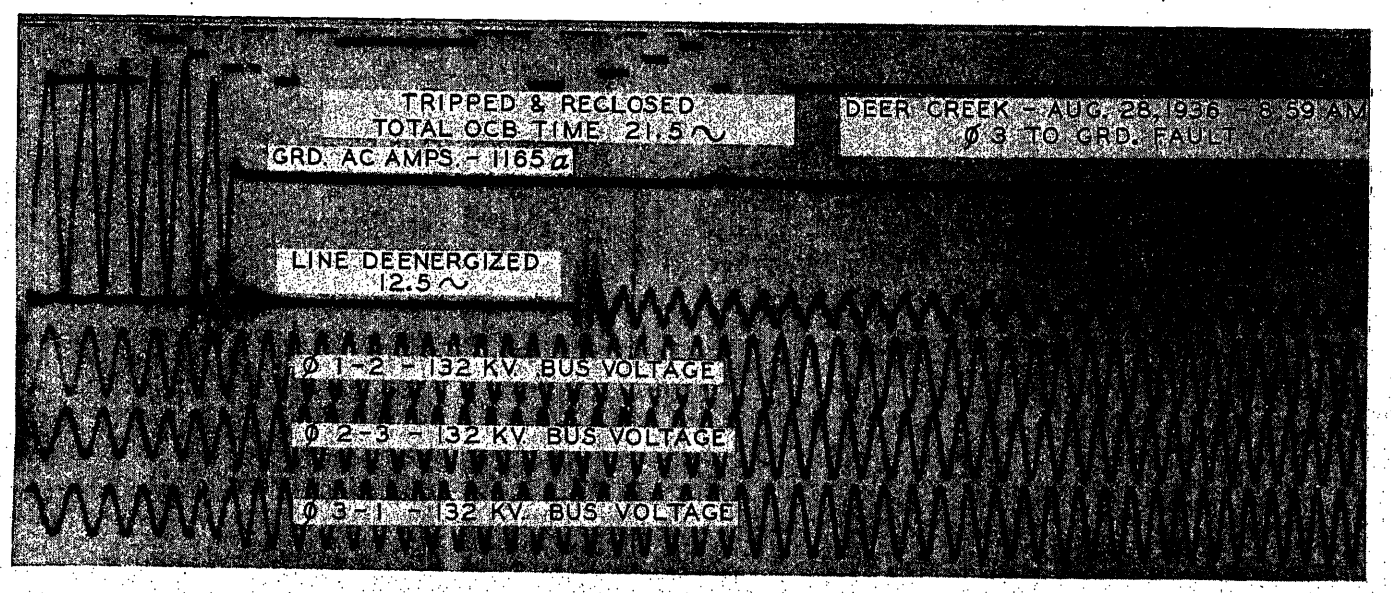



**Fig. 9. Oscillogram of operation resulting from lightning**

# Pole Flexibility as a Factor in Line Design

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**Poles are ordinarily considered as rigid struts in designing structures for supporting overhead lines, even in situations where they are not restrained by guys and it is known that movement takes place under variation in loading. This paper points out the importance of making allowance for this factor under certain conditions and gives the theory and practical methods for its solution.**

ALTHOUGH it is customary, in designing a structure for supporting overhead lines, to consider a pole as a rigid strut, there are situations where this assumption leads to considerable error. The processes whereby the flexibility of the supports can be taken into account are by no means obvious.

In certain cases, which are not at all infrequent in practice however, the neglect of this inherent characteristic of the materials will lead to unnecessary strength in some parts and insufficient strength in others. It is the purpose of this paper to point out some of these cases, to discuss methods by which this effect may be determined, and to indicate how these may be applied to the development of working rules and charts which can be applied to field problems with sufficient accuracy for practical purposes.

## Typical Cases in Which Flexibility Is of Importance

As a simple illustration of the effect of pole flexibility, consider a line dead-ended on a pole which, for some reason, cannot be guyed. A common practice in such a case would be to guy the next-to-last pole, either to an anchor or to the end pole itself, holding the greater part of the conductor tension on the guyed pole. The conductors in the end span are then slacked off to reduce the tension to an amount which will not exceed the allowable load on the unguyed pole under the heaviest condition of loading which is anticipated (see figure 1). If it is assumed that the total dead-end tension of the conductors must be held by the guy on pole $A$, that guy will be made unnecessarily strong, since part of this load is balanced by the tension of the conductors in the end span. If, on the contrary, the end pole $B$ is considered rigid, and full allowance is made for the guying effect of the conductors in the slack span on this basis, the load assigned to the guy will be too small. This is evident when the actual effect of the flexing of the pole $B$ is considered. As the load on the wires (wind and ice) increases, the tension in the end span would tend to increase. This increase in tension applied to pole $B$ will cause it to deflect toward pole $A$. This, in turn, will increase the sag in the conductors, tending to reduce their tension. Equilibrium is reached when, under the assumed loading conditions, the sag in the conductors is just sufficient to produce a tension which will deflect the pole an amount necessary to produce that sag. The tension in these conductors will naturally be less than it would be if pole $B$ were rigid, hence the load actually held by the guy must be more than would be indicated by a calculation based on the assumption of rigidity. However, the strength necessary in pole $B$ will be appreciably less than would be required if no deflection occurred.

Figure 2 shows a dead-end pole guyed to an unguyed stub, with a guy on the pole ahead. Here the deflection of both pole $A$ and the stub, acting together, affects the conductor tension in the end span and allowance must be made for it if the sizes of pole $B$, the stub, and the 2 guys are to be accurately determined. Such a situation is frequently encountered in alleys in Detroit, wherein the stub is a telephone pole subject to joint use. Consideration of flexibility allows an appreciably smaller class of pole to be used for the stub than would be required under the usual assumption of rigidity.

Figure 3 shows a short run between 2 dead-end poles. Considering flexibility, it may be feasible to leave both poles unguyed, if guying is difficult. Figure 4 shows an unguyed angle in the line with the adjacent poles guyed. Here the effect of deflection is somewhat different due to the angle, but it can sometimes be used to advantage in determining the size of the corner pole and the guys. Figure 5 shows a street lamp supported on a span wire. Allowance for the reduction in stress resulting from pole flexibility may make guying unnecessary.

There are other similar situations wherein the allowance for flexibility will serve to give a better and more economical design, but these are typical and will serve to illustrate the problem.

## General Method of Solution

The general method of attacking the problem of making proper allowance for pole flexibility may be indicated by reference to the simple case shown in figure 1. The movement of the pole under a varying applied force, such as the tension in the wires, may be plotted in the form of line $B$ in figure 6. The relation between the tension in the wires and the span length or the change in span length (that is, the pole

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movement) may also be plotted in the form of curve $A$ in figure 6. The point at which these curves intersect gives the solution at which equilibrium is reached, that is, the tension which is just sufficient to move the pole an amount which will sag the wire

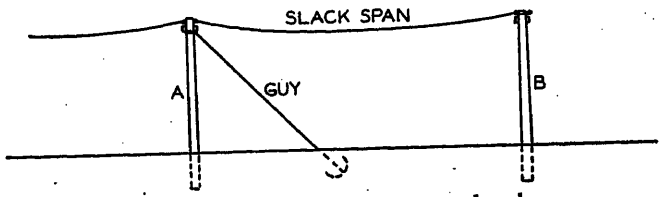



Fig. 1. Dead end on unguyed pole

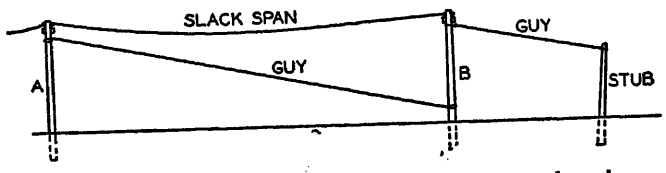



Fig. 2. Dead-end pole guyed to unguyed stub

sufficiently to produce that tension. This is the basis of the methods followed in this study.

Two methods will be described. The first is an elaboration of the general solution by the plotting of the 2 curves just discussed. This is accurate within the limits of accuracy of the methods used in determining tension-span relations but is somewhat cumbersome for general application to a variety of problems. The second method, which is more convenient to use, introduces several approximations, the errors involved being relatively insignificant, however.

## Exact Solution

*Pole Characteristic.* The derivation of the curves shown on figure 6 requires some explanation. In order to plot curve $B$, the relation between the flexure in a pole and the applied force must be determined. The theory for calculating this characteristic for any given pole is shown in the appendix. A "deflection constant" is derived which gives the number of pounds of applied horizontal load per foot of deflection, the butt being held fixed. It is recognized that in some cases there may be a movement of the pole in the ground which will add to the effect of its flexure. Allowance can be made for this in choosing the deflection constant if its magnitude is known. Since this quantity is indeterminate, however, and the data which are available are meager, and also since it is practicable to support the pole by blocking or concreting against any considerable foundation movement under the loads considered, the effect of such movement has been ignored in this paper. This relationship is assumed to be reasonably constant throughout an ordinary range of loading, within the elastic limit, hence the stress-strain curve (and curve $B$ of figure 6) is a straight line. The slope of the line is equal to the deflection constant $p$. For the condition illustrated, where the horizontal scale is in terms of movement from the position of initial loading, the intercept with the vertical axis (load for 0 movement) is $T_1$, which is the applied load or the tension in the wires under the assumed initial loading conditions. The intercept with the horizontal axis (pole position at zero load) is at a negative value equal to the deflection of the pole under initial conditions. The scale may be arranged to show total pole movement from the unloaded condition, if desired, in which case the intercept with the horizontal axis will be the zero point.

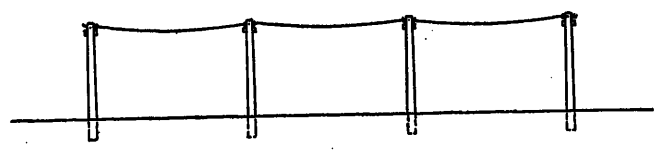


Fig. 3. Short line with neither end guyed

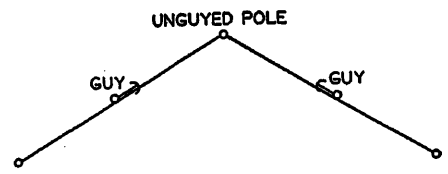



Fig. 4. Plan of angle with corner pole unguyed

*Wire Characteristic.* The $A$ curve may be derived by any of the well-known methods of determining sag-tension relations in a wire span. The Thomas chart has been found convenient for ordinary spans with copper wire. If composite conductors such as *ACSR* (aluminum-cable steel-reinforced) are used, or if greater accuracy is desired with copper, some of the more refined methods using stress-strain curves obtained by test may be necessary. The Thomas chart method will be described in the following.

It may be remembered that the Thomas chart uses a curve showing the relationship between tension and length of wire in the span. Specifically, the co-ordinates are a "stress factor" $(T/wS)$ equal to

$$\frac{\text{tension}}{\text{load per foot span} \times \text{span}}$$

and length of wire per foot span, $(L/S) = l$, as shown in figure 7. For a given span $S$, an initial loading $w_1$ per foot, and an initial sag, the initial value of $T_1/(w_1S)$ is calculated and the value of $l_1$ found from the chart. From this, a quantity $l_0$, the "unstressed length," is derived by subtracting from $l_1$ the elongation resulting from the tension in the wire

$$l_0 = \frac{l_1}{1 + \frac{T_1}{AE}}$$

where $A$ is the cross-sectional area of the wire and $E$ the modulus of elasticity. The line $l_0r_1$ plotted on the chart, figure 7, is the stress-stretch line of the

wire for loading $w_1$. For a change in load to $w_2$, a new stress-stretch line similar to $l_0r$ is plotted between $l_0$ and a point $r'$ whose co-ordinates are $T_1/(w_1S)$ and $l_0 + (w_2/w_1)\ (l_1 - l_0)$. The intersection of $l_0r'$ with the curve at $r_2$ gives the new value of $T_2/(w_2S)$ and hence of $T_2$.

For a change in temperature, the unstressed length $l_0$ changes to a new length $l_0' = l_0(1 + \alpha t)$, where $\alpha$ is the coefficient of expansion and $t$ the change in temperature, using the proper sign for $t$. The new stress-stretch line for load $w_1$ at the new temperature (not shown on figure 7) is parallel to $l_0r_1$; the new stress-stretch line for $w_2$ is parallel to $l_0r_2$.

Determination of the effect of a change in span as the result of pole movement is quite similar to that for temperature change. The actual unstressed length of the wire remains the same, but, since the span changes, $L_0/S$ (and hence $l_0$) will change. If the pole should move so that the span will be shortened

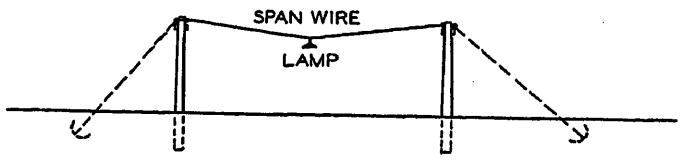



**Fig. 5. Street-lamp suspension with customary guys shown**

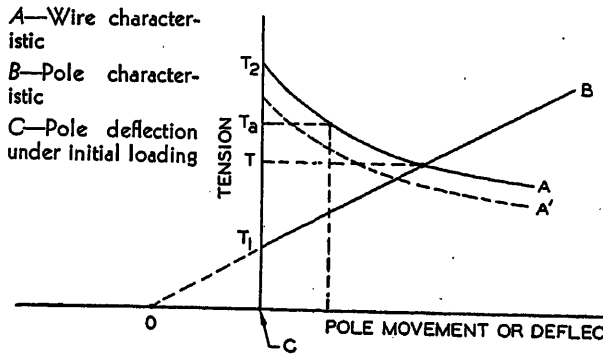



**Fig. 6. Construction of graphic solution for flexible span**

one per cent, $l_0 = L_0/S$ changes to $l_0'' = L_0/0.99S = l_0/0.99$. The stress-stretch line through this new point $l_0''$ for the new span will be parallel to the one through $l_0$ for the same loading, since the slope of this line is

$$\frac{T}{wS} \div \frac{L - L_0}{S} = \frac{T}{w(L - L_0)}$$

which is independent of span length. On figure 7, $l_0''r_a$ is parallel to $l_0r_2$, for loading $w_2$, and its intersection with the curve at $r_a$ gives the solution for $T_a/(w_2S_a)$ and hence $T_a$ for the reduced span.

This is the basis for plotting curve $A$ of figure 6. For example, if initial conditions $w_1$, $S_1$, and sag are given, $T_1$ and $l_0$ may be determined. The pole is initially deflected by $T_1$ an amount $T_1/p$. If the pole were held fixed at that point, $T_2$ for a new loading, $w_2$, would be found by figure 7. This $T_2$ will give the intercept of the curve $A$ (figure 6) with the vertical axis, since it is the tension in the wire for zero movement. Assume a certain reduction in span such as one foot or one per cent, and find the corresponding $T_a$ as herein described. Plot this as a second point on the $A$ curve. Assume other possible pole movements and find the corresponding values of $T_a$, locating other points on the $A$ curve until it is completely plotted. The intersection of this $A$ curve with the $B$ line is the solution for the loading $w_2$. For other loadings, such as $w_3$, another $A$ curve such as $A'$ in figure 6 can be similarly derived and the solution obtained. It should be remembered that the load applied to the pole is the total of all the wires carried, hence the $A$ curve must represent the sum of all the wire tensions. Where different sizes are present, separate curves may be plotted and totaled into one combined $A$ curve. The error is usually not great, however, if the combined curve is obtained by using the total cross-sectional area, loading, and tensions of all wires.

This method, although relatively accurate and not difficult for a specific problem, is somewhat cumbersome for general use, where various wire sizes, spans, and loadings are being considered. The second method to be described is sufficiently accurate for most purposes and is more easily handled for a variety of problems. This method and the resulting charts will also be found useful in solving spans with rigid supports as well as those with flexible supports.*

## Approximate Method

For this solution the parabolic formulas for wire-span relationship are used instead of the catenary

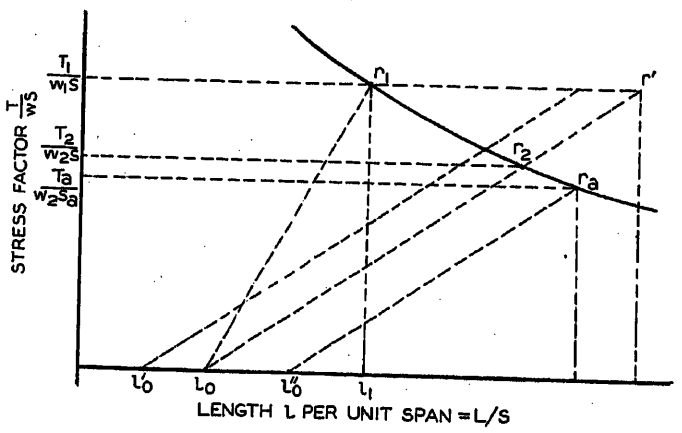



**Fig. 7. Thomas chart**

as being more convenient and not introducing serious error. For any wire hanging in a span, the following relationships exist:

$$\text{Length of wire} = L = S + \frac{8D^2}{3S} \qquad (1)$$

* Originality is not claimed for this method of solving spans with rigid supports since the principles are referred to in several previous publications, both in this country and abroad. See "Sag Problems Readily Solved by Aid of Alignment Chart," by D. C. Stewart, *Electrical World*, volume 96, September 20, 1930, page 518, and others. The detailed application here is somewhat different, however, and the development for flexible supports is believed to be new.

$$\text{Tension in wire} = T = \frac{wS^2}{8D} \qquad (2)$$

Where

$S$ = span in feet
$D$ = sag or deflection in feet
$w$ = load in pounds per foot

*Rigid Supports.* For the ordinary case of rigid supports, the span length is fixed, hence the relationship of equation 1 is between 2 variables, length of wire and deflection, the latter also being dependent upon loading and tension in accordance with equation 2. On account of its elastic characteristic, the length of wire varies with the tension; it also varies with the temperature. The unstressed length of the wire at a given temperature, that is, its length if removed from the span and laid on the ground is a fixed quantity, however, and can be used as a reference in determining the effect of various changes in conditions. The unstressed length can be obtained from equation 1 by subtracting from $L$ the elongation caused by the tension obtained from equation 2.

$$L = L_0\left(1 + \frac{T}{AE}\right) \qquad L_0 = \frac{L}{1 + \frac{T}{AE}}$$

For the present purpose it is somewhat more convenient to change this to a form which is approximately as correct:

$$L_0 = L\left(1 - \frac{T}{AE}\right)$$

Substituting equations 1 and 2, respectively,

$$L_0 = \left(S + \frac{8D^2}{3S}\right)\left(1 - \frac{T}{AE}\right)$$

$$L_0 = \left(S + \frac{8D^2}{3S}\right)\left(1 - \frac{wS^2}{8DAE}\right) \qquad (3)$$

Equation 3 is a general expression for the unstressed length of the wire for any given loading, sag, and temperature. The value remains the same for any other loading which may be imposed on the wire, provided the temperature does not change. Hence its value, determined for an initial loading $w_1$, may be used to find sags and tensions for other loadings such as $w_2$.

$$L_0 = \left(S + \frac{8D_1^2}{3S}\right)\left(1 - \frac{w_1S^2}{8D_1AE}\right) = \left(S + \frac{8D_2^2}{3S}\right)\left(1 - \frac{w_2S^2}{8D_2AE}\right)$$

This expression can be solved for $D_2$ if $L_0$ is obtained from $w_1$ and $D_1$.

If equation 3 is expanded, the expression becomes

$$L_0 = S + \frac{8D^2}{3S} - \frac{wS^3}{8DAE} - \frac{wSD}{3AE}$$

It will be found that the last term is of insignificant size compared with the others and may be dropped from the equation without appreciable error, leaving

$$L_0 = S + \frac{8D^2}{3S} - \frac{wS^3}{8DAE} \qquad (4)$$

For convenience equation 4 may be operated upon mathematically by subtracting the span length $S$ (a constant for any problem with rigid supports) from both members and also by dividing both members by $S$. The deflection per foot of span, $d = D/S$ is also introduced. This gives a quantity designated as $e$, which is the difference per unit span between unstressed length of wire and span length.

$$e = \frac{L_0 - S}{S} = \frac{8}{3}d^2 - \frac{1}{8d}\frac{wS}{AE} \qquad (5)$$

It is possible to plot a nomograph from this equation using as variables $e$, $d$, and $(wS)/(AE)$ as illustrated by figure 8. If the value of $(w_1S)/(AE)$ is computed for an initial loading $w_1$, a straight line from that point on the left-hand scale through the value of initial deflection $d_1$ on the middle scale

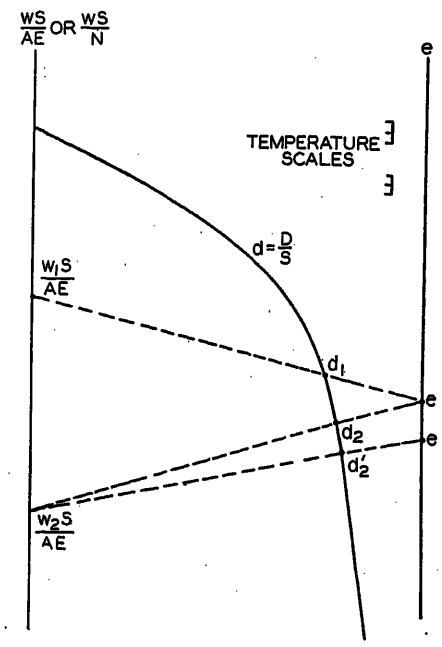



**Fig. 8. Nomographic method of solution for rigid or flexible span**

intersects the right-hand scale at the value of $e$. Since $e$ is constant (for a given temperature) another straight line from $e$ to the calculated value of $(w_2S)/(AE)$ for a new loading $w_2$ will give a new deflection $d_2$, from which the new tension can be computed from the formula

$$T = \frac{wS^2}{8D} = \frac{wS}{8d} \qquad (6)$$

A change in temperature changes the unstressed length, $L_0$, to some new value $L_0(1 + \alpha t)$ where

$\alpha$ = temperature coefficient of expansion
$t$ = change in temperature in degrees, positive for a rise, negative for a fall

If $L_0$ has been determined for given initial conditions including temperature $t_1$, $L_0'$ for some other temperature $t_2$ will be

$$L_0' = L_0[1 + \alpha(t_2 - t_1)] = L_0 + L_0\alpha t$$

Since the length $L_0$ is not greatly different from the span length $S$, no appreciable error is introduced if the last term is written $S\alpha t$.

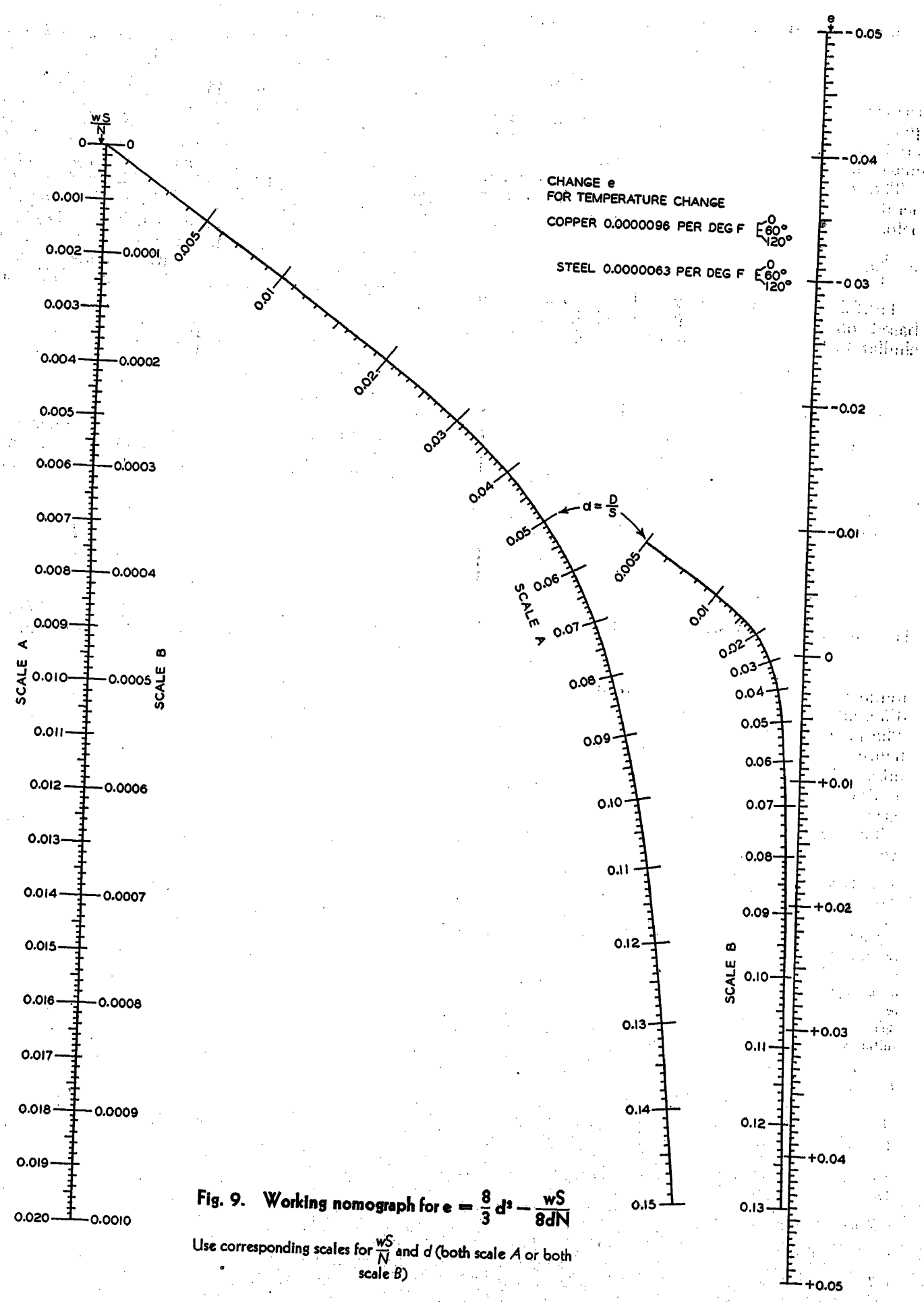



**Fig. 9. Working nomograph for $e = \frac{8}{3} d^2 - \frac{wS}{8dN}$**

Use corresponding scales for $\frac{wS}{N}$ and $d$ (both scale $A$ or both scale $B$)

Introducing this quantity into the equation for $e$,

$$e' = e + \alpha t \tag{7}$$

If $e$ has been determined from the chart as described, $e'$ can be found by adding or subtracting the quantity $\alpha t$. This may be done graphically, if desired, by using a small supplemental scale on the chart which shows $\alpha t$ for any value of $t$.

The value of $d_2'$ and hence $T_2'$ for the new temperature, $t_2$, can now be obtained from the chart as before, since the chart solves the equation

$$e' = \frac{8}{3}d_2^2 - \frac{1}{8d_2}\frac{w_2 S}{AE}$$

The following example is solved by a working chart based on the principles illustrated by figure 8, similar to that given in figure 9. It will usually be

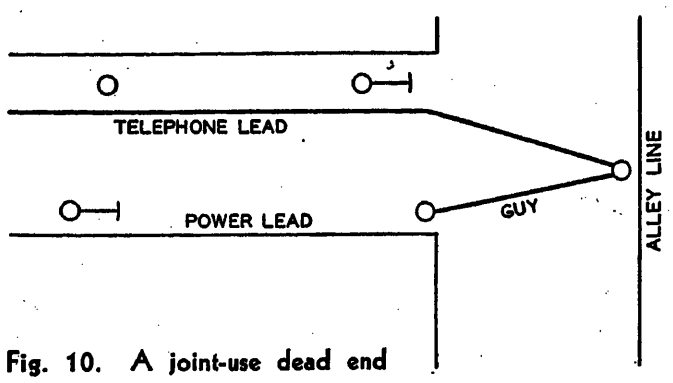



**Fig. 10. A joint-use dead end**

found convenient to plot several of these charts to different scales to cover different ranges of values. The present example can be solved by the chart of figure 9 with fair accuracy but since the latter was intended for the flexible span problems which follow, another chart with a smaller range was actually used.

This example is for 3 number 0 triple-braid weather-proof copper wires where

| | |
|---|---|
| Initial loading $w_1$ | = 0.424 pounds per foot |
| Heavy loading $w_2$ | = 1.55 pounds per foot |
| $AE$ | = 1,160,000 per conductor |
| Initial temperature $t_1$ | = 60 degrees Fahrenheit |
| Loaded temperature $t_2$ | = 0 degrees Fahrenheit |
| $t$ | = −60 |
| $\alpha$ for copper | = $9.6 \times 10^{-6}$ |
| $\alpha t$ | = $-5.76 \times 10^{-4}$ |
| Span | = 100 feet |
| Initial wire deflection $D_1$ | = 1.5 feet |

$$d_1 = \frac{D_1}{S} = 0.015$$

$$\frac{1}{AE} = 0.861 \times 10^{-6}$$

$$\frac{w_1 S}{AE} = 0.424 \times 100 \times 0.861 \times 10^{-6} = 36.5 \times 10^{-4}$$

$e_1$ (from chart) = 0.000298

$$e' = e_1 + \alpha t = 0.000298 - 0.000576 = -0.000278$$

$$\frac{w_2 S}{AE} = 1.55 \times 100 \times 0.861 \times 10^{-6} = 133.2 \times 10^{-4}$$

$d_2$ (from chart) = 0.0166

$T_2 = (w_2 S)/(8d_2) = 155/(8 \times 0.0166) =$ 1,165 pounds per wire or 3,495 pounds for 3 wires

*Flexible Span.* If the support is not fixed, but can move as the wire tension changes, the span becomes a variable in the equation instead of being a constant. Assuming the span fixed at one end, flexible at the other, with a pole deflection constant of $p$, for any tension $T$ the pole will move $T/p$ and hence the span will be shortened that amount. If the initial span is $S$, the span for any wire tension $T$ will be $S - (T/p)$.

Referring to equations 4, 5, and 7, the unstressed length $L_0$ under any such conditions would be obtained by use of the actual span length $S - (T/p)$ in the form

$$L_0 = S - \frac{T}{p} + \frac{8D^2}{3\left(S - \frac{T}{p}\right)} - \frac{w\left(S - \frac{T}{p}\right)^3}{8DAE}$$

The quantity $e$ is defined as the difference per unit of *original* span $S$, between unstressed length of wire and *original span*, since the original span is a constant.

$$e = \frac{L_0 - S}{S} = -\frac{T}{pS} + \frac{8D^2}{3S\left(S - \frac{T}{p}\right)} - \frac{w\left(S - \frac{T}{p}\right)^3}{8DAES}$$

No appreciable error is introduced if $(S - T/p)$ is changed to $S$ in the last 2 terms, giving the simpler form

$$e = \frac{8}{3}d^2 - \frac{wS}{8dAE} - \frac{T}{pS}$$

but, since $T = (wS)/(8d)$,

$$e = \frac{8}{3}d^2 - \frac{wS}{8d}\left(\frac{1}{AE} + \frac{1}{pS}\right) \tag{8}$$

It may be noticed that the expression in the last term $(1/AE + 1/pS)$ is a constant for a given problem. The equation can therefore be solved by the chart except that the scale for $wS/AE$ now becomes a scale for $wS/N$ where

$$\frac{1}{N} = \frac{1}{AE} + \frac{1}{pS}$$

$$e = \frac{8}{3}d^2 - \frac{1}{8d}\frac{wS}{N} \tag{9}$$

The problem is approached in exactly the same manner as previously described, going from an initial value of $(w_1 S)/N$ and $d_1$ to a value of $e$; adding the proper amount for temperature change to obtain $e'$; then solving for $d_2$ from $(w_2 S)/N$, and from $d_2'$ obtaining the final tension $T_2'$. In calculations involving more than one wire, of the same or different sizes, in the same span, the total cross-sectional area, total loading, and total tension should be used with this method as was indicated for the more accurate method previously described. If different sags are used for the different wires, a "weighted sag" can be obtained from the sum of the products

of sag and loading for each wire, divided by total loading.

The chart in figure 9 is a working chart for such problems. Taking as a typical example the same conditions used in the previous example, except for the rigidity of the pole, the solution is carried out as follows for 3 number 0 triple-braid weather-proof copper wires and 40-foot class 4 western-cedar pole:

Stringing load $w_1$ = $3 \times 0.424 = 1.272$ pounds per foot for 3 wires
Heavy loading $w_2$ = $3 \times 1.55 = 4.65$ pounds per foot for 3 wires
$AE$ = 1,160,000 per conductor
$\alpha t$ = $-60 \times 9.6 \times 10^{-6} = -5.76 \times 10^{-4}$
Deflection constant $p$ = 600 pounds per foot
Initial wire deflection $D_1$ = 1.5 feet

$$d_1 = \frac{1.5}{100} = 0.015$$

$$\frac{1}{N} = \frac{1}{AE} + \frac{1}{pS} = \frac{1}{3 \times 1{,}160{,}000} + \frac{1}{600 \times 100} = 16.954 \times 10^{-6}$$

$$\frac{w_1 S}{N} = 1.272 \times 100 \times 16.954 \times 10^{-6} = 0.00216$$

$$e = -0.0174$$

$$e' = e + \alpha t = -0.0174 - 0.000576 = -0.01798$$

$$\frac{w_2 S}{N} = 4.65 \times 100 \times 16.954 \times 10^{-6} = 0.00788$$

$$d_2 = 0.043$$

$$T_2 = \frac{w_2 S}{8 d_2} = \frac{465}{8 \times 0.043} = 1{,}350 \text{ pounds or } 450 \text{ pounds per wire}$$

It is apparent by comparing these results with those previously calculated for the rigid span that if the pole $B$ had been assumed rigid, its load would have been calculated as 3,495 pounds instead of 1,350 pounds. If the tension in the normal span to the left of pole $A$ (figure 1) were calculated at 2,000 pounds per wire, or 6,000 pounds total at full loading, the guy must actually assume 6,000 − 1,350 = 4,650 pounds instead of only 2,505 pounds which would result from a calculation with pole $B$ rigid. The improvement in design is evident.

## Special Conditions

In the early part of the paper a number of different cases were cited in which the effect of flexibility of supports was of importance. The application of the method of solution which has just been described to the conditions peculiar to some of these will be indicated.

*Both Poles Flexible.* The span is shortened by the flexure of both poles under the tension $T$, hence in computing $1/N$ both must be included

$$\frac{1}{N} = \frac{1}{AE} + \frac{1}{p_1 S} + \frac{1}{p_2 S}$$

where $p_1$ and $p_2$ are the deflection constants of the 2 poles.

*Two Flexible Poles at One End of a Span.* Where the dead end is made on a pole guyed to an unguyed

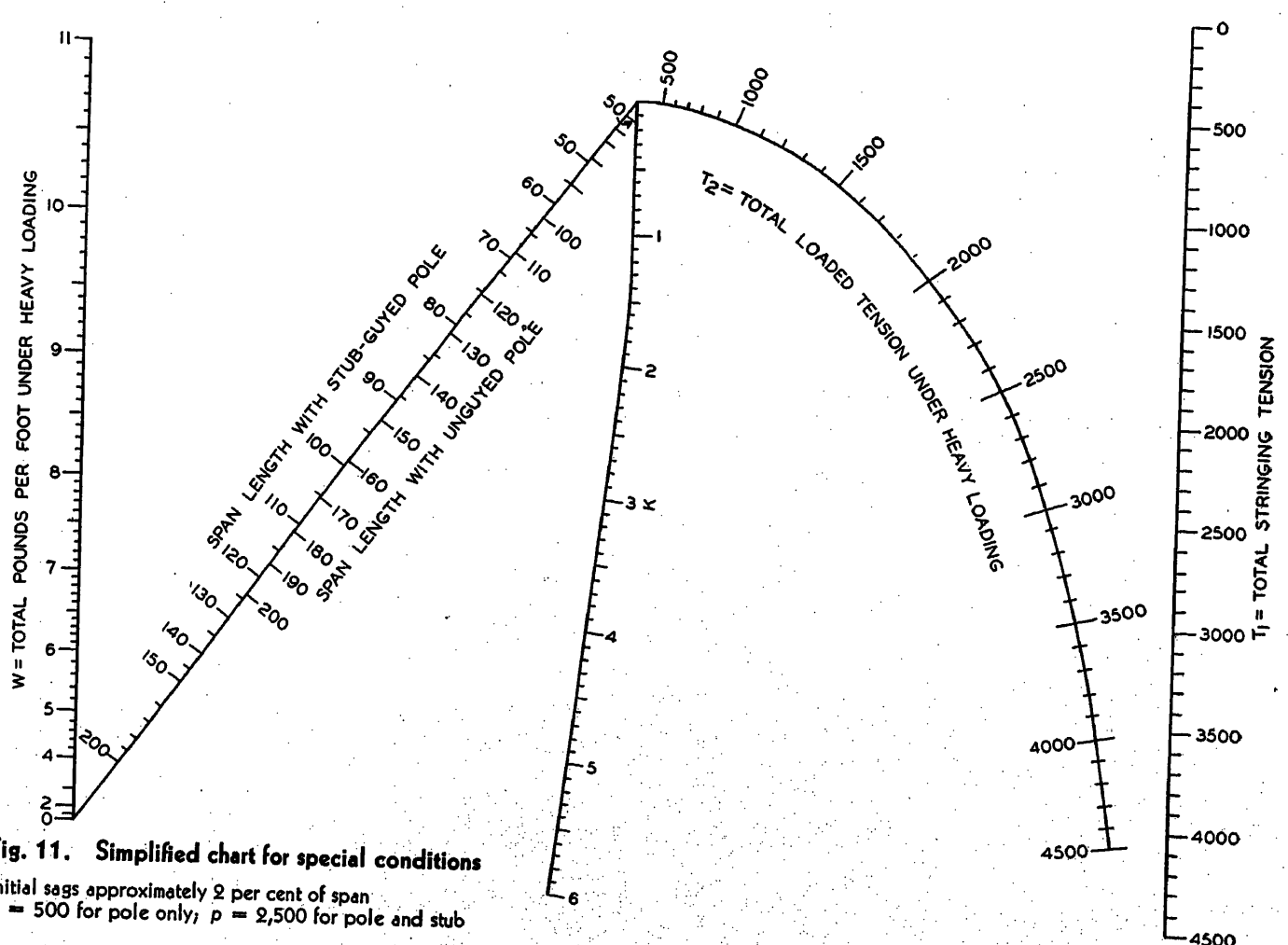



**Fig. 11. Simplified chart for special conditions**

Initial sags approximately 2 per cent of span
$p$ = 500 for pole only; $p$ = 2,500 for pole and stub

stub, both enter into the change in the span caused by flexure. In this case, if the guy is short and tight, the deflection constant of the 2 poles acting together is equal to the sum of their individual deflection constants.

$$\frac{1}{N} = \frac{1}{AE} + \frac{1}{(p_1 + p_2)S}$$

The load divides between pole and stub in proportion to their deflection constants.

*External Force.* Sometimes there will be forces other than the tension in the wire acting to bend the pole. An example of such a case would be a pole

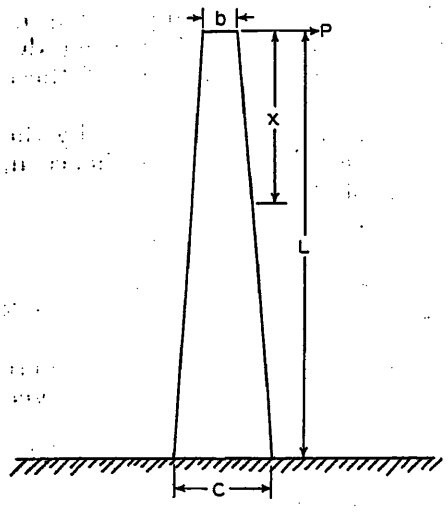



**Fig. 12. Representation of a pole as a cantilever beam**

carrying transverse wires which are acted upon by wind at the same time the wires in the span have ice loading only. If

$F$ = the force thus produced on the end pole

$\frac{F}{p}$ = the movement of the pole due to this force

$\frac{F}{pS}$ = the movement per unit of span

This quantity $F/(pS)$ is a change in the quantity $e$ given in the general equations. If $F$ tends to shorten the span, acting only when the loading $w_2$ is on the wire, $e_2$ will be greater than $e_1$ by an amount $F/(pS)$, since $e$ represents the difference between $L$ and $S$ for any condition and either a decrease in $S$ or an increase in $L$ tends to increase $e$.

$$e_2 = e_1 + \frac{F}{pS} \tag{10}$$

If $e_1$ is located on the chart for initial conditions, $e_2$ is found by adding $F/(pS)$ to it, and $d_2$ is then derived from $e_2$ as before. For example, in the example previously given, if there were an external force of 100 pounds acting to shorten the span at the time of $w_2$ loading,

$$\frac{F}{pS} = \frac{100}{60{,}000} = 0.00167$$

$$e_2 = -0.01798 + 0.00167 = -0.0163$$

$$d_2 = 0.0451 \qquad T_2 = 1{,}290 \text{ pounds}$$

*Joint Use.* In certain cases the pole which acts as a guy stub for the end pole acts also as a dead-end pole for telephone cable carried on a parallel lead (see figure 10). The tension in the messenger supporting the telephone cable changes with the loading. If telephone and power spans are of approximately equal length, the problem may be solved just as if all wires were on the same poles. If span lengths are different, however, a solution may be reached by a series of convergent approximations as follows: Consider the loaded tension $T_T$ in the telephone messenger first as a constant external force similar to that discussed in the preceding paragraph. It is assumed that the initial span for the power wires is that obtained after $T_T$ is applied to the end pole. The equivalent deflection constant for the whole system is the same whether $T_T$ and $T_P$ are applied to the same pole or to different poles, being equal to $p_1 + p_2$ for the total tension. The power span is solved in the usual manner and a value for tension in the power wires found. Returning to the telephone span, a solution is made similarly except that in determining $e_2$, an amount $(T_2 - T_1)_P/(pS_T)$ is added to $e_1$ to allow for the *increase* in tension in the power wires $(T_2 - T_1)_P$, $S_T$ being the telephone span. The resulting tension in the telephone messenger having thus been determined, the power span is recalculated, increasing $e_1$ now by the amount $(T_2 - T_1)_T/(pS_P)$ where $(T_2 - T_1)_T$ is the *increase* in messenger tension and $S_P$ the power span. Successive approximations will give the final result, but in most cases only the first few steps will be necessary for sufficient accuracy. The following is given as an example:

| | Power Span | Telephone Span |
|---|---|---|
| Wire | 3 number 0 *TBWP* copper† | 202-24 cable, on 6*M* strand‡ |
| Initial load $w_1$ per foot, pounds | $3 \times 0.424 = 1.272$ | 1.9 |
| Heavy loading $w^2$ per foot, pounds | $3 \times 1.55 = 4.65$ | 4.3 |
| $AE$ per conductor | 1,160,000 | 1,757,000 |
| Span, feet | $S_P = 100$ | $S_T = 60$ |
| Pole | 40-foot, class 4 | 30-foot class 2 |
| Deflection constant $p$, pounds per foot | 600 | 1,500 |
| $p_{eq}$ for both poles | $600 + 1500 = 2{,}100$ | 2,100 |
| $\frac{S}{AE}$ | $0.287 \times 10^{-4}$ (3 wires) | $0.341 \times 10^{-4}$ |
| $\frac{S}{p_{eq}S} = \frac{1}{p_{eq}}$ | $4.76 \times 10^{-4}$ | $4.76 \times 10^{-4}$ |
| $\frac{S}{N} = S\left(\frac{1}{AE} + \frac{1}{p_{eq}}\right)$ | $5.047 \times 10^{-4}$ | $5.10 \times 10^{-4}$ |
| $\frac{w_1 S}{N}$ | $1.272 \times 5.047 \times 10^{-4} = 6.42 \times 10^{-4}$ | $1.9 \times 5.10 \times 10^{-4} = 9.697 \times 10^{-4}$ |
| Initial deflection $d_1$, feet | 1.5 | 0.85 |
| $d_1 = \frac{D_1}{S}$ | 0.015 | 0.0142 |
| $T_1 = \frac{w_1 S}{8d_1}$, pounds | 1,060, or 353 per wire | 1,000 |

† Triple-braid weather-proof.
‡ Number 24 wire, 202 pairs in cable; breaking strength of messenger 6,000 pounds.

| | Power Span | Telephone Span |
|---|---|---|
| $e_1 = \frac{8}{3} d_1 - \frac{w_1 S}{8 d_1 N}$ (chart) | $-0.0048$ | $-0.0081$ |
| $\alpha$ (temperature coefficient) | $9.6 \times 10^{-6}$ (copper) | $6.6 \times 10^{-6}$ (steel) |
| $\alpha t$ for $-60$ degrees | $-6 \times 10^{-4}$ | $-4 \times 10^{-4}$ |
| $e' = e_1 + \alpha t$ | $-0.0048 - 0.0006 = -0.0055$ | $-0.0081 - 0.0004 = -0.0084$ |
| $\frac{w_2 S}{N}$ | $4.65 \times 5.047 \times 10^{-4} = 23.5 \times 10^{-4}$ | $4.3 \times 5.10 \times 10^{-4} = 21.95 \times 10^{-4}$ |
| $\frac{1}{p_{eq} S}$ | $\frac{1}{210{,}000} = 4.76 \times 10^{-6}$ | $\frac{1}{126{,}000} = 7.94 \times 10^{-6}$ |

**Successive Approximations***

| | Power Span | | |
|---|---|---|---|
| | 1 | 2 | 3 |
| $\frac{(T_2 - T_1)_T}{p_{eq} S_P}$ | 0 | $-0.0008$ | $-0.0009$ |
| $e_2 = e' + \frac{(T_2 - T_1)_T}{p_{eq} S_P}$ | $-0.0055$ | $-0.0063$ | $-0.0064$ |
| $d_2$ (from chart) | 0.0340 | 0.0324 | 0.0320 |
| $T_2 = \frac{w_2 S}{8 d_2}$ | 1,710 lbs | 1,795 | 1,820 |
| $(T_2 - T_1)_P$ | 650 | 735 | 760 |
| | **Telephone Span** | | |
| | 1 | 2 | 3 |
| $\frac{(T_2 - T_1)_P}{p_{eq} S_T}$ | 0.0052 | 0.0058 | 0.0060 |
| $e_2$ | $-0.0032$ | $-0.0026$ | $-0.0024$ |
| $d_2$ | 0.0384 | 0.040 | 0.0405 |
| $T_2$ | 840 | 805 | 795 |
| $(T_2 - T_1)_T$ | $-160$ | $-195$ | $-205$ |

* Proceed from column 1 under "Power Span" to column 1 under "Telephone Span," to column 2 under "Power Span," etc.

Further approximations show no appreciable change in the tensions so the solution is 1,820 pounds for the power span (607 pounds per wire) and 795 pounds in the telephone span. It is evident that this calculation could be shortened somewhat if, after the trend of the change in the telephone span is discovered in the first approximation, a larger change is assumed at once rather than the actual change thus found. In the table given, the first step shows a reduction of 160 pounds; if this were arbitrarily increased to 200 pounds the final result would be obtained in the next calculation.

## Field Application

Although the methods of calculation and charts which have been presented are comparatively simple and easy to apply, they still involve an amount of calculation which would be troublesome in the everyday run of problems encountered in the field. Their chief use is for the development of working rules and charts which may not be general but may cover a range of conditions sufficient for the greater majority of the cases. Since there is so much variation in local conditions and standards of construction, such working rules should be set up for one's own system in accordance with the combinations of circumstances most often occurring on that system. Two examples of such specific instructions will be given as illustrations.

Study of many actual cases of unguyed end poles and pole-stub combinations in the Detroit territory, both with and without joint use with telephone lines, led to the working rule:

"The initial load on an unguyed end pole or pole-stub combination should not exceed one half the ultimate allowable load."

This does not give actual resulting load under storm conditions but it does assume that a severe overload will be avoided and also that too much stress and deflection will not be placed on the pole under ordinary loading conditions. For pole-stub combinations, the criterion will be the load on the weaker of the 2 poles of course.

Another chart, which is somewhat simplified for field use, is shown in figure 11. In preparing this the initial sags were fixed at a given percentage of span, and ordinary values for deflection constants were assumed. From the total heavy load per foot and the span length, a point on the turning scale is found, from which, and the initial tension, the total loaded tension is found. Still simpler charts for special conditions can be similarly prepared with a little study, although it must be recognized that with the large number of variables no very simple complete solution is possible.

**Table I—Pole Deflection Constants and Ultimate Strengths**

| Individual Poles | | | | Combinations | | | |
|---|---|---|---|---|---|---|---|
| Length, Feet | Class | p | Ultimate Strength, Pounds | Length, Feet | Class | p | Ultimate Strength, Pounds |
| 25 | 1 | 3,000 | 4,500 | 25 / 35 | 1 / 2 | 4,200 | 6,300 |
| 25 | 2 | 2,300 | 3,700 | | | | |
| 25 | 3 | 1,700 | 3,000 | | | | |
| 30 | 1 | 2,000 | 4,500 | | | | |
| 30 | 2 | 1,500 | 3,700 | 25 / 35 | 2 / 4 | 3,100 | 5,000 |
| 30 | 3 | 1,100 | 3,000 | | | | |
| 35 | 2 | 1,200 | 3,700 | | | | |
| 35 | 4 | 800 | 2,400 | 30 / 40 | 2 / 2 | 2,250 | 5,500 |
| 40 | 2 | 850 | 3,700 | | | | |
| 40 | 4 | 600 | 2,400 | | | | |
| 45 | 2 | 650 | 3,700 | 30 / 45 | 2 / 2 | 2,150 | 5,300 |
| 45 | 4 | 450 | 2,400 | | | | |

## Summary

It has been pointed out that the flexure of supports may constitute a major factor in the design of structures for supporting overhead lines, and examples of such cases have been given. The general method of attacking the problem was described and 2 specific ways of working out the solution were given in detail. Simpler field rules derived by these means are also mentioned. These methods have been used in practical applications and it is believed that they can be of considerable benefit to those who are interested in the careful and accurate design of their structures.

## Appendix—Determination of Deflection Characteristics for Wood Poles

Assume the pole to be in effect a tapered cantilever beam, with the load applied at the end (see figure 12). The increment deflec-

tion at the load end of the beam resulting from the stress at any point at distance $x$ from that end is

$$dQ = \frac{Mx}{EI}\,dx = \frac{Px^2}{EI}\,dx$$

The total deflection therefore is

$$Q = \int_0^L \frac{P}{EI}\,x^2 dx$$

$I = 0.0491\,d^4$ for circular cross section of diameter $d$

For a taper of $a$ per foot,

$$d = ax + b \qquad a = \frac{c - b}{L} \qquad I = 0.0491(ax + b)^4$$

Therefore

$$\frac{0.0491\,E}{P}\,Q = \int_0^L \frac{x^2}{(ax + b)^4}\,dx$$

$$= \frac{1}{a^3}\left[-\frac{1}{ax + b} + \frac{2b}{2(ax + b)^2} - \frac{b^2}{3(ax + b)^3}\right]_0^L$$

Substituting for $a$,

$$\frac{0.0491\,E}{P}\,Q = \frac{L^3}{(c - b)^3}\,\frac{(c - b)^3}{3bc^3}$$

$$= \frac{L^3}{3bc^3}$$

"Deflection constant" $p = \frac{P}{Q} = \frac{0.0491E \times 3bc^3}{L^3}$

$= 0.1473Eb(c/L)^3$ pounds per inch deflection

All quantities must be expressed in inches. The deflection constant in pounds per foot deflection will be 12 times that given by the equation.

Values of $E$ given in the 1935 "Wood Handbook" of the U.S. Department of Agriculture are as follows:

| | |
|---|---|
| Northern white cedar | 800,000 pounds per square inch |
| Western red cedar | 1,120,000 pounds per square inch |
| Southern yellow pine | 1,800,000 pounds per square inch |

## Example

35-foot class 4 western-cedar pole

$b$ = top diameter, average for class approximately 8.5 inches

$c$ = ground line diameter, average for class approximately 11.7 inches

$L$ = length from 2 feet below top to ground line = 35 − 8 = 27 feet = 324 inches

$$p = \frac{P}{Q} = 0.1473 \times 1{,}120{,}000 \times 8.5\left(\frac{11.7}{324}\right)^3$$

$= 66$ pounds per inch

$66 \times 12 = 800$ pounds per foot

For a pole and stub acting together, connected by a guy, the deflection of both is the same, hence the deflection constant of the combination is equal to the sum of their individual deflection constants. The ultimate strength of the combination is limited by the strength of the one which has the lower ratio of strength to deflection constant, since that one reaches its ultimate strength before the other one does. For example,

| | p | Ultimate Strength, Pounds |
|---|---|---|
| 35-foot class 2 pole | 1,200 | 3,700 |
| 25-foot class 1 stub | 3,000 | 4,500 |
| Combination | 4,200 | $4{,}200\,\frac{4{,}500}{3{,}000} = 6{,}300$ |

Table I gives deflection constants and rated ultimate strengths for a number of common sizes of western-cedar poles and stubs and some typical combinations.

# Ultrahigh-Speed Reclosing of High-Voltage Transmission Lines

(*Continued from page 90*)

In a large measure the field of application of this development will be determined, as would be expected, by the additional cost of ultrahigh-speed mechanisms as against standard mechanisms but here the reverse is also true that the cost will in turn be influenced to a considerable extent by the development of applications for the mechanisms and by whether quantity production will be possible. In any event it would appear that a very definitely new and ingenious tool has been made available to the transmission-system designer and operator that gives promise of improved service and lower costs.

## Conclusions

The authors believe that it is perhaps premature to draw final conclusions as to the nature, scope, and significance of the development described herein and such was not within the limited scope of this paper, but nevertheless it would appear that the following have been fairly well established:

1. On high-voltage lines, particularly on overhead lines, outages caused by lightning and possibly other outages can be materially reduced, perhaps to the extent of 75 per cent, by ultrarapid reclosing.

2. Apparently the occurrence in nature of intervals between multiple strokes is such as to give a fortuitously happy arrangement from the standpoint of possible reclosure. This, however, is a phase that needs not only further theoretical but a great deal of practical verification.

3. While a great deal of benefit can be obtained in the reducing of outage resulting from phase-to-ground troubles, phase-to-phase troubles are much more bothersome and a great deal of additional work needs to be done either in the way of bringing them within the range of treatment that can be so successfully applied to phase-to-ground faults or in the direction of reducing their frequency.

4. Finally, it appears that as is true in so many other cases of research and development, the by-product of the search for speed in circuit-breaker practice and speed on relay protection has given most fruitful results, perhaps equal to those obtained from the original line of research, and promises to yield a great deal more.

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# Lightning Investigation on Transmission Lines—VI

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**Continuing a series of papers reporting a study of lightning on transmission lines, the authors present herewith data obtained during 1935 and part of 1936 on 66-, 110-, 132-, and 220-kv lines. Values of lightning current are presented, and the effectiveness of overhead ground wires and low footing resistance in preventing tripouts is shown.**

IN PREVIOUS papers the authors have reported the results of an investigation of lightning effects on transmission lines, which began in the year 1926. The immediately preceding paper[1] gave the results for 1933 and 1934. The present paper will summarize the 1935 and part of the 1936 results. The participating power companies in this investigation are the Pennsylvania Power and Light Company, Appalachian Electric Power Company, Philadelphia Electric Company, Pennsylvania Water and Power Company, Public Service Company of New Jersey, Consumers Power Company, American Gas and Electric Company, and the Electric Bond and Share Company.

In the years 1935 and 1936 data were gathered by means of the surge crest ammeter[2] on lightning currents in tower legs and crossarms, overhead ground wires, counterpoise wires and lightning rods erected at the tops of towers. These data, together with supplementary data from lightning stroke recorders, surge indicators, and automatic oscillographs have permitted a rather complete picture to be drawn of the effects of individual strokes. Additional mass statistics permit further confirmation of the theories in regard to the behavior of overhead ground wires and counterpoise wires.

## Summary

Line performance data and current and voltage measurements now at hand give a reasonably clear qualitative and quantitative idea of the essential elements in the line protection problem.

First, it is apparent from line performance data that overhead ground wires reduce tripouts in the order of 20 to 1. Current measurements on the ground wire have demonstrated that it is serving as a lightning stroke terminal for many strokes which otherwise might reach the conductor and cause flashover. Measurement experience seems to bear out that the overhead ground wires also act to assist in reducing tower potentials for strokes to a tower.

The second important element has been shown by measurement to be the tower footing resistance. With marked consistency it has been shown that when a stroke terminates on a tower, flashover and tripout will quite likely result if footing resistance is high. The product of current and footing resistance must be below insulator flashover for the wave shape applied if flashover is to be prevented.

Both the parallel and radial type counterpoise wires have been shown to be effective in reducing the voltage drop at the tower footing. The tower-to-tower buried ground wire has been shown in one case to have entirely eliminated flashover of insulation at a point previously very susceptible to flashover. The radial counterpoise has been shown in one case to be effective for most lightning currents when some 150 feet long.

Simultaneous measurements of lightning currents have been made in counterpoise wires, in tower legs, in tower arms, in ground wires and lightning rods. Such readings have permitted the location of the general point of contact of the stroke to be known, the direction of flow of current from positive ground to negative cloud to be definitely determined, and have provided quantitative values of lightning current.

## Flashover on Lines With and Without Overhead Ground Wires

In table VII of paper IV of this series[3] data were given as to the insulation and conductor and ground wire arrangement for 9 systems in eastern United States, ranging from 66 kv to 220 kv, also data as to the number of tripouts on these lines for a period of years up to and including 1933. In table I of the present paper the same systems are listed, with the tripout data brought up to and including 1935. In addition, data for the section of the Wallenpaupack-Siegfried line without overhead ground wires are given.

Two of the lines have an almost perfect record of 0.4 tripouts per 100 miles per year. The other lines with overhead ground wires range up to 2.8 tripouts per 100 miles per year, while the one line without overhead ground wires had 47 tripouts per 100 miles per year, that is, 17 or more times as many tripouts as on the lines with overhead ground wires.

In table II are given the location of the flashovers which caused tripout on the Wallenpaupack-Siegfried line,[4] segregated with respect to the overhead ground wire construction and method of grounding, for the 10 years from 1926 to 1935 inclusive. Of the 112 faults whose locations are known, 108 occurred on the section of line

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1. For all numbered references see list at end of paper.

## Table I—Tripouts on Transmission Lines, Data Up to and Including 1935

| | Line Name | Kilovolts | Miles | Average Length of Span, Feet | Footing Resistance, Ohms | Tripouts | Years | Tripouts per 100 Miles per Year |
|---|---|---|---|---|---|---|---|---|
| 1*a* | Wallenpaupack-Siegfried (Without overhead ground wires) | 220 | 36.9 | 1,100 | 5–325 | 13§† | 8 | 4.7 |
| 1*b* | Wallenpaupack-Siegfried (With overhead ground wires) | 220 | 27.8 | 1,100 | 1–1.5*<br>5–75** | 6† | 8 | 2.8 |
| 2 | Bushkill-Roseland | 220 | 47 | 1,150 | 5–300 | 4† | 4 | 2.1 |
| 3 | Siegfried-Plymouth | 220 | 49 | 1,270 | 5–60 | 6 | 8 | 1.5 |
| 4 | Conowingo-Plymouth (No. 1) | 220 | 57 | 1,170 | 5–100 | 8 | 8 | 1.8 |
| | Conowingo-Plymouth (No. 2) | 220 | 57 | 1,170 | 5–100 | 8 | 8 | 1.8 |
| 5 | Roseland-Plymouth | 220 | 72 | 1,050 | 5–100 | 9 | 5 | 2.5 |
| 6 | Safe Harbor-Westport | 220 | 70 | 1,050 | 2–85 | 1 | 4 | 0.4 |
| 7 | Philadelphia-Chester | 66 | 14 | 480 | Below 5 | 1 | 18 | 0.4 |
| 8 | Greenbush-Pleasant Valley | 110 | 64 | 735 | 1–175‡ | 7 | 4 | 2.74 |
| 9 | Pleasant Valley-Millwood | 132 | 40.5 | 620 | 5–800‡ | 4 | 4 | 2.47 |

* Section with continuous counterpoise.
** Section with radial counterpoise.
† The location of faults causing 53 tripouts on lines 1*a*, 1*b*, and 2 were not known definitely, but these have been assigned to section with or without ground wires in accordance with correlated information.
‡ Before counterpoise and ground rods installed.

without overhead ground wire and 4 on the overhead ground wire section. In 7 years the section with tower-to-tower counterpoise had no flashovers. It is interesting to know that in the same section in the years 1926, 1927, and 1928, before the counterpoise was installed, there was a total of 29 flashovers.

## Relation Between Tower Voltage and Flashover

In table III are given the data for 15 records of tower current exceeding 30,000 amperes, secured on the Wallenpaupack-Siegfried line during the years 1933 to 1935 inclusive.

It will be noted that 5 cases of flashover occurred on the section without overhead ground wire, and that the product of current and resistance in all but one case exceeded 1,500 kv. The assigned flashover voltage[5] for this line with standard test waves is as follows:

| Units | Positive Wave | Kilovolts |
|---|---|---|
| 14 | 1.5x40 | 1,265 |
| 14 | 1x5 | 1,565 |
| 16 | 1.5x40 | 1,425 |
| 16 | 1x5 | 1,775 |

An analysis of items 11 to 15, inclusive, indicates strokes to the towers in all cases. This analysis follows:

Item 11—The stroke was confined to a single tower. All 3 phases flashed over.

Item 12—The stroke was confined to a single tower. All 3 phases flashed over.

Item 13—A current reading of 4,000 amperes was obtained in the legs of adjacent tower *WT* 28–1. This tower had a footing resistance of 45 ohms. It is believed that the stroke hit tower *WT* 27–6 and flashed over to *Y*-phase conductor. This conductor was in turn raised in potential and flashover took place from this conductor to the tower at *WT* 28–1.

Item 14—Only one tower was involved in this stroke, and the flashover took place to 2 conductors. Current measurements were made on only one leg and the actual tower current may have been somewhat larger than estimated from the one leg reading. On the other hand, a long wave with low flashover value is possible.

Item 15—Five towers were involved in this stroke and the data pertaining to these towers follow:

| Tower | Footing Resistance | Tower Amperes | Product I × R, Kv | Flashed Phases |
|---|---|---|---|---|
| *SR* 9–2 | 15 | 10,000 | 150 | *W* |
| *SR* 9–3 | 28 | 29,000 | 810 | *W* and *Y* |
| *SR* 9–4 | 28 | 54,000 | 1,510 | *W* and *X* |
| *SR* 9–5 | 34 | 7,000 | 240 | *W* and *Y* |
| *SR* 10–1 | 15 | 8,000 | 120 | *Y* |
| | | 108,000 | | |

It would appear from this record that the stroke hit tower *SR* 9–4, causing flashover from this tower to conductors *W* and *X*. The surge then traveled to the 2 adjacent towers in both directions, flashing over from conductor to tower. There is some inconsistency in the phases affected at the different towers in that the surge started on *W* and *X* phases and wound up on *W* and *Y*

## Table II—Locations of Flashovers Causing Tripouts on Wallenpaupack-Siegfried 220-Kv Line Tabulated With Respect to Overhead Ground Wire Construction and Method of Grounding

| | | Overhead Ground Wires | | | |
|---|---|---|---|---|---|
| Year | Location Unknown | No Overhead Ground Wires | Tower-to-Tower Standard Grounding* | Tower-to-Tower Counterpoise | Radial Counterpoise | Total |
| 1926 | | 15 | | | | 15 |
| 1927 | 3 | 4 | 0 | | | 7 |
| 1928 | 11 | 2 | 1 | | | 14 |
| 1929 | 27 | 10 | 1 | 0 | | 38 |
| 1930 | 9 | 14 | 1 | 0 | 0 | 24 |
| 1931 | 0 | 20 | 0 | 0 | 0 | 20 |
| 1932 | 1 | 8 | 0 | 0 | 1 | 10 |
| 1933 | 2 | 13 | 0 | 0 | 0 | 15 |
| 1934 | 1 | 11 | 0 | 0 | 0 | 12 |
| 1935 | 2 | 11 | 0 | 0 | 0 | 13 |
| Total | 56** | 108 | 3 | 0 | 1 | 168 |
| Miles† | | 36.9 | 2.6 | | 25.2‡ | 64.7 |

* After the latter part of 1930 this section was equipped with radial counterpoise wires.
** This necessarily includes unknown locations on the Bushkill-Roseland line, the probable number of which is 2.
† Present mileage of each item. This mileage has changed from time to time as construction has been changed.
‡ Includes diverter cable section.

**Table III—Relation Between Tower Voltage and Flashover, Wallenpaupack-Siegfried 220-Kv Line**

| Item | Tower Number | Overhead Ground Wire | Footing Resistance, Ohms | Amperes in Tower Legs | Product I × R, Kilovolts | Flash-over | Year |
|---|---|---|---|---|---|---|---|
| 1 | *WT* 12–3 | Yes | 1.4 | 38,700 | 54 | No | 1934 |
| 2 | *WT* 8–5 | Yes | 7 | 40,000 | 280 | No | 1933 |
| 3 | *WT* 8–4 | Yes | 8 | 35,000 | 280 | No | 1933 |
| 4 | *SR* 2–4 | Yes | 10 | 36,000 | 360 | No | 1933 |
| 5 | *SR* 2–1 | Yes | 15 | 38,000 | 570 | No | 1933 |
| 6 | *SR* 2–2 | Yes | 15 | 30,000 | 450 | No | 1934 |
| 7 | *SR* 4–4 | Yes | 19 | 35,000 | 665 | No | 1933 |
| 8 | *SR* 21–2 | No | 20 | 42,000 | 840 | No | 1933 |
| 9 | *SR* 8–4 | No | 20 | 49,000 | 980 | No | 1934 |
| 10 | *SR* 33–2 | No | 18 | 30,800 | 555 | No | 1933 |
| 11 | *SR* 31–3 | No | 34 | 51,000 | 1,730 | Yes | 1933 |
| 12 | *SR* 19–3 | No | 45 | 40,000 | 1,800 | Yes | 1933 |
| 13 | *WT* 27–6 | No | 58 | 36,000 | 2,100 | Yes | 1933 |
| 14 | *SR* 18–1 | No | 28 | 30,000 | 840 | Yes | 1934 |
| 15 | *SR* 9–4 | No | 28 | 54,000 | 1,510 | Yes | 1935 |

phases. It is barely possible that tower 9–3 was raised sufficiently high in potential by the flashover of phase *W* to involve phase *Y* in the trouble. It is also possible that flashover took place on *Y*-phase at *SR* 9–4 but left no marks that could be detected.

The Glenlyn-Roanoke line[6] of the Appalachian Electric Power Company is a double circuit line, approximately 65 miles long, with one overhead ground wire at the peak of the towers. It is not possible from the measuring equipment on this line to associate the point of flashover with a particular tripout as definitely as on the Wallenpaupack-Siegfried line.

The Glenlyn-Roanoke line is insulated with 10 units, spaced $4^3/_4$ inches apart, with flashover voltage approximately as follows:

$1^1/_2$x40 positive wave—820 kv
1x5 positive wave—970 kv

In 1934 there were 51 lightning strokes to this line. Tower potentials, that is, the product of tower current and tower footing resistance, for the towers which appeared to be the center of disturbance in each of the 51 strokes, ranged as shown in the following tabulation:

| Kilovolts Range | Number |
|---|---|
| 40– 200 | 13 |
| 201– 800 | 23 |
| 801–1,000 | 5 |
| 1,001–4,200 | 10 |
| Total | 51 |

In 15 of the 51 cases listed the tower potential was of sufficient magnitude to be in the flashover range. In 13 of the 15 cases a possible correlating tripout was reported. There were 3 other tripouts which may have correlated with tower potentials lower than the assigned flashover voltage.

In 1935 there were 32 strokes to the Glenlyn-Roanoke line. Potentials of the towers which were the apparent center of disturbance may be grouped as follows (excluding 3 cases in which the tower current was classified as a "trace").

| Kilovolts Range | Number |
|---|---|
| 20– 200 | 6 |
| 201– 800 | 17 |
| 801–1,000 | 0 |
| 1,001–2,610 | 6 |
| Total | 29 |

Of the 32 cases there were 6 cases in which the tower potential was of the order of the insulator flashover and 6 tripouts due to lightning occurred on this line during the period of measurements.

**Table IV—Range of Tower and Probable Stroke Currents in 4 Transmission Lines; 1933, 1934, and 1935**

| Range of Current, Amperes | Tower Current: W-S* 1933 | W-S* 1934 | W-S* 1935 | G-R** 1933 | G-R** 1934 | G-R** 1935 | SH-W-T† 1934 | SH-W-T† 1935 | P-D‡ 1935 | Total | Probable Stroke Current: W-S* 1933 | W-S* 1934 | W-S* 1935 | G-R** 1933 | G-R** 1934 | G-R** 1935 | SH-W-T† 1934 | SH-W-T† 1935 | P-D‡ 1935 | Total |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1,000–5,000 | 4 | 4 | 9 | 0 | 2 | 0 | 0 | 14 | 0 | 33 | 4 | 4 | 8 | 0 | 2 | 0 | 0 | 14 | 0 | 32 |
| 5,001–10,000 | 3 | 5 | 8 | 8 | 3 | 7 | 11 | 28 | 2 | 75 | 3 | 1 | 3 | 7 | 3 | 7 | 9 | 20 | 1 | 54 |
| 10,001–20,000 | 7 | 2 | 6 | 9 | 7 | 4 | 7 | 30 | 2 | 74 | 6 | 4 | 7 | 10 | 2 | 2 | 8 | 22 | 3 | 64 |
| 20,001–30,000 | 0 | 0 | 2 | 4 | 11 | 3 | 17 | 22 | 5 | 64 | 1 | 2 | 4 | 2 | 10 | 4 | 7 | 23 | 1 | 54 |
| 30,001–40,000 | 6 | 3 | 1 | 0 | 15 | 8 | 16 | 16 | 6 | 71 | 3 | 2 | 2 | 1 | 11 | 2 | 11 | 12 | 6 | 50 |
| 40,001–50,000 | 2 | 0 | 0 | 0 | 4 | 2 | 8 | 4 | 0 | 20 | 4 | 0 | 1 | 1 | 7 | 4 | 8 | 9 | 1 | 35 |
| 50,001–60,000 | 1 | 0 | 1 | 1 | 2 | 1 | 1 | 1 | 0 | 8 | 1 | 0 | 0 | 0 | 1 | 1 | 3 | 7 | 1 | 14 |
| 60,001–70,000 | | | | 1 | 3 | 0 | 1 | 0 | 1 | 6 | 0 | 0 | 1 | 1 | 0 | 2 | 7 | 4 | 2 | 17 |
| 70,001–80,000 | | | | 0 | 1 | | | 1 | 0 | 2 | 1 | 0 | 0 | 0 | 3 | 0 | 1 | 1 | 0 | 6 |
| 80,001–90,000 | | | | 0 | | | | | 0 | 0 | | | 0 | 0 | 2 | 1 | 2 | 1 | 0 | 6 |
| 90,001–100,000 | | | | 2 | | | | | 0 | 2 | | | 0 | 0 | 1 | 0 | 2 | 0 | 1 | 4 |
| 100,001–110,000 | | | | | | | | | 0 | 0 | | | 1 | 1 | 0 | 0 | 1 | 1 | 0 | 4 |
| 110,001–120,000 | | | | | | | | | 1 | 1 | | | | 1 | 1 | 1 | 0 | 0 | 0 | 3 |
| 120,001–130,000 | | | | | | | | | 1 | 1 | | | | | 1 | 2 | 2 | 0 | 0 | 5 |
| 130,001–140,000 | | | | | | | | | 1 | 1 | | | | | 2 | | 1 | 1 | 1 | 5 |
| 140,001–150,000 | | | | | | | | | | | | | | | 0 | | | 0 | 0 | 0 |
| 150,001–160,000 | | | | | | | | | | | | | | | 0 | | | 1 | 2 | 3 |
| 160,001–170,000 | | | | | | | | | | | | | | | 0 | | | | | 0 |
| 170,001–180,000 | | | | | | | | | | | | | | | 0 | | | | | 0 |
| 180,001–190,000 | | | | | | | | | | | | | | | 0 | | | | | 0 |
| 190,001–200,000 | | | | | | | | | | | | | | | 1 | | | | | 1 |
| 200,001–210,000 | | | | | | | | | | | | | | | 0 | | | | | 0 |
| 210,001–220,000 | | | | | | | | | | | | | | | 1 | | | | | 1 |
| Total | 23 | 14 | 27 | 23 | 49 | 26 | 61 | 116 | 19 | 358 | 23 | 14 | 27 | 23 | 49 | 26 | 61 | 116 | 19 | 358 |

* Wallenpaupack-Siegfried 220-kv line.
** Glenlyn-Roanoke 132-kv line.
† Safe Harbor-Westport-Takoma 220-kv line.
‡ Philadelphia-Delaware 66-kv line.

## Current in Towers and Strokes

Table IV gives the range of current and the number of times these currents were recorded by surge crest ammeter for 4 systems during the years 1933 to 1935 inclusive.

Records of 358 strokes were obtained in these years. The table gives data for the tower with the highest current where several towers are involved in a stroke, and for the probable total stroke current, obtained by adding the currents in all the towers affected by a stroke.

Figure 1 summarizes in cumulative curves, the tower current and probable stroke current of the 4 transmission lines based on the data of table IV. It will be noted from figure 1 that although the tower currents go to approximately 130,000 amperes, only about one per cent exceed 100,000 amperes and about 6 per cent exceed 50,000 amperes, also that the probable stroke currents go to 220,000 amperes but only about 6 per cent exceed 100,000 amperes. Of the 358 strokes recorded approximately 95 per cent were of negative polarity, that is, top of tower negative with respect to bottom of tower and ground.

The use of surge measuring instruments of several types, and in many cases a great number of each type, permits analysis of results on a statistical basis as well as for single strokes. The statistical method establishes the range of stroke current, voltage, and frequency of occurrence, but the exact electrical mechanism of the stroke in the transmission structure can be established only through correlation of a great number of records for a single stroke. For instance, the single stroke surge voltage recorder data, obtained at a number of stations along the conductor resulted in the practical attenuation formula previously given.[7] Also each cathode-ray oscillogram of conductor voltage when examined with accompanying surge voltage recorder and surge indicator data for the same stroke provides a more complete record of the surge mechanism. The surge crest ammeter is peculiarly adapted to the se-

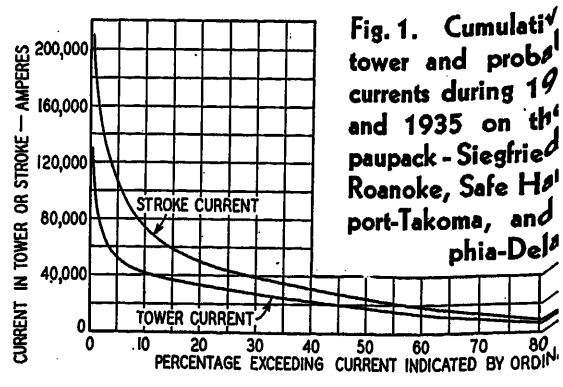



**Fig. 1. Cumulati tower and prob currents during 19 and 1935 on th paupack - Siegfrie Roanoke, Safe Ha port-Takoma, and phia-Del**

curing of a great number of current records at a the line structure for each stroke.

In figure 2 is shown a sample of current mea in the counterpoise, tower legs, tower arms, and ground wire. Polarity directions are indicate arrows pointing in the conventional plus to mi tion. The 2 counterpoise wires fed into the bas 10 from the adjacent earth some 15,800 ampe longer, or 150-foot, counterpoise gathered some peres per foot and this was about the same for of its length. The shorter, or 40-foot, counterp ered about 80 amperes per foot. Assuming tha and short counterpoise wires on which no mea were taken also carried 15,800 amperes, a total poise current of 31,600 is obtained. This agree upward current of the 4 legs which measured so amperes. This current flowed into the tower into the ground wire at the tower tip, being joine about 12,000 amperes coming from the lef currents together gave a crest of 33,000 amper overhead ground wire just a few feet to the rig tower tip. As the measurement station on th wire at the left of tower 9 showed 12,500 amper

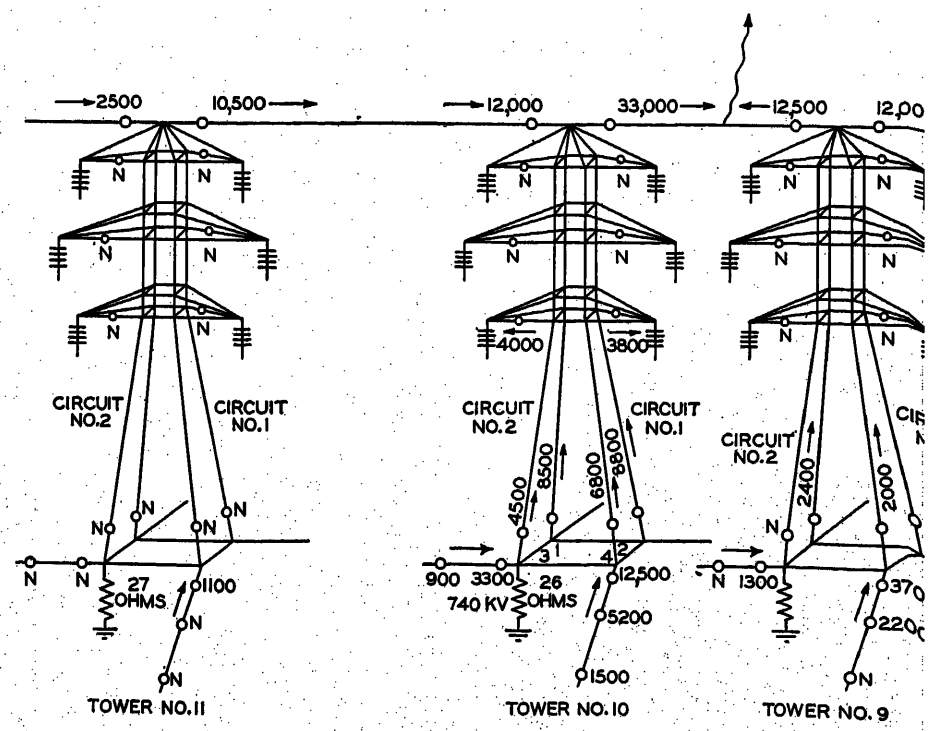



**Fig. 2. Current measurements obtained during stroke occurring on Glenlyn-Roanoke line, June 1936**

Circles indicate measurement stations

N—Current less than measuring range of station

in the opposite direction, the assumption of the stroke to the ground wire between these 2 stations appears justifiable. The current of the stroke is some 45,500 amperes. It will be noted that the individual currents do not add to exactly equal the measured sum. Two factors are important in this connection. First, the magnetic links are adjusted to read crest current to 10 per cent accuracy. Second, the measurement station at the right of tower 9 on the ground wire showed 12,000 amperes flowing to the right. Another stroke along the line in this direction is indicated, but this stroke occurred further to the right than tower 8, as this tower did not show any leg current within the measurable range.

To the left of tower 10 the measurement station in the ground wire on the right side of tower 11 gave a reading of 10,500 amperes. This 10,500 amperes is made up of 2,500 amperes coming in over the ground wire from tower 12 and some tower leg current in tower 11, which was below the measurement range of the magnetic link setting. The middle phase insulator assemblies of circuit number 1, towers 8 and 10, flashed over. The tower footing resistance at tower 10 of 26 ohms with 28,600 amperes flowing gives a tower potential of 740 kv. At tower 8 the high resistance of 147 ohms requires only 5,000 amperes to give insulator flashover voltage, and this value divided among the 4 legs evenly gives but 1,250 amperes per leg, a value below the measuring level of the magnetic links as installed.

Reviewing briefly this one set of records locates the point of contact of the stroke and gives the magnitude and direction of the component surge currents in the structure. The overhead ground wire shields the line conductors and the counterpoise wires operate to reduce footing resistance, but the high ground resistance gives a high tower potential which causes insulator flashover. Many similar records have been obtained of strokes to the ground wire and occasional records indicate strokes to the conductor and to the tower.

## The Counterpoise

On the Glenlyn-Roanoke line the counterpoises are made of 1/16 by 1.5 inch galvanized iron strap. Two lengths each 150 feet long extend out from diagonally opposite tower legs and run parallel with the conductors; 2 lengths each 40 feet long extend at right angles to the line from the other 2 tower legs. The counterpoise conductors are buried approximately 18 inches under the surface of the ground. The counterpoise wires on 20 towers near each end of the line were equipped with current measurement means as follows:

In 1934 one 150-foot wire and one 40-foot wire, each had one magnet bracket installed at approximately 3 feet from the tower leg. In 1935 the equipment on the short cable was unchanged, but on the long cable 2 additional brackets were mounted at approximately 80 and 147 feet from the tower leg.

In 1935 readings were obtained in 26 cases of current at all 3 points on the 150-foot counterpoise. These readings are given in table V. In all cases but one, the polarity indicates current flowing from the free end of the counterpoise toward the tower.

In figure 3 are plotted a summation of counterpoise currents for each of the 3 stations located along the wire. This summation was made by arranging the data in order of increasing current magnitudes for the station nearest the tower, and beginning at the lowest current adding each time the next higher current value.

**Table V—Current in Long (150-Foot) Counterpoise Wire at Different Distances From Tower, Glenlyn-Roanoke 132-Kv Line, 1935**

| Reference Number | Tower Number | Amperes at Indicated Distance From Tower | | |
|---|---|---|---|---|
| | | 3 Feet | 80 Feet | 147 Feet |
| 1–3 | 22 *G* | 750 | Trace* | 0 |
| 1–3 | 24 *G* | 1,600 | 750 | Trace* |
| 1–3 | 25 *G* | 8,500 | 5,600 | 0 |
| 1–3 | 26 *G* | 2,900 | 2,400 | 0 |
| 1–3 | 27 *G* | 2,800 | 0 | 0 |
| 2–1 | 7 *R* | 3,500 | 2,000 | Trace* |
| 2–1 | 8 *R* | 8,900 | 3,800 | Trace* |
| 2–1 | 9 *R* | 2,300 | 1,400 | Trace* |
| 3–1 | 13 *G* | 1,800 | 1,400 | 0 |
| 3–2 | 16 *G* | −3,000+** | −4,200** | N. I. |
| 3–3 | 18 *G* | 3,300 | 1,400 | 0 |
| 3–3 | 19 *G* | 2,600 | 1,300 | 0 |
| 3–3 | 20 *G* | 9,400 | 5,900 | 1,300 |
| 3–3 | 21 *G* | 10,700 | 5,400 | Trace* |
| 3–3 | 22 *G* | 17,500 | 13,000 | 2,300 |
| 3–3 | 23 *G* | 11,600 | 7,700 | 2,700 |
| 3–3 | 24 *G* | 2,500 | 800 | 0 |
| 3–3 | 25 *G* | 0 | 0 | 1,000 |
| 3–3 | 27 *G* | 0 | 900 | 0 |
| 4–1 | 18 *R* | 1,000 | 0 | 0 |
| 1–2 | 9 *G* | 15,000 | 4,700 | 2,600 |
| 1–2 | 10 *G* | 5,700 | 2,800 | 800 |
| 1–2 | 11 *G* | 1,600 | 1,000 | 0 |
| 6–1 | 12 *G* | 9,300 | 5,100 | 1,000 |
| 6–1 | 14 *G* | 800 | Trace | 0 |
| 6–1 | 15 *G* | 700 | Trace | 0 |
| Summation | | 124,750 | 68,850 | 14,200 |

* For the purpose of this tabulation a trace is assumed to be 500 amperes.

** In this case the polarity indicates current flowing from tower to free end of counterpoise. In all other cases current flows from free end of counterpoise toward tower. Values for this reading have been omitted from the summation.

N. I. = not installed.

**Table VI—Relation Between Current in Long (150-Foot) and Short (40-Foot) Counterpoise Wires, Glenlyn-Roanoke 132-Kv Line, 1935**

| Reference Number | Tower Number | Amperes | | Ratio Long to Short |
|---|---|---|---|---|
| | | Long Counterpoise | Short Counterpoise | |
| 1–3 | 25 *G* | 8,500 | 1,900 | 4.48 |
| 2–1 | 7 *R* | 3,500 | 1,200 | 2.92 |
| 2–1 | 8 *R* | 8,900 | 1,300 | 6.85 |
| 3–3 | 18 *G* | 3,300 | 1,100 | 3.0 |
| 3–3 | 19 *G* | 2,600 | 700 | 3.72 |
| 3–3 | 20 *G* | 9,400 | 1,600 | 5.87 |
| 3–3 | 21 *G* | 10,700 | 2,400 | 4.46 |
| 3–3 | 22 *G* | 17,500 | 6,800 | 2.58 |
| 3–3 | 23 *G* | 11,600 | 2,900 | 4.0 |
| 3–3 | 24 *G* | 2,500 | 750 | 3.34 |
| 1–2 | 9 *G* | 15,000 | 2,600 | 5.77 |
| 1–2 | 10 *G* | 5,700 | 900 | 6.33 |
| 6–1 | 12 *G* | 9,300 | 1,100 | 8.46 |
| Summation | | 108,500 | 25,250 | 4.3 |

Ratio of counterpoise lengths 3.75. Total counterpoise current approximately double above values. In all cases the polarity indicates current traveling from free end of counterpoise toward tower.

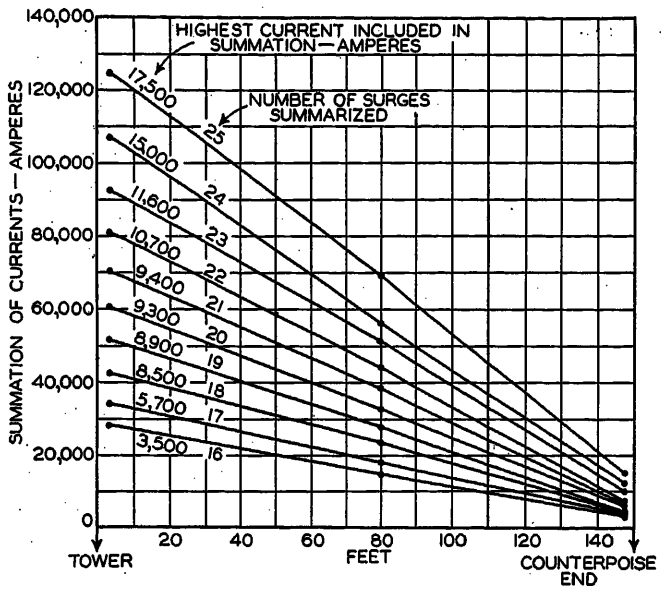


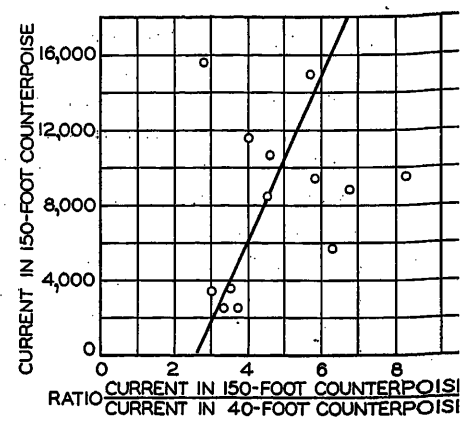

**Fig. 3. Summation of currents in 150-foot counterpoise wire at different distances from tower**

The figure shows that for all current levels the collection of current from the ground by the counterpoise is about the same for each foot of its length. There seems to be an indication, however, that at lower currents the portion nearer the tower collects a greater proportion per unit length than that away from the tower while for the higher currents the remote sections gather in the greater proportion of currents. Although not brought out clearly by the figure, a consideration of all the data indicates that the 150-foot counterpoise takes care of about 10,000 amperes with uniform collection of current throughout its entire length. This gives about 70 amperes earth current collected per foot of wire. Such an even ground current must be accompanied by good uniformity in distribution of earth potentials and an elimination of points of high earth current density and great earth potential differences, which result in high tower potentials. An effective utilization of the entire length of the counterpoise wire is therefore indicated at approximately 10,000 amperes. If the current ranged above this value more length would appear to be desirable, while for lower currents the remote end of the 150-foot wire would be of questionable value. On this basis 4 radial 150-foot wires would take care of a 40,000-ampere tower current, which is considerably above the average in magnitude.

In 13 cases simultaneous readings were obtained on the long and short counterpoise wires. In Table VI are given the readings in the short counterpoise and in the long counterpoise at the 3-foot station. Comparing the summation of all the readings on the long and short counterpoise wires, we find the ratio of current in long counterpoise to current in short counterpoise to be about 4.3. The ratio of lengths is 3.75, indicating that the current taken by a radial counterpoise of this sort, all conditions being equal, is practically in proportion to its length.

In figure 4 are plotted the ratio of current in the 150-foot counterpoise to the current in the 40-foot wire as

**Fig. 4. Relation between current in 150-foot and 40-foot counterpoise wires**




abscissas against the current in the 150-foot counterpoise as ordinates from the data of table VI.

With these data a tendency for the higher counterpoise currents to give higher ratios can be noted. This agrees shows the remote section of a buried ground wire to gathering in a proportionally greater amount of current at higher stroke currents. At some 5 to 6 thousand amperes the 2 wires are carrying currents in the same proportion as their lengths. Below this value on an average the short counterpoise carries a greater proportional part and above it the longer wire carries the greater proportion. Now, it seems to be a reasonable rule that the wire will carry the most current which performs most effectively in reducing earth potentials. This reduction of earth potentials is also the mechanism whereby the counterpoise serves to hold down the tower potential and prevent insulator flashover. Accordingly, a reasonable conclusion from the ratio data appears to be that currents below 5 to 6 thousand amperes the 150-foot wire is more than necessary and for higher currents the 40-foot wire too short. These considerations, of course pertain to relative length and it is important to observe that the ratio-current magnitude trend is not clearly demonstrated by the available data. The variations in soil conductivity quite likely partially obscure this trend.

Table VII shows the relation between the total current

(*Concluded on page 189*)

**Table VII—Relation Between Current in Tower Legs and Counterpoise Wires, Glenlyn-Roanoke 132-Kv Line, 19**

| Reference Number | Tower Number | Total Tower Current, Amperes | Total Counterpoise Current, Amperes | Ratio To Current Counterpo Curre |
|---|---|---|---|---|
| 1–3 | 25 *G* | 30,300 | 20,800 | 1.46 |
| 2–1 | 7 *R* | 7,000 | 9,400 | 0.75 |
| 2–1 | 8 *R* | 10,800 | 20,400 | 0.53 |
| 3–3 | 20 *G* | 16,700 | 22,000 | 0.76 |
| 3–3 | 21 *G* | 22,000 | 26,200 | 0.84 |
| 3–3 | 22 *G* | 52,100 | 48,600 | 1.07 |
| 3–3 | 23 *G* | 21,500 | 29,000 | 0.74 |
| 3–3 | 24 *G* | 9,000 | 6,500 | 1.39 |
| 1–2 | 9 *G* | 34,200 | 35,200 | 0.98 |
| 1–2 | 10 *G* | 17,000 | 13,200 | 1.29 |
| 6–1 | 12 *G* | 20,000 | 20,800 | 0.96 |
| Summation | | 240,600 | 252,100 | 0.95 |

In all cases the polarity indicates current traveling from free end of counterpoise to tower and from bottom of tower to top.

# Arc Characteristics Applying to Flashing on Commutators

By R. E. HELLMUND
FELLOW AIEE

**This paper gives the results of experimental investigations relating to arc characteristics as they apply in commutator flashing. A knowledge of these characteristics is necessary for the application of the theory outlined in a previous paper[1] on flashing of commutators by the same author, as well as for the investigation of flashing due to other causes.**

IN A previous paper,[1] a method of analyzing flashing on commutators caused by jumping of the brushes was given. This method assumes that an arc ($S$) is formed between segment ($a$) and brush ($b$) when the brush leaves the commutator, as indicated in figure 1$A$. This arc is likely to persist as shown in figure 1$C$ after the commutator has moved a certain distance and the brush has returned to the commutator. The method consists essentially in comparing during successive periods the voltage necessary for sustaining the arc with the voltage induced in the armature coils and existing between the arc terminals. For a practical application of this method, a knowledge of the arc characteristics applying to the commutators is therefore a prerequisite, and it is the purpose of the present paper to give the results of experimental investigations of this nature.

The data given will also be of value in investigations of flashing brought about by other causes. In railway motors, for instance, flashing is caused at times by certain transient conditions applying when the voltage of the motor is suddenly re-established while the motor is running and after an interruption of power supply caused by section breaks in the line, trolley bouncing, etc. Flashing is further caused by transient conditions applying in generators when a short occurs in the line, or in large motors when there is a short-circuit in the system and the motors temporarily act as generators feeding current into the short. Under these various operating conditions, flashing is caused by an appreciable voltage being induced in the short-circuited armature coil ($g$) during these temporary or transient conditions. When, as shown in figure 1$B$, this short-circuit current is opened because of segment ($a$) leaving the brush ($b$), an arc ($S$) is formed. As in the case of brush jumping, the sustaining of this arc depends upon the relative values of the voltage necessary for sustaining it and the voltages existing between the terminals of the arc for various successive positions of the commutator segment ($a$). Therefore, we are again interested in a knowledge of the arc characteristics around the commutator. This case may be somewhat complicated by the fact that a new arc is formed on each segment leaving the brush, resulting possibly in the formation of a number of different arcs on the several commutator segments, as indicated in figure 2 by $S$, $S_1$, $S_2$, and $S_3$. However, a knowledge of the arc characteristics of the individual arcs formed should prove a desirable first step toward a complete analysis of the various transient conditions.

In order to study the arc characteristics around the commutator, a simple arrangement as shown in figure 3 was used in our experimental work. A number of connected segments ($a$) of a commutator ($C$) were connected to a slip ring ($D$). A d-c voltage source was connected through an adjustable resistance ($r$) to the brushes ($b$ and $b_1$). Whenever the segments ($a$) are in contact with the brush ($b$), current flows and is interrupted by means of an arc ($S$) when the last segment ($a$) leaves the brush ($b$). With this operating condition, oscillograms were obtained giving the current as well as the voltage across the arc terminals. An example of these oscillograms is shown in figure 4. Tests were carried out with different initial current values and also for different speeds of the commutator. From an analysis and careful scaling of these oscillograms, curves such as shown in figures 5 and 6 were derived for a number of different speeds of the commutator.

The results for only 2, but widely different, speeds are given in these 2 figures. The full-line curves show the relation between arc current and arc voltage as scaled directly from the oscillograms. The test points thus obtained and entered in the figures gave in most cases rather smooth curves, which is to be expected because of the fact that the oscillograms gave rather smooth curves, as indicated in figure 4, and were void of erratic irregularities frequently encountered in connection with arc phenomena. Whatever discrepancies do exist are due essentially to difficulties in scaling the oscillograms, some of which were not taken on as large a scale as that of figure 4. It was furthermore observed that in spite of the widely diverging speeds at which these tests were made, the solid-line curves of figures 5 and 6, when compared for an equal initial current, did not vary appreciably from each other for different speeds. In considering all the curves drawn, it is difficult to find any marked tendency of variation with speed in one direction or another in the solid-line curves. Further analysis revealed, however,

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1. For all numbered references see list at end of paper.

that with a given current, a certain arc voltage corresponds to different arc lengths with different operating speeds. By means of the timing curves taken with the oscillograms, it was possible to calculate the arc length corresponding to any test points. This was done

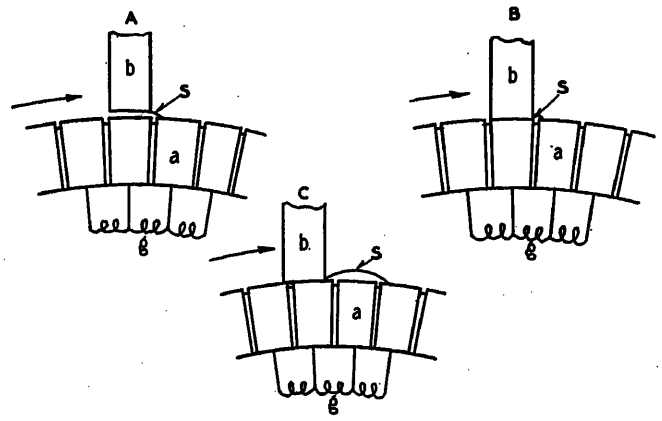



**Fig. 1. Illustration of arc formation prior to flashing on commutators**

and the points entered in figures 5 and 6 corresponding to a certain arc length were marked by like designations; thus the dotted-line curves each corresponding to a given arc length, as indicated, were obtained.

The agreement of the test points with the dotted-line curves is not quite so good as with the solid-line curves, nevertheless the consistency of the results is quite remarkable, taking into consideration the usual difficulty in obtaining consistent results with arc phenomena. The reason for this seems to be that in these tests the condition of the air currents near the arc was more or less definitely established by the nature of the air film carried around near the surface of a rotating cylinder for any given speed. Usually arc phenomena tested in open air are subject to varying air currents caused by convection and other causes, and they frequently are further influenced by electromagnetic effects, all of which lead to irregularities. Furthermore, the electrode spots are often moved about by these irregularities, which further increases

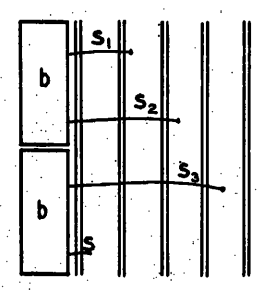



**Fig. 2. Illustration of multiple arcs forming on commutators under certain conditions of flashing**

the difficulty of obtaining consistent results. (This is noticeable on some of the oscillograms given toward the end of the paper which show very irregular curves during periods when the location of the electrode spots is changing. See figure 12.)

In considering the phenomena further, it must be appreciated that while the dotted-line curves somewhat simulate the usual arc characteristic curves, they do not represent a static relation between current and voltage because the points to which the curves are drawn are in all cases the points from a transient arc condition obtained by starting with a certain value and lengthening the arc while the current decreases and the voltage increases. By means of the full-line curves, it is possible to determine the starting currents corresponding to the current values at the points of intersection between the

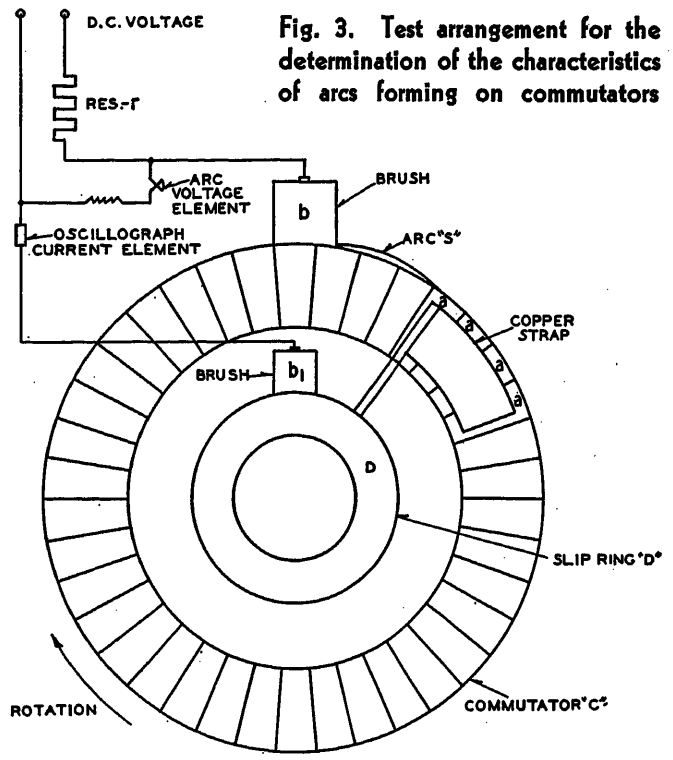



**Fig. 3. Test arrangement for the determination of the characteristics of arcs forming on commutators**

solid-line and the dotted-line curves. Normally, that is with constant length of arc and without high air velocity around the arc, it is to be expected that with a diminishing arc current the voltage will be the lower the shorter the time interval allowed for the decrease in current. The reason for this is that during a shorter time interval, less deionization will take place. Comparison of definite points between the low- and the high-speed curves in figures 5 and 6, respectively, shows that the opposite condition applies here. If we consider, for instance, the 20-ampere point for the $2^1/_2$-inch arc length in figure 5, which corresponds to a starting current of about 28 amperes, we find a voltage of 167 volts for the slow speed. If we then consider the 20-ampere point for the $2^1/_2$-inch arc length in figure 6, we find a higher voltage of 215 volts in spite of the fact that the time of drawing this arc was only $^1/_3$ that of figure 5 and that the starting current was over 30 amperes. Likewise, if we consider the 14-ampere point of the 1-inch arc length, with a starting current of about 18 amperes the voltage indicated is 115 volts for the low speed, while with approximately the

same starting current, a voltage of 155 is obtained for the high speed. The conclusion drawn from this is that the speed at which the commutator is rotating has a marked influence upon the deionization, resulting in higher voltages for a given current with the higher speed. This is more clearly shown in figure 7, which gives the arc voltages for certain arc lengths at different speeds for instantaneous arc currents of 10 and 60 amperes. As should be expected, the speed is of relatively minor influence with the shorter arcs but is, in general, of greater influence with the longer arcs. It will be further noted that with the heavier currents the influence of the speed is not very marked, while with the small currents it is appreciable. Since the voltages for the transient currents for which the curves of figure 7 are plotted may be influenced by the initial currents

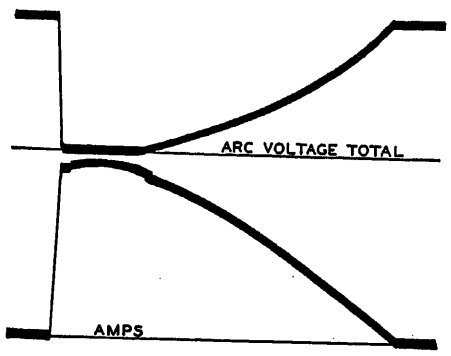



**Fig. 4. Tracing of oscillogram giving arc current and arc voltage**

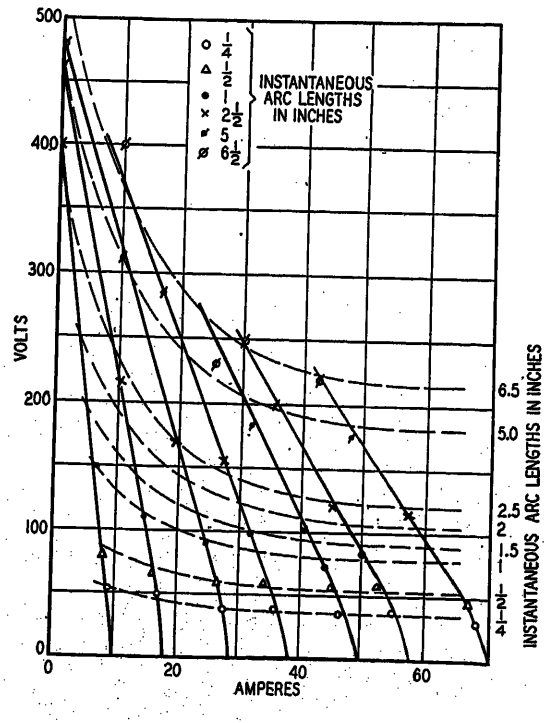
and the corresponding ionization, the values of the initial currents are of interest. The values of these initial currents happen to be practically constant for each of the curves and therefore the difference in voltages evidently is caused by the difference in speed; these values are shown at the right of the curves in figure 7.

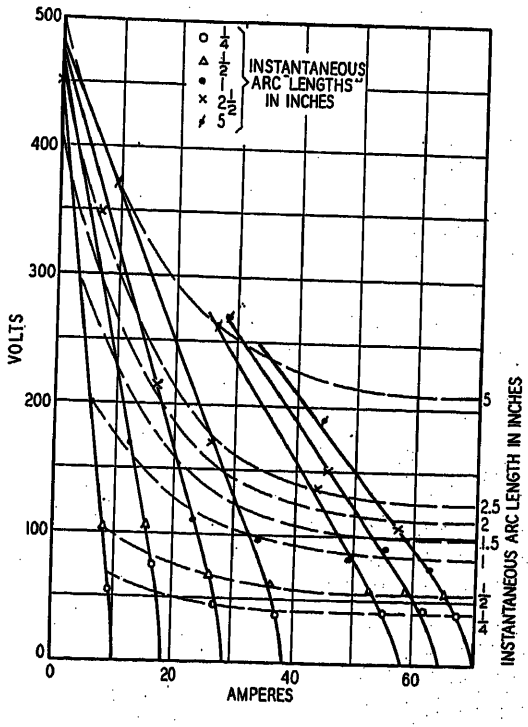
Although, as already pointed out, the curves in figures 5 and 6 cannot be considered as representing static arc characteristics, figure 8 has been prepared showing a comparison of some of the curves of figures 5 and 6 with the static-arc characteristics as calculated from a formula given by Rüdenberg.[2]

In commutator flashing we do not at any time deal with constant arc currents, but the conditions are much the same as the test conditions of figure 3. What we are really interested in, especially in the light of the theory advanced in my previous paper,[1] is the arc voltage for different lengths of arc for any given initial arc current and for various commutator speeds. The curves in figures 9*A* and 9*B* show this. These curves can be directly applied as the arc voltage curves designated *A*-*B* in the previous paper and compared with the curves of the voltages induced in the armature between the arc terminals. Figure 10 gives a number of these voltages as compared with the curves applying to given initial currents indicated for a speed of 2,200 feet per minute. The distance to the points at which the arc-characteristic curves and the induced-voltage curves cross each other should, therefore, be a direct indication of the comparative likelihood of motor flashing at 2,200 feet per minute for the different initial currents and for the 3 different curves of induced voltage corresponding to different main-pole shapes.

In order to check any influence which different brush locations might have upon the arc characteristics, a number of tests were made with the brush mounted at the bottom of the commutator. The results thus obtained did not differ materially from those obtained with the brush mounted at the top. Visual inspection indicated that the arc formed close to the surface of the commutator with the brush in either position, and, in general, the phenomena seemed to be the same.

With the testing arrangement in figure 3, it is evident




**Figs. 5 (left) and 6 (right). Curves showing relation of voltage to current as obtained from oscillograms such as shown in figure 4 (full lines), and curves showing relation of voltage to current for various lengths of arc (dotted lines)**

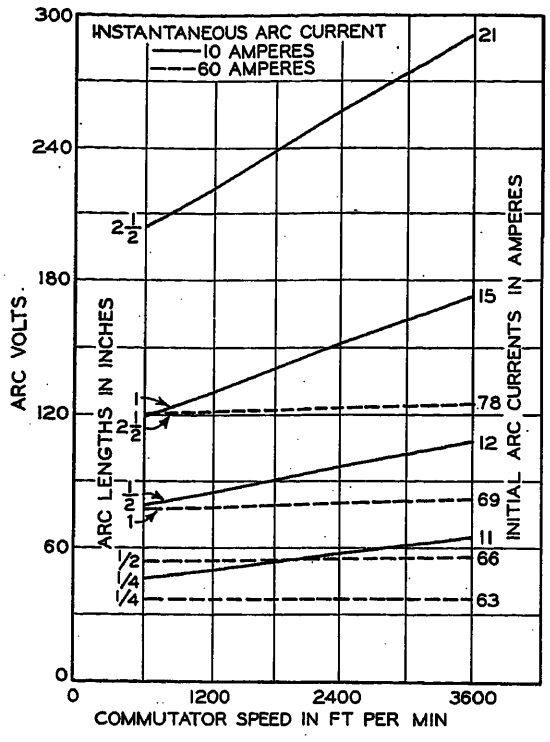



**Fig. 7 (left). Curves showing arc voltage as influenced by speed for various currents and arc lengths**

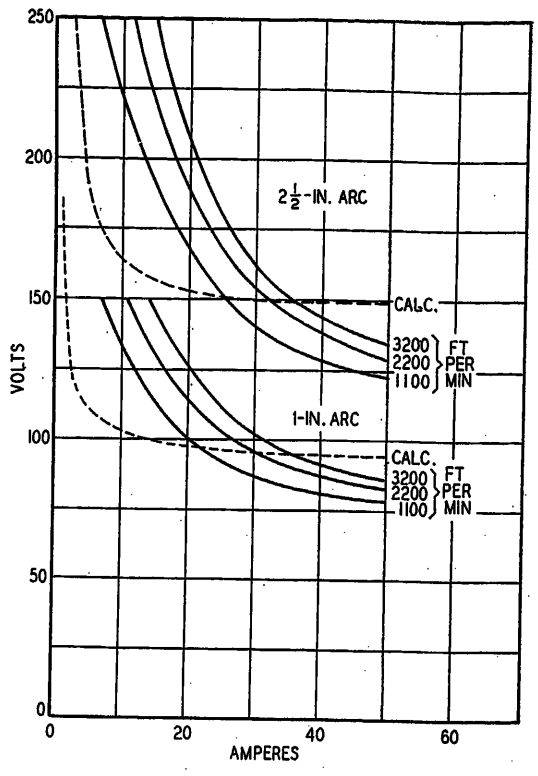



**Fig. 8 (right). Comparison of calculated static arc characteristics with transient characteristics tested on commutators**

that the hot-cathode spot would very likely remain on the last segment (*a*) for the entire duration of the arc, unless there were appreciable air currents or magnetic effects to disturb conditions. However, in checking some tests made on motors with artificially produced brush jumping, it seemed that at times flashing did not occur when according to the basic theory given in my previous paper[1] it should have occurred. This theory assumes that the hot-cathode spot remains on the segment on which it originally forms. The only possible explanation therefore seemed to be that in reality the hot-cathode spot moved from the original segment in a backward direction to other segments, thus preventing the drawing of the arc into the high-voltage regions of the commutator. In order to check this a test arrangement as shown in figure 11 was devised. A number of segments (*a*, *z*, *y*, *x*) were connected together as in the previous tests and the current from these segments was conducted through a slip ring (1). The 2 segments (*b* and *c*) following the interconnected segments were also connected to slip rings 2 and 3, respectively. The voltage of the arc was recorded as before by the oscillograph and the currents in the 3 slip rings were also recorded by the current elements of an oscillograph. On the commutator surface 2 strips of insulating material were arranged as shown in figure 11 to lift the brush slightly off the commutator when it was about to pass segment (*a*). This, of course, resulted in the formation of an arc (*S*), the current of which was measured through the current of slip ring (1) and it is evident that in case the hot-cathode spot would move to segments *b* and *c*, this would be indicated by currents in the slip rings 2 and 3. In order to determine the effectiveness of this arrangement, some tests were first made with the brush negative—that is, with the hot-cathode spot on the brush and the anode end of the arc forming on segment (*a*). Figure 12*A* is a tracing of an oscillogram taken under this condition. As is well known, the anode spot moves readily and it will be seen that the arc formed on segment (*a*) at the left end of the oscillogram, persisted for a short period, and then transferred to segment (*b*). Subsequently the current was divided for a time between segments (*b*) and (*c*) and finally transferred entirely to segment (*c*). In the case of the second arc on the same oscillogram, the current again is on segment (*a*) for a certain period, then is transferred for a short time to (*b*); and then instead of dividing as in the first case, is entirely transferred to segment (*c*). The latter condition is obtained in the majority of cases with a negative brush.

After these preliminary tests, the brush was made positive and a total of 22 arcs was recorded. It was found that in only 2 of these 22 cases a transfer of the arc from segment (*a*) to other segments took place. In view of the fact that the brush is wider than segment (*a*), it could not be safely assumed that the original arc always formed on segment (*a*), there being the possibility that the brush when lifted by the insulating strips would tilt and therefore make contact last with segment (*z*) preceding (*a*). In a case like this, the subsequent move of the arc to segment (*a*) would not be recorded by the oscillograph. For this reason the brush was beveled, as shown by dotted lines, sufficiently to insure that it would make its last contact with segment (*a*). A total of 7 arcs were recorded with this arrangement and it was found that a transfer of the hot-cathode spot occurred in 2 cases. Figure 12*B* shows the currents in 3 of the arcs formed. It will be seen that in 2 of the 3 cases in this oscillogram no transfer took place, but in the third a transfer occurred and the current split between segments (*b*) and (*c*) for the remainder of the arc duration.

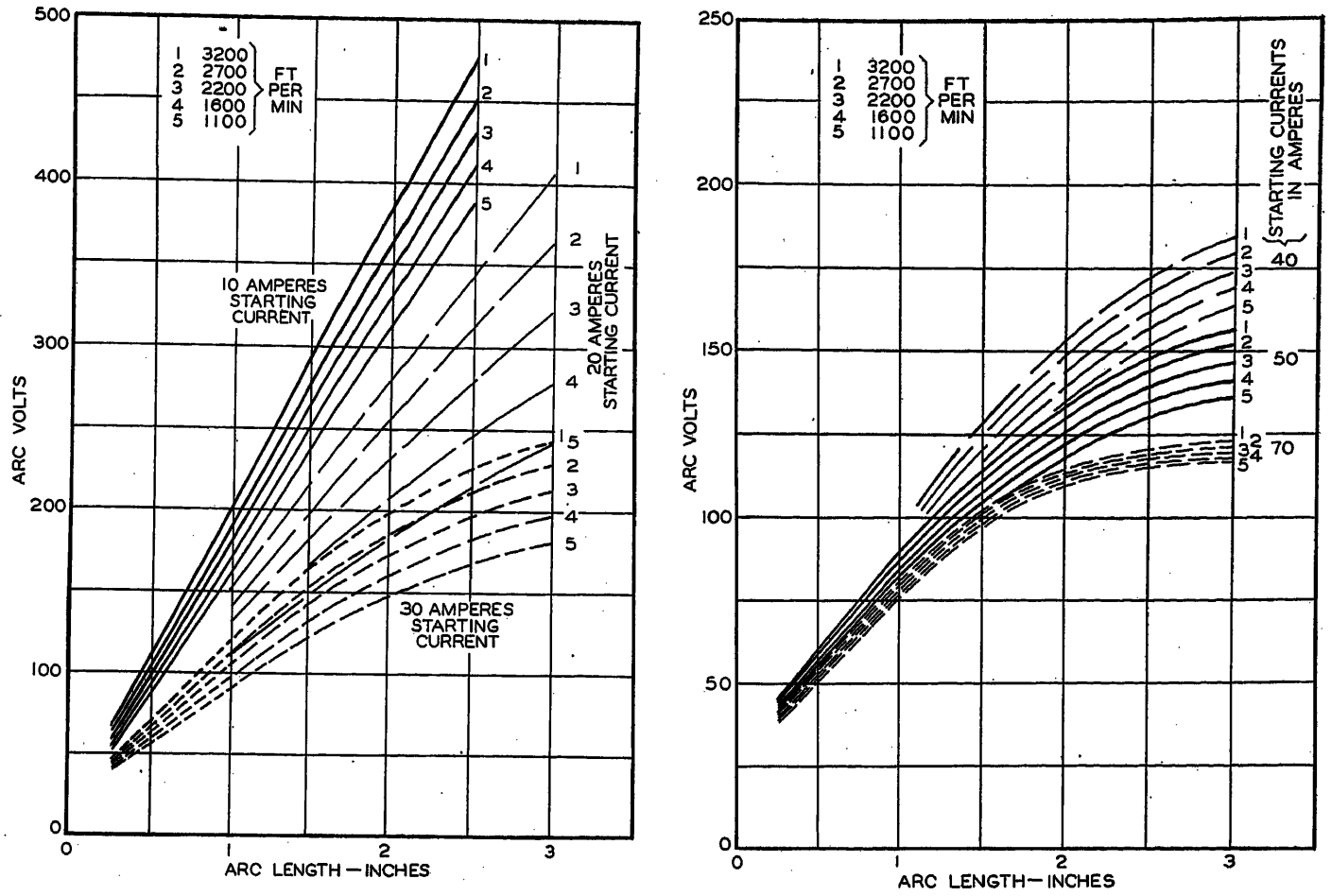



**Fig. 9A (left) and 9B (right). Curves showing relation of arc voltages to arc lengths for various values of speeds and initial currents**

In order to provide for the possibility of the arcs transferring to segments following segment (*c*), the arrangement was changed so that segment (*c*) was connected to a number of succeeding segments (*f*, *g*, and *h*), as indicated by the dotted connection in figure 11. A typical oscillogram taken under this condition is shown in figure 12*C*. It will be seen that with the first 2 arcs no transfer took place; with the third a transfer of current to segment (*b*) occurred, and subsequently to the sector including segment (*c*). The sudden breaks in the current of slip ring (3) seems to indicate a further shift of the hot-cathode spot from one of the connected segments to another. The formation of the fourth arc seems to be similar to that of the third, except that the arc transferred from the leading to the lagging sector without touching the intermediate bar.

In another oscillogram shown in figure 12*D*, it will be noted that a transfer from the leading to the lagging segment took place in 2 instances, while no transfer occurred in the third. It will also be noted that the time at which the transfer took place in the first 2 cases differs. The oscillogram shows no definite evidence of an intermediate time during which segment (*b*) carried the current.

Summarizing: It is found that of 125 arc formations recorded, no transfer took place in 84, or 67 per cent of the total. Eliminating the tests with unbeveled brushes because of the uncertainty as to whether transfer took place between segments (*z*) or (*a*), it is found that of the remaining 103 arc formations there was no transfer of any kind in 64, or about 62 per cent of the cases. Current values of 30 and 65 amperes were used in the tests. With the 30-ampere current, transfer took place in 21 out of 55 cases, or 38 per cent; with the 65-ampere current, in 20 out of 71, or 28 per cent. Considering only the tests with beveled brushes, with the 30-ampere current a transfer took place in 44 per cent of the cases; with the 65-ampere current, in 33 per cent. There is, therefore, a general indication that with a lower current the tendency to transfer is greater, though it may be inadvisable to draw such a definite conclusion without carrying on a greater number of tests. At speeds of about 1,600, 2,200, and 3,200 feet per minute, the percentages of cases in which transfers took place were 43 per cent, 19 per cent, and 44 per cent, respectively, when all tests are considered; at speeds of 1,600, 2,200, 3,200, 4,300, 4,900, and 5,400 feet per minute, the percentages are 53 per cent, 18 per cent, 47 per cent, 11 per cent, 22 per cent, and 45 per cent, respectively, when only the tests with the beveled brushes are taken into account. These figures do not indicate any very definite tendency to transfer with increasing speed.

It was thought that the tendency of the arc to transfer might be influenced somewhat by the undercutting of the commutator and some tests were therefore run with under-

cutting and some without. However, the percentage of transfers under the 2 conditions was practically the same.

For the purpose of determining whether the position of the brush had any marked influence, tests were made with the brush on top and also at the bottom of the commutator. With 65 amperes, the percentage of transfers was 44 with the brush on top and 40 with the brush at the bottom; with 30 amperes, the percentages were 40 and 62.5, respectively. Since the number of tests for each of the 4 conditions is not very large, it would be unwise to conclude that there is any decided difference between the 2 brush locations; as a matter of fact, it seems that the location of the brush makes very little, if any, difference.

Some of the above data are given merely for the purpose of answering certain questions that may occur to those interested in the problem. The essential fact brought out by the rather extensive series of tests is that a transfer of the hot-cathode spot from the segment on which it is first formed to other segments takes place at times, but that this is more or less a matter of chance and certainly cannot be depended upon for reducing the tendency of a motor to flash. In other words, in order to be safe the designer should assume that the hot-cathode spot may travel with the segment on which it is first formed, which condition in turn is the one most likely to bring about objectionable flashing conditions.

In conclusion it may therefore be stated that with curves as presented in this paper and the fundamental method outlined in my previous paper,[1] it is possible to analyze the inherent electrical tendency of motors to flash when the brushes jump. It is appreciated that this phenomenon is also greatly influenced by the length of time the brush is off the commutator, which in turn is influenced by a great many mechanical factors, such as workmanship in the building of the commutators, seasoning of the commutators, balancing of the armature, mounting of the motor as a whole and resultant mechanical vibrations, commutator irregularities brought about by commutation characteristics and the type of brush used, brush tension applied to the brushes, weight and elasticity of the brushes, etc. It is obvious that the great variety of influencing factors makes it practically impossible to determine theoretically the time the brush is likely to leave the commutator at different commutator speeds and that a complete and exact theoretical analysis of this flashing problem therefore seems impossible. However, the method and data given are useful and of practical value in a comparative quantitative analysis of different motor designs and, in particular, of their field distributions. Moreover, some of the variables enumerated, such as the commutation characteristics, the choice of brushes, etc., can be handled by the designer in such a way as to eliminate them as factors of practical importance. On the other hand, the variations caused by manufacturing and maintenance operations can, with reasonably controlled shop processes, be reduced to chance phenomena of a limited amplitude of variation. Consequently, the comparative analysis outlined furnishes a means by which the adequacy of new designs can be predicted with a considerable degree of assurance. As already indicated at the beginning of the paper, the experimental results given here will also be useful in other types of flashing. A more complete analysis of these will require experimental investigations regarding the initial current that may exist at the brush when a short-circuited coil passes from under the brush under different conditions of load and commutation. Furthermore, it would be necessary to make a quantitative analysis of the transient current, field, and

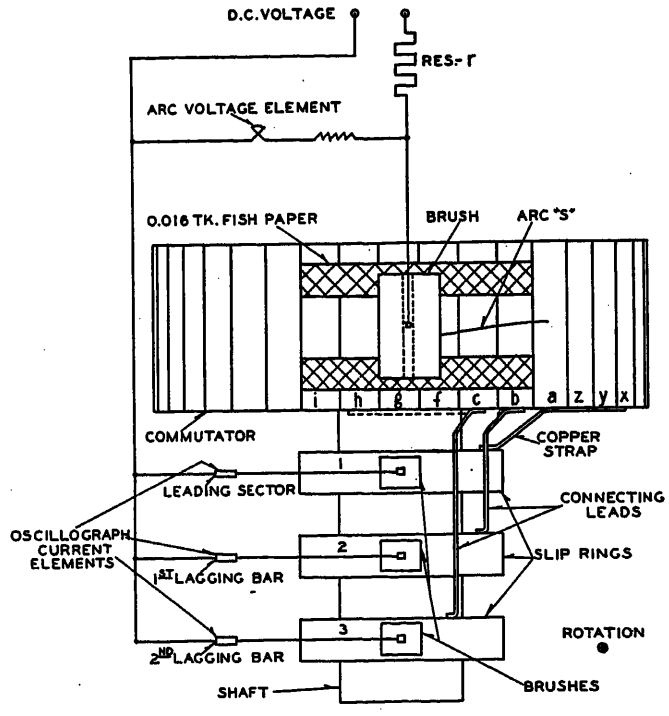



**Fig. 11. Test arrangement for investigating the tendency of the arc to shift from one segment to another**

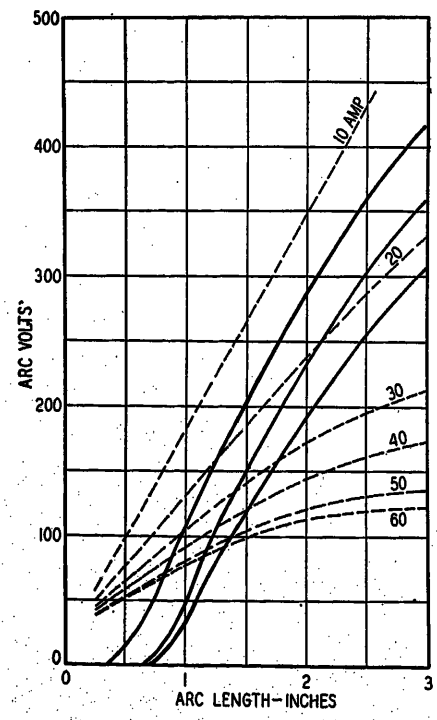



**Fig. 10. Curves comparing arc voltages with voltages as induced in armature with various field forms**

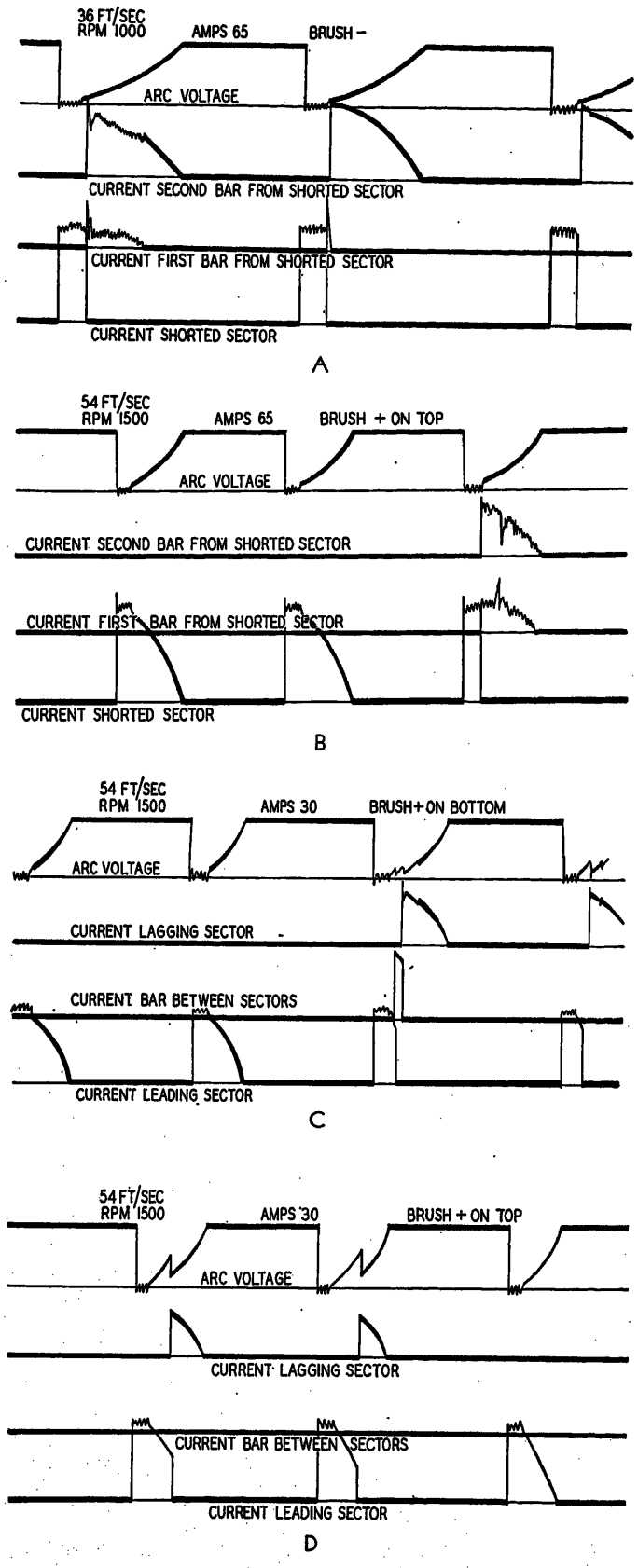



**Fig. 12. Oscillograms showing tendency of arc to shift from one segment to another**

voltage conditions existing in the machine at the time when flashing is likely to occur. However, through the judicious use of a qualitative analysis of these factors given by the author in an earlier article,[3] together with the considerations and data given in this and the previous paper,[1] considerable progress has been made in predicting the flashing characteristics of motors during transient conditions such as may exist after temporary interruptions of power supply to the motors.

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# A Single-Element Polyphase Directional Relay

(*Continued from page 80*)

## Appendix III

### Conductor Voltages at Location of Arc Fault

| Three-Phase Fault | Phase-to-Phase Fault |
|---|---|
| $E_1 = I_1R$ | $E_2 = -I_2(Z_2 + Z_L)$ |
| $I_1$ is in phase with $E_1$ | $E_1 = -I_2(Z_2 + Z_L + 2R) = I_1(Z_2 + Z_L + 2R)$ |
| | $-I_2$ and $I_1$ lag $E_2$ and $E_1$, respectively |

## Appendix IV

### A. Connections Figure 3a

The total input to the relay is

$$P_R + jQ_R = E_c\bar{I}_b + \underline{E_b\bar{I}_b} - E_b\bar{I}_c + E_a\bar{I}_c - E_a\bar{I}_b - \underline{E_b\bar{I}_b} + E_b\bar{I}_a - E_c\bar{I}_a$$

The underlined terms cancel and

$$-E_a\bar{I}_b + E_c\bar{I}_b = (E_c - E_a)\bar{I}_b = -E_B\bar{I}_b$$
$$-E_b\bar{I}_c + E_a\bar{I}_c = (E_a - E_b)\bar{I} = -E_C\bar{I}_c$$
$$-E_c\bar{I}_a + E_b\bar{I}_a = (E_b - E_c)\bar{I}_a = -E_A\bar{I}_a$$

Therefore

$$P_R + jQ_R = -E_A\bar{I}_a - E_B\bar{I}_b - E_C\bar{I}_c$$

### B. Connections Figure 3b

The total power to the relay is

$$P_R + jQ_R = -E_C\bar{I}_a - E_A\bar{I}_a + E_A\bar{I}_c + E_B\bar{I}_c - E_B\bar{I}_a - E_A\bar{I}_a + E_A\bar{I}_b + E_C\bar{I}_b$$

since $E_A + E_B + E_C = 0$

$$E_A\bar{I}_b + E_C\bar{I}_b = (E_A + E_C)\bar{I}_b = -E_B\bar{I}_b$$
$$E_A\bar{I}_c + E_B\bar{I}_c = (E_A + E_B)\bar{I}_c = -E_C\bar{I}_c$$
$$-E_C\bar{I}_a - E_A\bar{I}_a - E_B\bar{I}_a - E_A\bar{I}_a = -(E_C + E_A + E_B + E_A)\bar{I}_a = -E_A\bar{I}_a$$

therefore

$$P_R + jQ_R = -E_A\bar{I}_a - E_B\bar{I}_b - E_C\bar{I}_c$$

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# A Review of Overhead Secondary Distribution

By W. P. HOLBEN
MEMBER AIEE

**This paper provides a comparison of results of 5 economic studies* that were made to determine the economic relationship between conductor sizes and distribution transformer sizes for various load densities and rates of load growth. The progressive method of distribution design, which provides additions rather than replacements, has been found most economical. Increase in load density can be handled most economically by the subdivision of secondary mains and the installation of intermediate transformers. Numbers 4, 3, or 2 conductors and 15-kva transformers should be favored for overhead secondary distribution in residential areas in cities and towns. Rural lines and service to rural communities are not considered in this comparison.**

SPECIAL interest in the economics of secondary distribution design has developed during recent years among the various electric utility companies. Extensive studies covering technical and practical features of secondary design have been made and reports completed to show the results of these studies in a most interesting and enlightening manner. Through the courtesy and co-operation of 5 operating companies, and the authors of the respective reports, it is now possible to present the combined results of these studies in a comparative form.

The comparisons of the conclusions reached in the various investigations are especially interesting, since they represent a variety of operating conditions, locations, and engineering and operating opinions. There is sufficient similarity in the conclusions reached to indicate that all these reports are based on sound engineering principles and that, in general, the economic and technical solutions of such problems are not restricted by local conditions or individual opinions. On the other hand, certain qualified conclusions indicate the effects of good engineering judgment to meet special local problems, and provide ample reason for separate and independent studies based on conditions and practices in the various operating territories.

While no technical analysis will be undertaken in this paper, it is proposed to present the essential data and results in a concise manner, adding explanatory discussion only as may appear necessary to provide a better understanding of the variety of conditions and variables encountered in these investigations. Several of the reports include the complete technical analysis and tabulated results of each step of their computations. Each of these reports provides excellent reference material for any one interested in the economics of distribution design. Many of the fine points developed in the reports cannot be reviewed in this paper, but the writer highly recommends the use of the methods and the technique for similar studies. Each of the reports uses a somewhat different form of graphical analysis but all of them are extremely interesting.

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* This paper represents a composite review of the findings resulting from 5 separate studies on the subject of "Economics of Overhead Distribution Design." The author is therefore indebted to the company managements and the authors of the respective company reports, without whose contributions a paper of this type would be impossible at this time. The author is especially grateful for the constructive suggestions made as a result of the review of the paper in preliminary form. The following contributed to the studies on which this paper is based:

Boston Edison Company; report by A. H. Sweetman and St. George T. Arnold, dated December 29, 1934.

Detroit Edison Company; report by H. P. Seelye and E. L. Leinbach, dated September 1, 1935.

Duquesne Light Company; report by C. T. Sinclair and W. P. Holben, dated January 16, 1934.

Philadelphia Electric Company; report by A. H. Kidder, dated November 5, 1934.

West Penn Power Company; report by Merrill DeMerit and R. C. McKee, dated June 1928.

## Summary

1. The progressive method of secondary circuit design, which provides additions rather than replacements, has been found most economical, and provides for growing loads on the basis of small increments of system capacity.

2. The economical conductor sizes are reported to be numbers 4, 3, and 2. The majority recommendation is number 2 where the reduction of appliance load flicker is a major need.

3. For load densities less than 20 kw per 1,000 feet, numbers 6 and 4 conductors show some advantage in annual costs but in some cases fail to meet flicker requirements. Over 20 kw per 1,000 feet, numbers 3 and 2 meet both the economy and flicker conditions.

4. For concentrated or high density load in commercial districts these recommendations do not apply, as lack of sufficient transformer poles or other congested conditions frequently necessitate larger conductors or special construction.

5. For overhead distribution in average residential districts in cities and towns, 15 kva transformers are generally most economical, with a later change to 25 and 37½ kva for higher densities resulting from growth in load and other special conditions.

6. For average residential loads, transformer loadings may range from 75 per cent at installation to 165 per cent at replacement, with the majority average recommendation 90 per cent to 150 per cent. (The overloading becomes permissible because of the usual low ambient temperature at the time of the winter peak load on transformers on overhead lines.)

7. Growing loads in overhead distribution areas can be handled most economically when the secondary system is designed on a progressive basis to allow for subdivision of secondary mains and the installation of intermediate transformers as required, including possibly some transformer relocations.

## Comparison of Methods, Assumptions, and System Conditions

Table I outlines the methods, conditions, and assumptions that were considered by the authors in their respective investigations, to arrive at the most economical secondary design.

### Type of System

The comparison in item 1 shows that each of the 5 companies has studied the problems and economics relating to a 3-wire single-phase overhead radial system of secondary distribution. Companies *A* and *B* have selected the "straight line" plan of distribution with continuous secondaries on streets with long blocks, using the 2-way feed from transformers. Three- and 4-way feeds are rare because of difficulty in locating transformers on corner poles. Cross ties between secondary mains and "H" construction are generally considered unnecessary and uneconomical as a result of these studies, except where closed radial loops or banked secondaries are in use. Company *D* reports the use of some radial loop construction, although not used extensively, while company *E* uses banked secondaries as well as radial circuits, with the former predominating. Company *C* does not state a preference. Where short branches from secondary mains are in use, the load on such branches may generally be considered located at the point of connection to the main, while the longest branch may be regarded as part of the main. For most of the studies, the load density has been considered in kilovolt-amperes or kilowatts per thousand feet, distributed uniformly along the main at the respective pole locations.

### Method of Comparison

Item 2 indicates that companies *A*, *B*, and *D* have based their investigations on a study of annual costs and companies *C* and *E* on a study of investment costs. Company *E* also includes capitalized losses in the total costs. It is interesting to note that company *B* has included also the annual lost revenue due to secondary drop.

Annual costs include the following items:

(*a*). Fixed annual charges (included by all companies)
1. Interest
2. Dividends
3. Taxes
4. Insurance
5. Depreciation

(*b*). Energy losses (included by all companies)
1. Transformer iron losses
2. Transformer copper losses
3. Secondary copper losses

(*c*). Operation and maintenance for (included by company *A*)
1. Transformers
2. Secondaries

(*d*). Lost revenue due to secondary drop (included by company *B*)

Depreciation as expressed in item (*a*)-5 is dependent in part on the life of transformers and secondaries resulting from failure, inadequacy, and obsolescence, but must also provide for retirement to meet new conditions resulting from growth in load. Replacement before the end of a normally useful life requires a larger retirement re-

### Table I—Comparative Statement of Methods, Assumptions, and System Conditions

| | | Company | | | | |
|---|---|---|---|---|---|---|
| | | A | B | C | D | E |
| 1. | Type of system | 3-wire 1-phase overhead radial straight-line | 3-wire 1-phase overhead radial straight-line | 3-wire 1-phase overhead radial | 3-wire 1-phase overhead radial straight-line, 2-way and 4-way | 3-wire 1-phase overhead radial and banked |
| 2. | Method of comparison | Annual costs | Annual costs incl. lost revenue due to secondary drop | Investment costs | Annual costs per peak kilowatt | Investment costs incl. capitalized losses |
| 3. | Cost of losses | | | | | |
| | Secondary copper | 0.0164 | | | 0.00456 and 0.01 | 0.005 |
| | Transformer iron | 0.0073 | 0.0035 and 0.007 | | 0.003 and 0.01 | 0.005 |
| | Transformer copper | 0.0155 | 0.0070 and 0.014 | | 0.00456 and 0.01 | 0.005 |
| 4. | Losses capitalized @ | | | | | 15 per cent |
| 5. | Equivalent hours of full load use per year | 1,500 | 1,095 and 2,190 | | 1,200 | 1,095 |
| 6. | Voltage regulation | | | | | |
| | Secondary drop, per cent | 2–3 | 3 | | | 2½ |
| | Total regulation | | | 121 volts (first customer) 109 volts (last customer) | 4–7 per cent (113–121) | |
| 7. | Allowable flicker | | | | 5 per cent of 115 volts 20 amp @ 50% power factor | 2–4 per cent of 115 volts 20 amp @ 50% power factor |
| | Noticeable flicker | | 2 per cent of 115 volts 15 amp @ 50% power factor | | | |
| 8. | Wire cost, triple-braided weatherproof, cents | 12 | 20 | | | 5, 10, 20, and 30 copper |
| 9. | Standard wire sizes | Nos. 6, 3, 1/0, and 4/0 | Nos. 6, 4, 2. 1/0, 2/0, and 4/0 | Nos. 6, 4, 2, and 2/0 | Nos. 6, 4, 2. 2 No. 1/0 and 1 No. 2 2 No. 4/0 and 1 No. 2/0 | Nos. 6, 4, 2 1/0, and 4/0 |
| 10. | Type of load | Residential and light commercial | Residential | Residential including ranges | Residential | Residential |
| 11. | Load growth rates, per cent | 7½ | 5, 10, and 15 | 5 | 5 linear 5 and 10 compound | "*a*," "*b*," and "*c*" |
| 12. | Load density, kilowatts per 1,000 feet | 10 to 110 | 10 and 20, initial load | | 7½, 15, 22½, and 30 | 10 to 100 |

serve, and most of the companies have therefore extended their investigations to include accumulated annual charges over a considerable period of years, ranging from 15 to 25 years.

### Cost of Losses

There is a wide variation in cost of energy losses used by the various companies in calculating this portion of the annual cost. This is apparently due at least in part to one being twice as great as the other, with cost curves resulting that are similar in form and an average variation in total costs of 7 per cent.

### Rate of Capitalizing Losses

Company *E* based their study on the total cost of transformers and secondaries in place on the system and included losses capitalized at 15 per cent. Company *C* refers to their comparison of investment costs but does

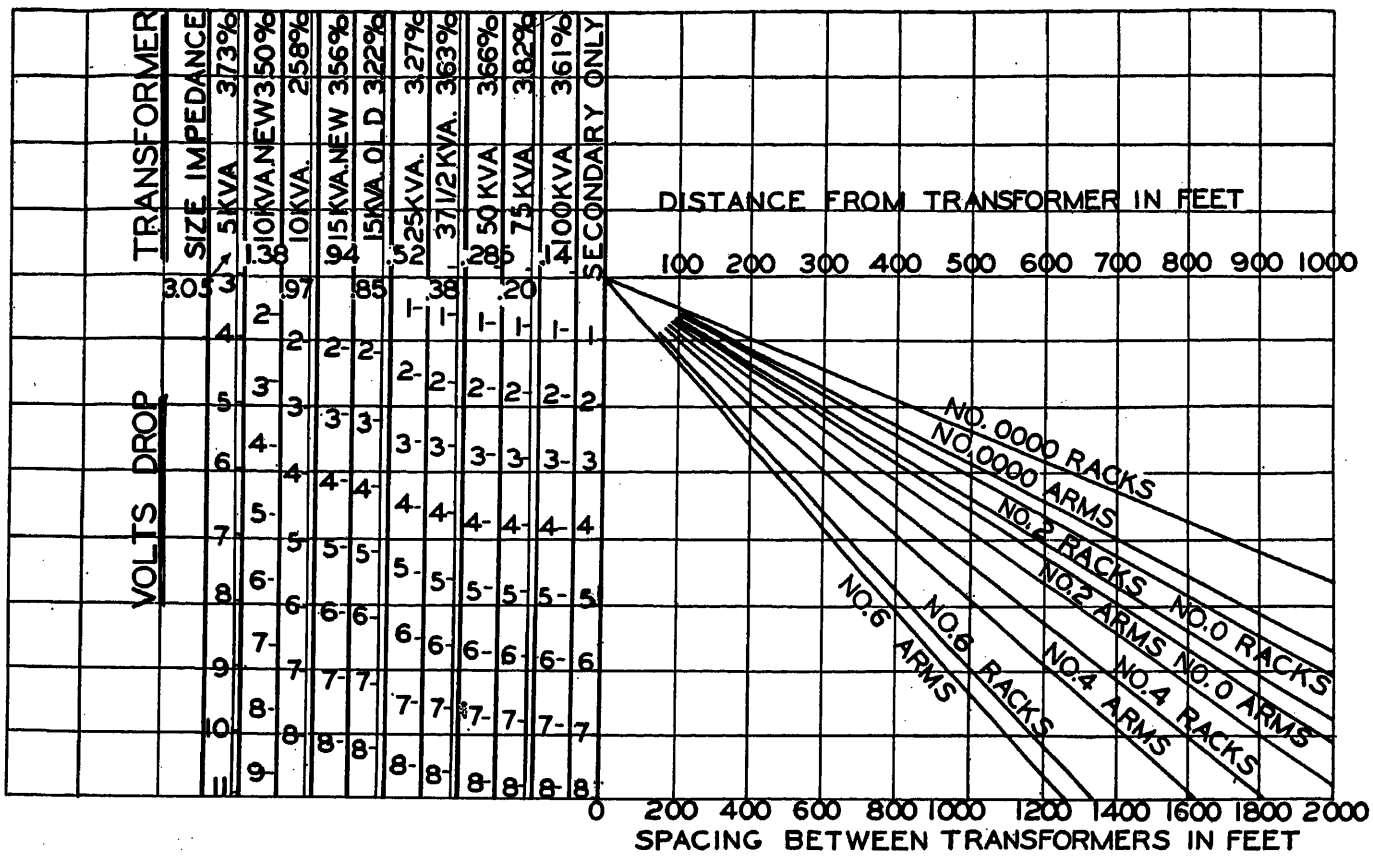



**Fig. 1. Flicker chart showing voltage drop with 20 amperes at 115 volts and 50 per cent power factor (company E)**

Use scale at left corresponding to transformer used for radial secondaries. This chart may be used for banked transformers by dividing scale readings at voltage drop by 2 if motor is midway between transformers

a difference in opinion regarding the demand charge factor as well as the load factor for such energy losses. Generally speaking, there should be very little difference in generating costs on these representative systems, but there will be a substantial variation when different points on the system to which the energy is to be delivered are taken into consideration. For example, since the secondaries are the remote part of the system, the unit cost for energy at that point will be a great deal more than at the generating station

It is unnecessary, however, to be greatly concerned about this point since losses represent less than 20 per cent of the total annual costs and regardless of the values used, the form of the annual cost curves are similar and therefore do not materially affect the choice of conductor or transformer sizes. This fact was substantiated by company *B* which included as part of their study the effect of using 2 values, not state the percentage for capitalizing losses. It is suggested however that a good practice to follow on this point provides a percentage for capitalizing losses equal to the annual fixed charges.

### Load Factor

The load factor based on the equivalent hours of full load use per year for the calculation of losses is reasonably uniform, as shown in table I, with one company somewhat more optimistic about their load curve for distribution transformers.

### Voltage Regulation

The allowable voltage drop in the secondaries represents a fairly uniform practice among all the companies. The total voltage regulation at the customer's service is the important consideration, and must include the voltage

drop in primary conductors beyond the regulating point on the main, the transformer drop, and the drop in the secondaries to the point of service. When transformers are located near the regulating point or when not fully loaded, it is possible to allow a greater drop in the sec-

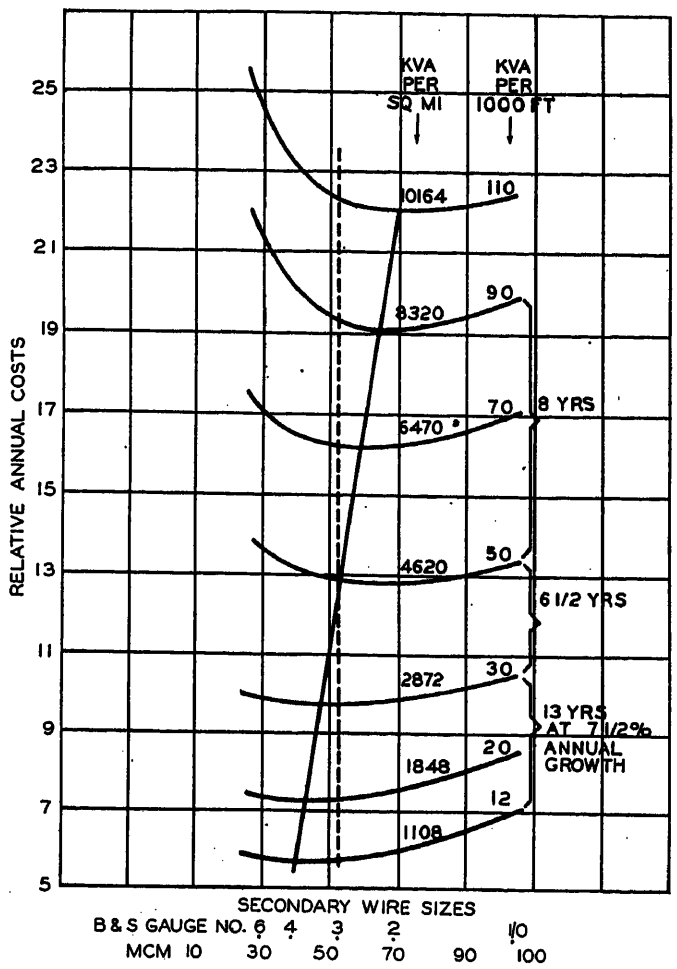



**Fig. 2. Annual costs of transformers and secondaries for various conductor sizes, pole spacing 100 feet, 2 per cent secondary regulation, and transformers 100 per cent loaded (company A)**

ondaries and still maintain satisfactory voltage at the customer's service, within the limits specified by company practice, or public service commission requirements.

A great deal of discussion has resulted from the claim that the feeder regulators may be used to correct transformer regulation. It should be noted that 2 conditions react against complete success in the use of regulators for this purpose:

1. The daily load cycle is not the same for all the transformers on a primary distribution circuit. Large present-day distribution circuits include transformers to supply residential, commercial, and industrial load.

2. The per cent loading of distribution transformers on any primary circuit is not the same, partly due to the difference in rate of growth and also because of the need to handle a large variety of load conditions and densities, therefore resulting in the use of a variety of transformer sizes.

### Allowable Flicker

The allowable flicker has been investigated by companies *B*, *D*, and *E*. The results in each case indicate that sudden voltage variations in excess of 2 per cent are noticeable and if they occur frequently will become the cause of complaints. Refrigerator motors and similar appliances are subject to starting currents of 15 to 20 amperes at 115 volts and 50 per cent power factor. As the density of these appliances increases, the question of flicker becomes a problem of major importance, and directly affects the choice of wire sizes and transformers as well as transformer spacing. Figure 1 has been prepared by company *E* to show voltage flicker due to appliance motors.

### Wire Costs

The effect of considerable variation in wire costs has been thoroughly investigated by company *E*. While an increase in wire price shows the effect of favoring smaller wire sizes, it is not a controlling factor in the choice of wire sizes. There is, of course, a natural reason for favoring larger conductors when copper prices are low but it cannot be adopted as a standard practice over an extended period of time. The use of an average price, such as 15 cents per pound for comparative studies, appears to be logical as a result of the facts developed in this investigation.

Iron losses 0.007 per kilowatt-hour for 8,760 hours annually

Copper losses 0.014 per kilowatt-hour for 1,095 hours annually

Sizes of wire for main sections designated on each curve. Number 4 wire used in all cases for short sections on side streets

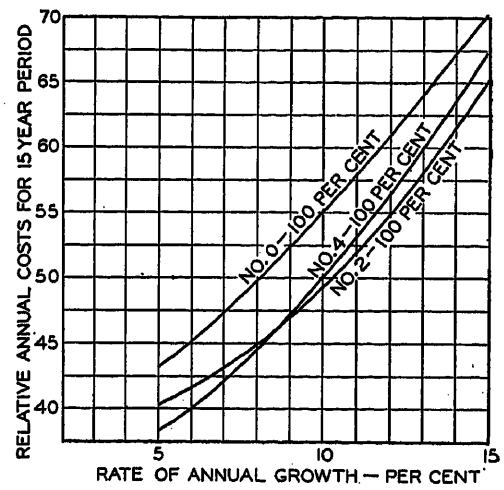



**Fig. 3. Total annual charges with varying yearly growth of load for straight line secondary distribution (company B)**

Initial loading on transformers 100 per cent, maximum loading approximately 150 per cent, and maximum secondary voltage drop of 3 per cent or less; initial load density of 20 kva per 1,000 feet. Total life of each layout 15 years with assumption for transformer life 30 years and wire 15 years

### Standard Wire Sizes

It will be noted that 4 of the companies use the even numbered wire sizes, while company *A* stocks and uses numbers 6, 3, 1/0, and 4/0. This naturally has some ef-

fect on the selection of the economical wire size as will be noted later, especially in the lower load densities.

### Type of Load

All of the studies apply to loads and economical designs in residential districts, but at the higher densities may apply equally well to light commercial districts, unless pole congestion and street conditions enter into the picture. Electric range load was studied by one company and is an important factor in some parts of the country. As ranges increase in number, the diversity and demand factors are expected to show a substantial improvement, and will be less of a problem than in the early stages of scattered and isolated installations.

### Load Growth Rates

Estimated load growth must necessarily include an element of speculation, although over a limited period of years, experience records show some fairly definite trends. Depressions have a serious effect not only on load growth records and charts but also result in greater caution in the selection of per cent load growth.

It should be noted that in residential districts growth in load may result from:

1. Increased usage
2. Additional customers
   - (*a*). Along existing secondary mains.
   - (*b*). Beyond but adjacent to existing mains.

These items do not follow the same trends in all districts and are the result of a large variety of conditions including changes in population, living and business conditions, new inventions, sales activities, and rates. Secondary design when intended to meet conditions over a long period of time must necessarily meet the composite or total result of all these factors.

Company *B* has gone into this matter of load growth very thoroughly by using 3 rates, 5, 10, and 15 per cent, respectively, as the basis for most of their charts. All of the companies have selected rates of load growth in connection with their computations of accumulated annual charges as indicated in table I.

Company *E* defines the rates of load growth *a*, *b*, and *c* as follows:

(*a*). Load 10 kw per 1,000 feet at beginning of first year
20 per cent load growth for first 5 years
7.5 per cent load growth for next 15 years

(*b*). Load 10 kw per 1,000 feet at beginning of first year
10 per cent load growth for first 5 years
5 per cent load growth for next 15 years

(*c*). Load 30 kw per 1,000 feet at beginning of first year
10 per cent annual growth to load density, 75 kw

### Load Density

Load density, both for static and increasing load conditions, has a very decided effect on the economics of secondary design. The density range has accordingly been covered from $7\frac{1}{2}$ to 110 kw per 1,000 feet of line, by the various companies as indicated in table I.

## Comparison of Results

Table II outlines the results of each of the studies, and the conclusions by the respective authors. These results represent the combined effect of economics, voltage regulation, flicker, load growth, load density, estimated life of conductors and transformers, copper costs, and available wire and transformer sizes. It is interesting to note 3 companies reporting flicker as one of the controlling factors in secondary system design at the low load densities, but voltage regulation and annual cost as the predominating factors at densities over 20 kw per 1,000 feet.

### Wire Sizes

Each of the companies reports results of a comprehensive study of costs to determine economical conductor sizes and 4 reports demonstrate in graphical form the

**Table II—Comparative Results of Economic Studies**

| | Company A | B | C | D | E |
|---|---|---|---|---|---|
| 1. Wire size numbers | | | | | |
| 20 kva per 1,000 feet and under | 3 | 4 | 4 minimum | 2 | 2 |
| Over 20 kva per 1,000 feet | 3 | 2 | 2,000 to 5,000 circular mils per kilovolt-ampere | 2 | 2 |
| 2. Transformer sizes, kilovolt-amperes | 15 for 12–60 kw/M feet<br>25 for 60–100 kw/M feet<br>$37\frac{1}{2}$ for 100–110 kw/M feet | | 2/0 maximum<br>25 maximum generally | 15 and 25<br>$37\frac{1}{2}$ maximum | 10 to $37\frac{1}{2}$ |
| 3. Transformer loading | | | | | |
| At installation, per cent | 90 | 100 | 100 for 3, 5, $7\frac{1}{2}$ kva<br>125 for 10 kva<br>140 for 15 kva and over | 75–100 | 50 minimum |
| At replacement, per cent | 140 | 150 | 165 | 150 | Over 125 |
| 4. Transformer spacing, feet | 1,200 for 5–19 kva/M feet<br>800 for 20–29 kva/M feet<br>600 for 30–49 kva/M feet<br>400 for 50 kva and over | | | 800 to 400 | 800 to 600<br>(2,000 to 600 studied) |
| 5. Load growth handled by* | Subdivision and replacement | Replacement and subdivision | Subdivision and replacement | Replacement and subdivision | Replacement and subdivision |

* Preferred method is shown first.

procedure followed in reaching their conclusions.

Both companies showing number 4 as the economical conductor size at low load densities, recognize the flicker limitations, but until complaints become numerous they seem to be willing to recommend the use of that size. This

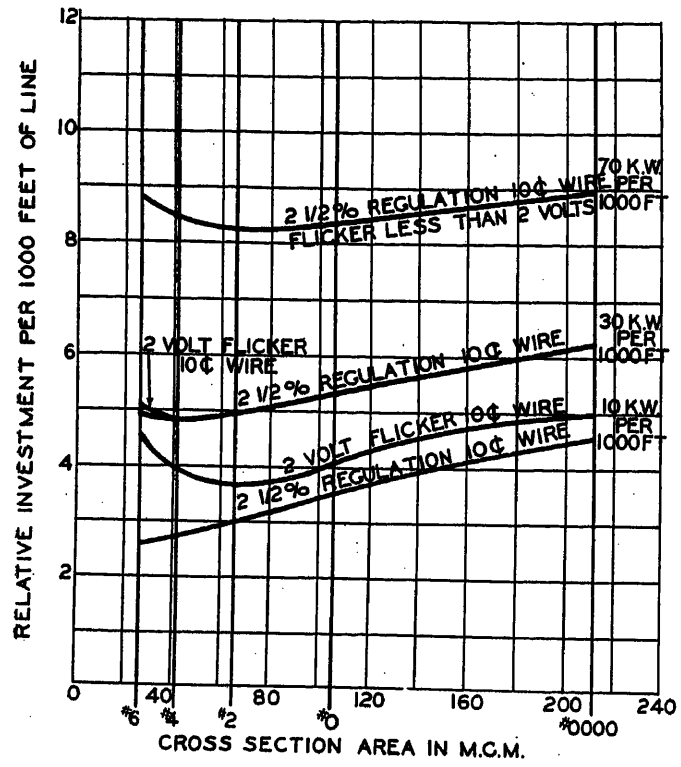



**Fig. 4. Variation in investment in secondary distribution with 2 volts allowable flicker for banked transformers and 4 volts for transformers not banked (company E)**

Assumptions include starting current of 115 volt motor, 20 amperes at 50 per cent power factor, voltage dip computed to customer's service pole, and wire price 10 cents. Motor location assumed to be midway between transformers

disadvantage may be offset to some extent by closer spacing of transformers. The other 3 companies report number 6 or number 4 conductors economical under 20 kw per 1,000 feet, but do not recommend them in order to avoid an early change to a larger size. Company *E* states the additional cost of number 2 is small and avoids flicker as well as the expensive operation of replacing secondary conductors. The choice of number 3 by company *A* is, of course, influenced considerably by the fact that numbers 4 and 2 are not stock sizes for them. This item of the respective reports shows unusual similarity of results. While conditions are recognized that may necessitate larger conductors for special applications, the consensus of engineering opinion favors these wire sizes over a large range of load densities.

Figures 2, 3, 4, 5, and 6 are typical graphs that were developed to demonstrate the relative economy of various conductor sizes. Company *C* did not include the charts used in reaching the conclusions stated in their report. Companies *B*, *D*, and *E* include an extensive series of charts for various conditions, but only typical charts are shown here.

### Transformer Sizes

On the question of transformer sizes the reports are not specific in their conclusions, except in the case of company *A*. This report illustrates by means of figure 7 the economy of 15-kva transformers up to 60 kw per 1,000 feet, 25-kva for 60 to 100, and 37½-kva above 100 kw per 1,000 feet for 2-way feed. Company *B* does not state any recommended size of transformer, but apparently uses the voltage drop and loading limitations to determine transformer sizes. Company *C* is very specific in stating the maximum size they consider most desirable, but do not indicate the extent of economical use for smaller sizes. Company *D* finds 15- and 25-kva transformers most economical and are explicit in recommending 37½-kva as the

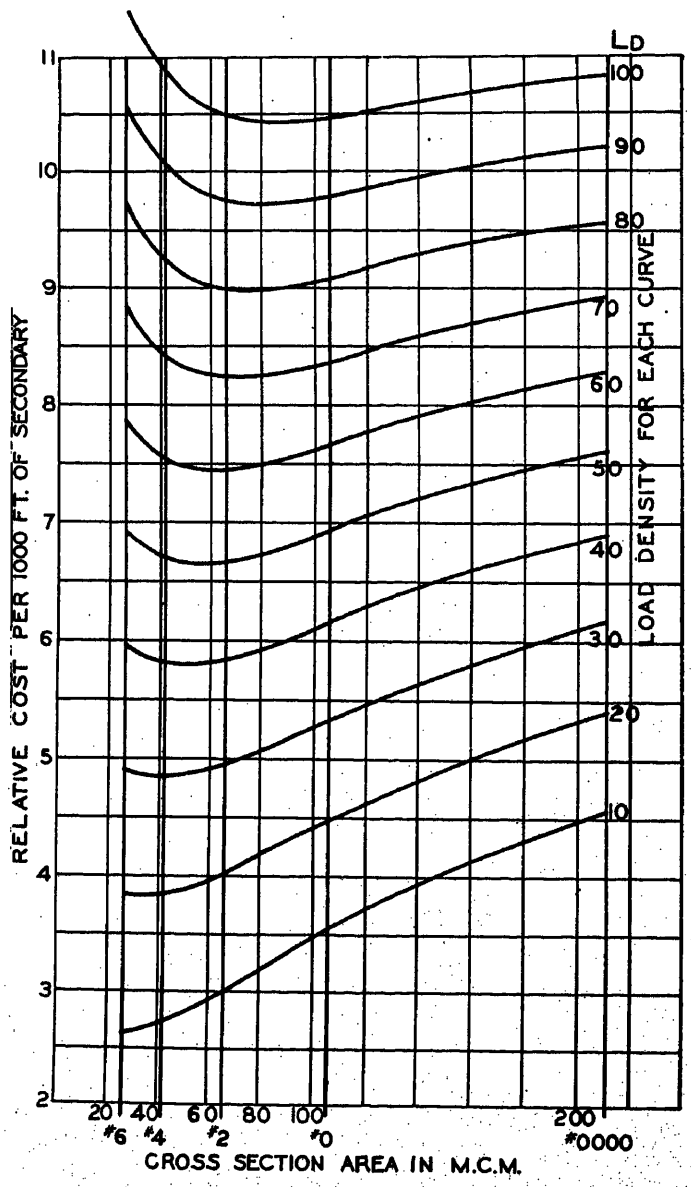



**Fig. 5. Relative total cost per 1,000 feet of secondaries and transformers, with wire at 10 cents per pound and capitalized losses included (company E)**

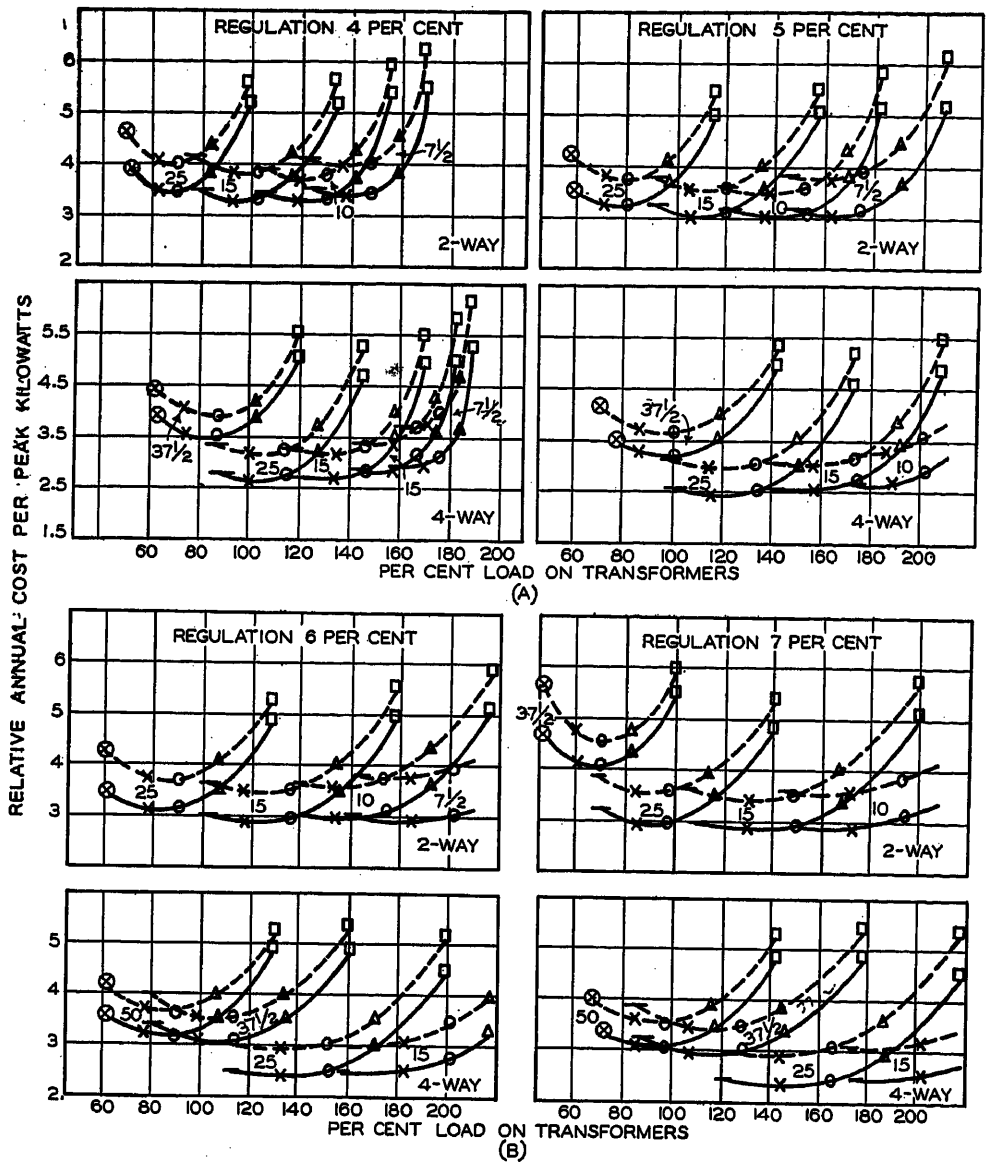



**Fig. 6. Annual cost of transformers and secondaries at various per cent loads on different transformer sizes for 2 assumed values of energy costs (company D)**

Broken line curves—Copper loss at 0.01 per kilowatt-hour; transformer loss at 0.01 per kilowatt-hour

Solid line curves—Copper loss at 0.00456 per kilowatt-hour; transformer loss at 0.003 per kilowatt-hour

Load density—15 kw per 1,000 feet

Numbers on curves are ratings in kilovolt-amperes

Total regulation of transformers and secondaries for each group of curves as shown

Two-way and 4-way distribution from transformers as indicated. Power factor 97 per cent

Secondary wire sizes: □—2 number 4/0 and 1 number 2/0; △—2 number 1/0 and 1 number 2; ⊙—3 number 2; X—3 number 4; ⊗—3 number 6

maximum size to be used. Figures 6*A* and 6*B* illustrate this conclusion. Company *E* finds 4 sizes, namely, 10-, 15-, 25-, and 37½-kva transformers, are needed to meet the various stages of load growth, stating however that 15- and 25-kva transformers are generally favored for average load densities. Figures 8*A* and 8*B* illustrate the relative economy of various transformer sizes as developed by company *E*.

### Transformer Loading

On the item of transformer loading there is an unusual variety of results and recommendations. Although companies *A*, *B*, and *D* are fairly uniform in their recommendations, company *E* seems to be extra conservative, but company *C* recommends an unusual percentage for initial loading at installation. This company assumes 5 per cent annual load growth which probably influences their conclusion.

These conclusions are based principally on the fact that peak loads on distribution transformers are expected during the winter season when ambient temperatures are low, whereas transformer ratings are based on temperature rise with 40-degree ambient. The increasing use of appliances may gradually change this condition and should therefore be checked from time to time. It should be noted also that this recommendation applies only to overhead transformer installations, and not to transformers in building or underground vaults, where the low ambient temperatures may not be available.

Generally, voltage regulation, rather than per cent overload, dictates the need for transformer replacement or respacing of transformers to reduce length of secondary mains. Increased transformer regulation is usually accompanied by a relatively high secondary drop hence both of these items will require attention, unless primary regulation is extremely favorable. The total voltage variation should be studied in each case, as well as the component voltage drops, to determine the best solution. It is evident therefore that the thermal capacity of distribution transformers is only part of the loading problem.

For small transformers, the annual transformation cost is materially reduced by overloading even up to 200 per cent. The exact effect on the life of the transformer under such conditions is not fully known, although

claimed by some to be satisfactory. There is no consensus of opinion on this point. Fortunately, on the 15-kva transformer and larger, the most economical loading ranges less than 150 per cent of name plate rating, hence there is less reason for risking failure on these larger units. In any event, the higher loadings may be expected to be troublesome and therefore result in increased operating and maintenance costs. The economics of transformer loading has been developed in a very interesting manner by company *D*, as shown in figures 6*A* and 6*B*.

It will be especially interesting to note the results of the various practices followed on transformer loading over a period of years. A further comparison of operating experiences will be desirable at a later date.

## Transformer Spacing

Transformer spacing is largely determined by load density and secondary voltage drop, especially after the selection of the economical wire size has been made. Companies *B* and *C* do not state their findings on this point. While companies *A*, *D*, and *E* have developed this item very thoroughly, the spacings listed represent preferred distances between transformers under ideal pole conditions and uniform load density. Experience indicates that it is well to favor these spacings, but actual field conditions and existing facilities will frequently change the secondary design including the transformer spacing. Company *E* illustrates by means of figures 8*A* and 8*B* the economics of transformer spacing. The limits for 2½ per cent voltage drop and 4 per cent flicker for radial secondaries are shown.

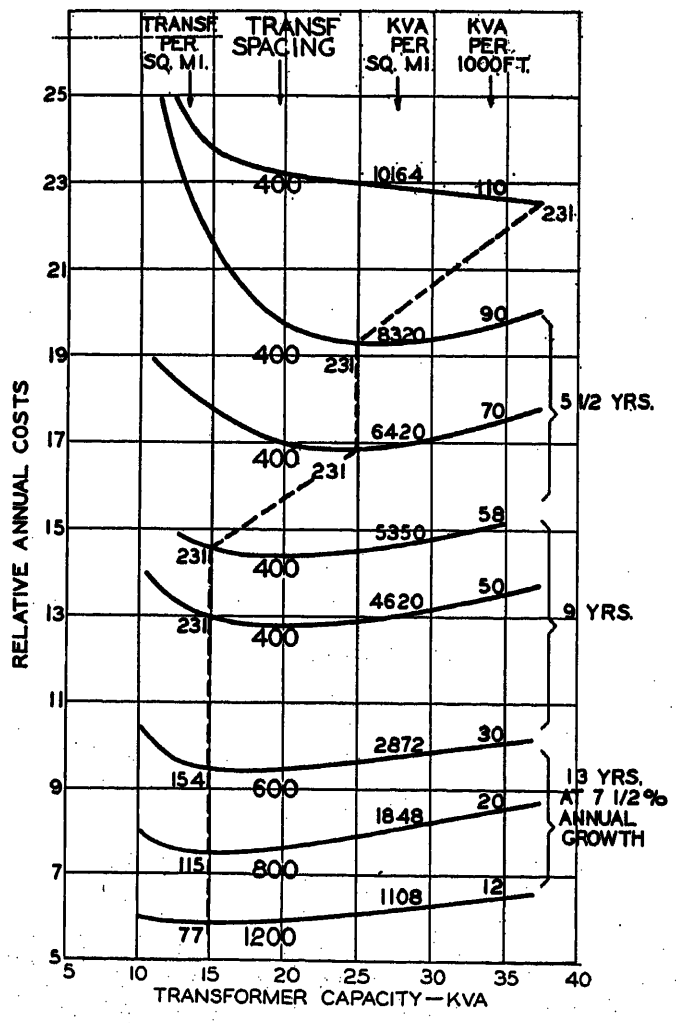



**Fig. 7. Relative annual cost of transformers and secondaries for various transformer sizes, number 3 secondary conductors, pole spacing 100 feet, and transformer and secondary regulation approximately 4.5 per cent (company A)**

### Table III—Transformer Costs in Relative Units

| Per Cent Loading | Transformer Rating in Kilovolt-amperes 7½ | 10 | 15 | 25 | 37½ | 50 |
|---|---|---|---|---|---|---|
| **Annual Transformer Cost*** | | | | | | |
| 40 | 23.9 | 27.0 | 31.9 | 45.9 | 56.7 | 70.0 |
| 60 | 24.6 | 27.9 | 33.1 | 47.8 | 59.8 | 73.4 |
| 80 | 25.6 | 29.2 | 34.8 | 50.4 | 63.0 | 78.2 |
| 100 | 26.8 | 30.8 | 37.0 | 53.7 | 67.8 | 84.4 |
| 120 | 28.4 | 32.8 | 39.7 | 57.7 | 73.7 | 91.9 |
| 140 | 30.2 | 35.1 | 42.9 | 62.5 | 80.5 | 100.8 |
| 160 | 32.3 | 37.8 | 46.5 | 68.0 | 88.5 | 113.4 |
| 180 | 34.9 | 40.9 | 50.7 | 74.2 | 97.6 | 122.6 |
| **Transformer Retirement Costs for** | | | | | | |
| **Location maintained—transformer re-used on job** | | | | | | |
| *A*—Cost installed | 140.0 | 159.0 | 182.5 | 270.0 | 328.0 | 409.0 |
| *B*—Reclaim value | 124.6 | 141.5 | 164.6 | 242.4 | 296.1 | 372.6 |
| *C*—L. and D. to remove | 5.0 | 5.0 | 5.0 | 8.0 | 8.0 | 8.0 |
| *D*—Net reclaim (*B* — *C*) | 119.6 | 136.5 | 159.6 | 234.4 | 288.1 | 364.6 |
| *E*—Retirement cost (*A* — *D*) | 20.4 | 22.5 | 23.9 | 25.5 | 39.8 | 44.3 |
| **Location maintained—transformer returned to storeroom** | | | | | | |
| Retirement cost | 35.0 | 39.0 | 43.0 | 64.8 | 76.8 | 92.8 |
| **Location abandoned—transformer re-used on job** | | | | | | |
| Retirement cost | 39.8 | 41.9 | 42.3 | 60.0 | 74.3 | 78.9 |
| **Location abandoned—transformer returned to storeroom** | | | | | | |
| Retirement cost | 54.4 | 58.5 | 61.4 | 99.3 | 111.3 | 127.4 |

* Comprised of 12½ per cent of installation cost as fixed charges, transformer iron losses, transformer copper losses, and transformer operation and maintenance cost.

### Table IV—Annual Transformer Costs

Load Growth 7½ Per Cent Per Year, 20-Year Period

| Year | Kva Load | Transformer Per Cent Load: 7½–15 Kva | 10–15 Kva | 15 Kva | Annual Cost Per Cent Comparison: 7½–15 Kva | 10–15 Kva | 15 Kva |
|---|---|---|---|---|---|---|---|
| 1 | 5.0 | 67 | 50 | 33 | 4.51* | 4.97* | 5.68* |
| 4 | 6.2 | 83 | 62 | 41 | 4.69 | 5.14 | 5.82 |
| 8 | 8.3 | 111 | 83 | 55 | 4.95 | 5.47 | 6.00 |
| 12 | 11.0 | 73† | 110 | 73 | 6.16† | 5.76 | 6.16 |
| 15 | 13.7 | 91 | 91† | 91 | 6.29 | 6.29† | 6.29 |
| 20 | 19.7 | 131 | 131 | 131 | 7.54 | 7.54 | 7.54 |
| Total annual cost (20 years) | | 113 | | | 117 | | 124 (*A*) |
| Retirement cost | | 6 | | | 7 | | (*B*) |
| Total annual cost plus retirement cost | | 119 | | | 124 | | 124 (*A* + *B*) |
| Depreciation reserve (compounded) | | 9 | | | 12 | | 24 (*C*) |
| Total net cost after applying credit for depreciation reserve‡ (compounded at 6 per cent less retirement cost) | | 104 | | | 105 | | 100 (*A* — *C*) |
| Total annual cost | | 113 | | | 117 | | 124 (*A*) |
| Depreciation reserve (not compounded) | | 5 | | | 5 | | 13 (*D*) |
| Total net cost after applying credit for depreciation reserve (not compounded) less retirement cost | | 108 | | | 112 | | 111 (*A*-*D*) |

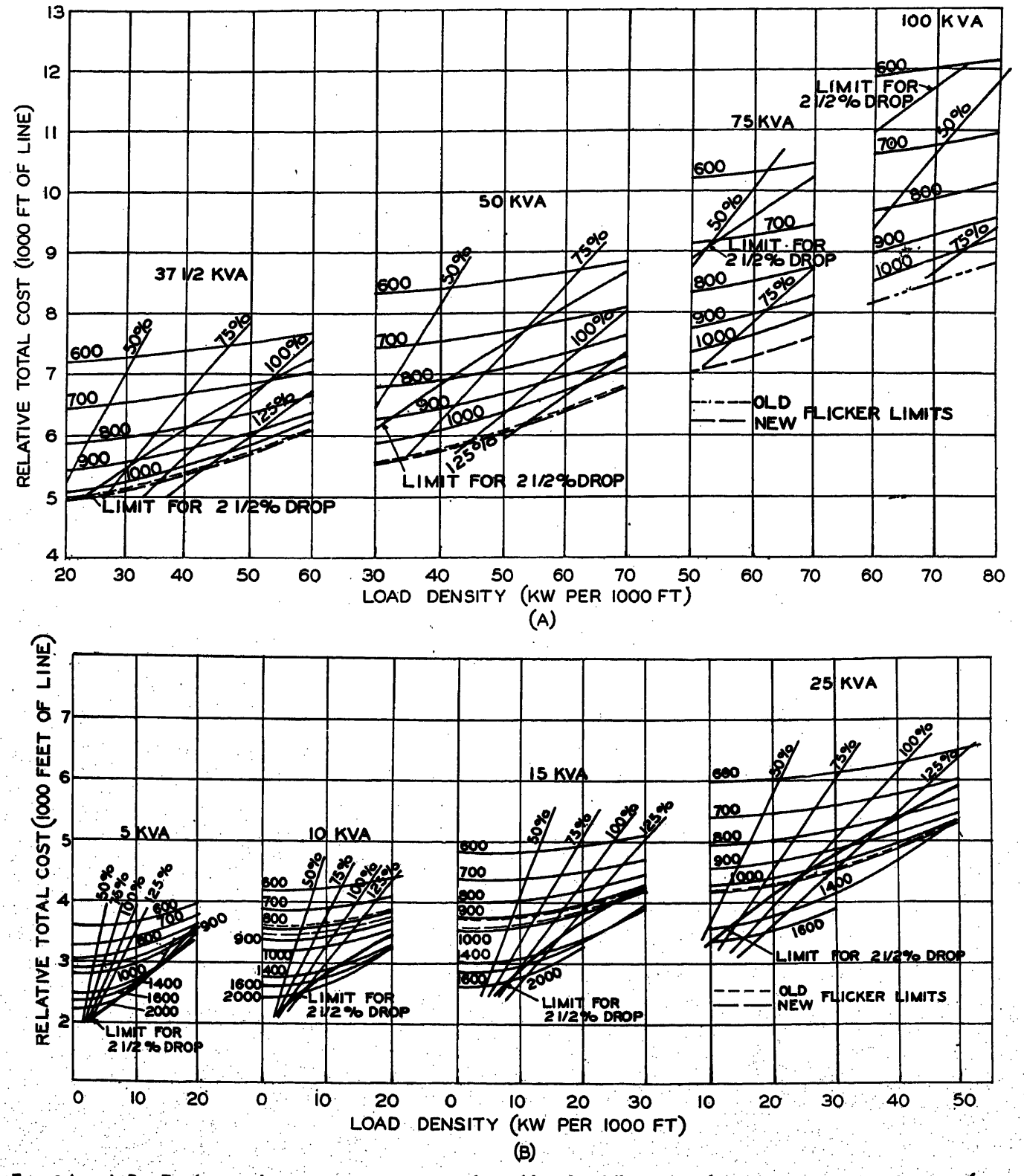
* Transformer annual cost expressed in per cent of total net cost for 20 years using a 15-kva (column 3).
† The change to a 15-kva transformer was made at this time.
‡ The depreciation reserve is included as a part of the annual cost, therefore, any part not used for retirement costs may be applied as a credit to determine total net cost.

## Load Growth

Various methods of handling load growth have been carefully studied to obtain the lowest total cost over a long period of years. This has been done by studying the accumulated annual costs for a number of possible methods. The method that involves the least retirements is usually most economical.

The subdivision method including the installation of additional or intermediate transformers is used by all the reporting companies but is especially favored by com-

(*Concluded on page 189*)




**Figs. 8A and 8B. Total equivalent investment per 1,000 feet of line for different transformer spacing using various transformer sizes and number 2 wire at $2^1/_2$ per cent maximum voltage drop (company E)**

Number 2 copper wire at 10 cents per pound

# Contact Drop and Wear of Sliding Contacts

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Membership Application Pending

**The results of a series of experiments, in which the processes of contact voltage drop and ring wear in sliding contacts are demonstrated by means of a direct method, are presented in this paper. The results show that the wear of metal-graphite brushes and the rings upon which they operate can be reduced if they be operated in an oxygen-free gas instead of air.**

THE relatively small amount of accurate knowledge gained through the enormous amount of effort expended in the study of sliding contacts is evidence enough of the complicity of the processes involved. This paper is intended to be only another step forward toward the ultimate goal of a perfect understanding. Each such step makes it just that much easier for the design and operating engineer to analyze and solve those practical problems with which he is continually confronted. It is felt that the experiments described represent a real advance in our understanding of contact drop and wear of sliding contacts. In order to conserve space and eliminate repetition, certain concepts developed in earlier published works will be used without explanation, and the reader not familiar with these concepts is referred to the original publications.[1,2,3,4] A general bibliography also is included at the end of this paper.

## Contact Resistance

The fact that the contact between a carbon brush and a copper slip-ring offers a high resistance to the flow of small currents has been attributed to the insulating effect of the oxide film which forms on the surface of the ring. Further, it is believed that increasing the current through the contact breaks down this high resistance film over certain areas, thus allowing the brush to make better contact with the metal of the ring and in this way lower the contact resistance.

This concept has been fairly well established[3] by experiments which show that the resistance of the contact between a carbon brush and a ring on which no oxide can form (a gold or carbon ring) is independent of current and remains low even for currents as low as 0.001 ampere. Although these experiments are convincing it seemed desirable to illustrate the correctness of the assumptions by some more direct method, and this has been accomplished by a special test arrangement which will be described below.

The apparatus used is shown in figure 1. It consisted of copper rings 13 inches in diameter driven by 2 motors; one a d-c motor and the other a synchronous motor connected in tandem. With such an arrangement it was possible to drive the rings at synchronous speed (1,800 rpm) or at any other speed differing slightly from synchronous speed. Each ring carried only one brush ($^3/_8$ inch thick and $^3/_4$ inch wide) of a soft electrographitic grade. Since the rings were electrically connected, the current flow at any instant was from one brush into its ring and from the other ring out into its brush. All tests were made with a resistance in series with the contacts and since the supply voltage was 40 volts, 60 cycle alternating, the current through the contacts was essentially sinusoidal and in phase with the applied voltage. The effective value of brush current was 12 amperes (42.8 amperes per square inch). The brush current was supplied from the same circuit which supplied the synchronous driving motor, thus insuring synchronism between the rotation of of the rings and the current supplied to the brushes. A stroboscopic lamp was used to bring the rings into synchronism always with a definite phase relation to the brush current. This lamp was also used when it was desired to let the rings slip one or more revolutions before being thrown back into synchronism again. When it was desired to operate the rings nonsynchronously, the synchronous motor was disconnected from the line and the rings were driven by the d-c motor. It now will be shown how this apparatus was used to illustrate the part played by oxide films in determining contact resistance.

With the rings running synchronously (1,800 rpm) it is obvious that the 60-cycle current through the brushes became zero 4 times each revolution of the rings. As the positions of current zero occurred at the same points on the ring surface each revolution, there were 4 sections of the ring surface which were never called upon to carry current. (This is not strictly true because of the finite brush width but the discrepancy is of small consequence.) Other points of the ring surface were called upon once each revolution to carry some value of current between zero and the maximum current through the brushes (17 amperes or 60.5 amperes per square inch), and it is especially important to observe that the same section of the ring surface was subjected to exactly the same value of current each time it passed under a brush. The condition can be pictured best perhaps by thinking of a standing wave of current around the ring. One quarter of the ring surface carried all values of positive current, the next quarter all values of negative current, and so on around the ring.

If the oxide film on the ring is responsible for the commonly observed large variation of contact resistance with

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1. For all numbered references, see list at end of paper.

current, it would be expected that the film on the ring surface near each of the 4 points of zero current might have a very high resistance, for it is never called upon to carry heavy current and therefore does not become broken down. Thus, it would be expected that with a sinusoidal current passing through the brushes, the variation of contact drop would be represented by a flat topped wave. That is, one would expect a relation between current and voltage similar to that obtained in the static characteristic. To what extent this prediction is fulfilled by experiment is shown by the oscillograms of figure 2, all of which were taken with the rings running synchronously.

Figure 2*a* shows the current through the contacts and the voltage drop in each contact just after the ring surfaces had been cleaned with very fine alundum cloth. It will be seen that the contact drop was low and almost sinusoidal. The oxide film was still so thin that it was not appreciably affecting the contact resistance anywhere around the ring.

The oscillogram shown in the figure 2*b* was taken about $1^1/_2$ hours later and it can be seen that the curves of contact drop were beginning to flatten somewhat. The oxide film was forming on the ring surface and was increasing the contact resistance more in the regions of low current than in the regions of high current.

The oscillogram of figure 2*c* was taken after the rings had operated synchronously for several days. The oxide film was fully formed and the curves of contact drop had become quite flat, especially over those sections of the ring where the current flowed from the ring to the brush. The resistance of the contact near current zero is very high but drops off rapidly at first and then more gradually until it reaches a minimum at the point of maximum current.

One might ask at this point what happens if the rings are not running in exact synchronism. In this case, every section of the ring surface is called upon to carry all possible values of current from zero to the maximum brush current. Thus, all sections of the film on the ring surface are broken down to the same extent and all offer the same resistance to the flow of current. If a sinusoidal wave of current is forced through the contacts, it would be expected that the curves of contact drop also would be essentially sinusoidal. An oscillogram taken after the rings had run for some time out of synchronism is shown in figure 3*a*.

It is especially interesting and instructive to compare the contact drop curves of figure 3*a* with those of figure 2*c*. In both cases the brushes carried the same value of alternating current, so it is fair to assume that the condition of the brush face was the same in both cases. It follows, therefore, that the large variation of contact resistance with current during synchronous operation is due to a condition on the ring surface rather than to some property of the brush face. This is an especially important conclusion for it follows that the same must be true in general for all sliding contacts which show a large change in contact resistance with current.

To demonstrate this fact in another way, a separate experiment was made. After the rings had been running synchronously for several days with alternating current in the brushes, the brush current supply was switched off and replaced by a dry cell in series with a 6-ohm resistor and an oscillograph element as shown by the diagram of figure 4. The oscillogram, figure 4*a*, was taken as soon as possible after the change was made. The peaked current record shows that each time the brushes passed over a part of the ring surfaces which previously carried low current, the current through the oscillograph element decreased. This can be interpreted to mean only that the condition of the ring surface over these parts was such as to produce a high contact resistance. Thus one sees that it was possible to set up a standing wave of resistance around the ring, during synchronous operation, perma-

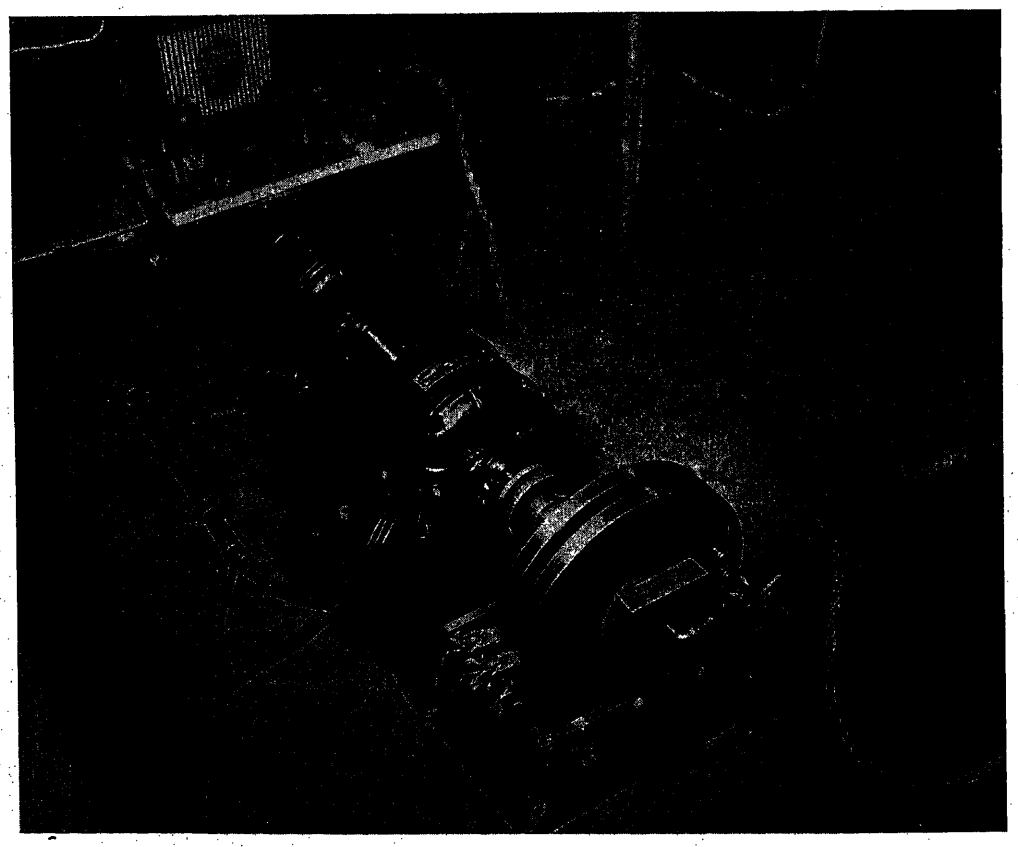


**Fig. 1. Test equipment used for studying brush performance during synchronous and asynchronous operation**

nent enough to be recorded or measured in a separate circuit some minutes after the a-c current supply had been disconnected from the brushes.

The record of figure 4*b* was taken after 10 minutes of operation with the dry cell connected in the brush circuit. In this time the oxide film on the ring surface had repaired considerably to produce an average increase in contact resistance. The high-resistance regions were gradually destroyed by the 1.5 volts applied across the contacts.

Figure 3*b* shows the current and contact drop curves with the rings stationary. The contact drop curves under this condition are practically sinusoidal, indicating constant resistance in the contact. The peculiar breakdown phenomena observed on the one ring (upper record) probably occurred because the ring happened to come to rest in such a position that the contact between the brush and the ring was especially poor. Such a record is seldom obtained and is included only as an oddity.

If one were to plot a curve between current and contact drop from the curves of figure 2*c*, the result would

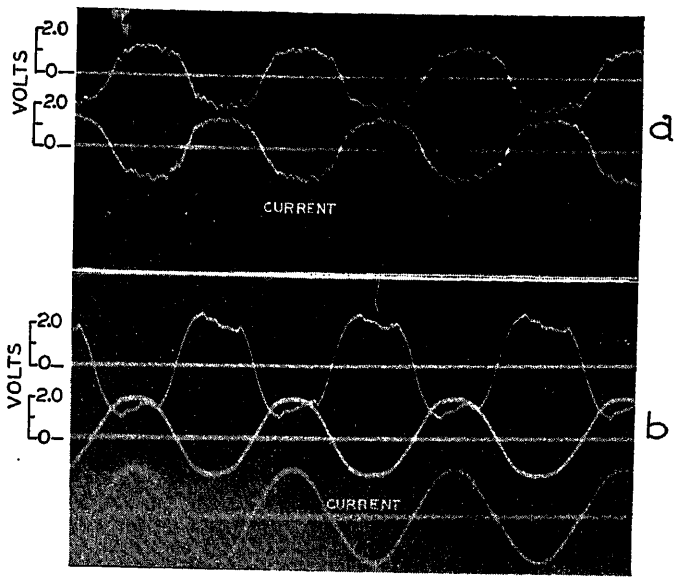



**Fig. 3. Current and contact voltage drop oscillograms taken during asynchronous operation**

(*a*)—Near synchronous speed
(*b*)—Rings stationary

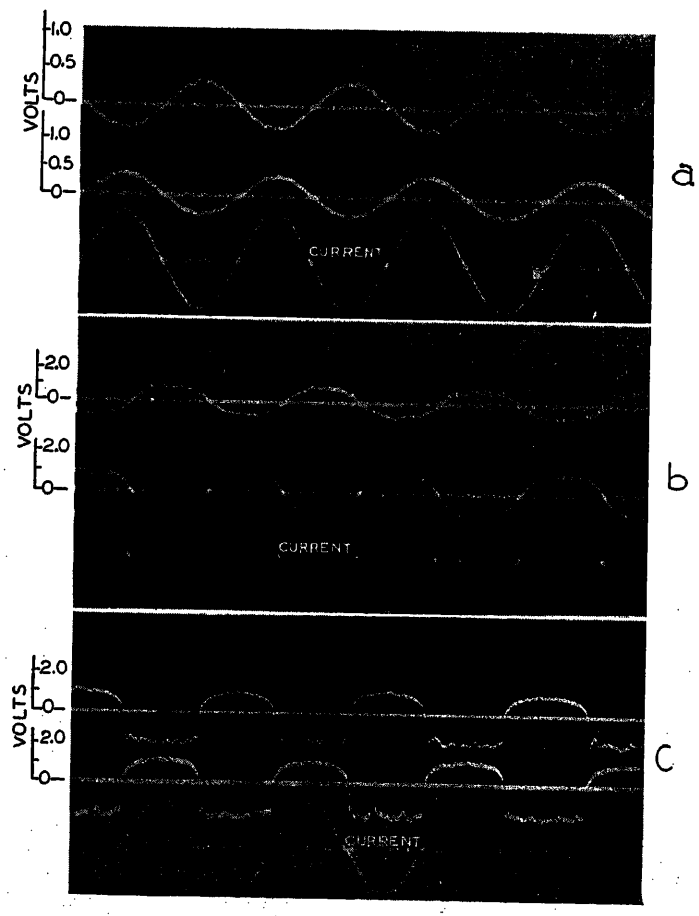



**Fig. 2. Oscillograms of current and contact voltage drop taken during synchronous operation**

A downward deflection of the contact voltage drop curve corresponds to a current flow from ring to brush

(*a*)—Ring surface free of oxide film
(*b*)—Taken after operation of 1½ hours
(*c*)—Taken after operation of several days

look very much like the static volt-ampere characteristic commonly taken by the tedious step-by-step method. In fact this might be a satisfactory and easy method of obtaining a static volt-ampere characteristic on a brush grade. It is in effect a method of operating a number of rings simultaneously with different currents and observing in rapid succession the contact drop in equilibrium with each value of current. The brushes are actually carrying alternating current but the individual sections of the ring surface have no way of detecting this unless the nature of the brush face is influenced by the current it carries. There is undoubtedly a difference in the polish of the brush face with different currents flowing but experiments indicate that this effect is small in comparison to that produced by the conditions on the ring surface.

A brush which is hard, or one which contains enough abrasive to prevent the formation of a uniform oxide film on the ring surface, will not build up such a high contact resistance at the very low current densities as will a soft nonabrasive brush such as used in the investigation described above. Neither will a hard abrasive brush produce contact drop curves with such sharp corners as those of figure 2*c*.

Previous experiments[3] have indicated that the breakdown of the oxide film and the resulting decrease in contact resistance occurs almost instantaneously when a high current is forced through the contact. It was expected therefore that allowing the rings to slip one revolution following synchronous operation before pulling them back into synchronism again would subject all sections of the ring surface to high current and make the surface uniformly conducting all around the ring. However, contrary to expectations, a record of contact drop taken immediately after the rings had slipped one revolution and were running synchronously again, showed curves

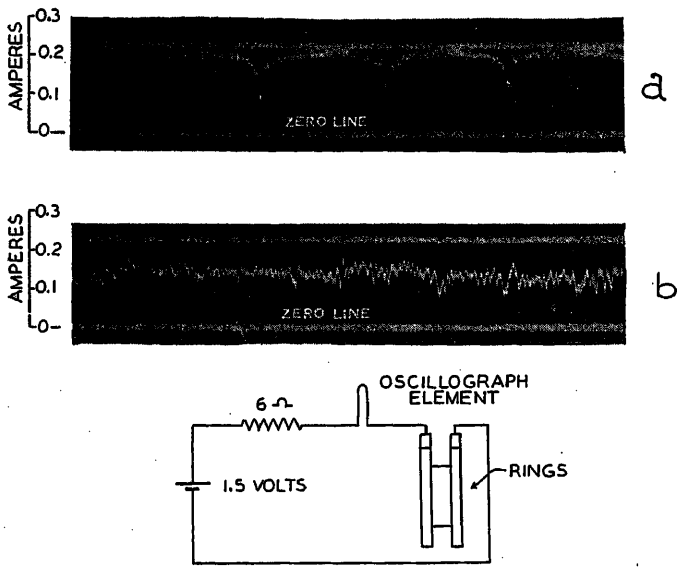



**Fig. 4. Distribution of film resistance around periphery of ring**

of contact drop almost identical with those of figure 2*c*. Only by allowing the rings to slip 10 revolutions (50 seconds nonsynchronous operation), could rounded contact drop curves similar to those of figure 3*a* be obtained. No attempt will be made at present to explain the unexpected results. It was necessary to operate the rings synchronously for half an hour or more to repair the damage done to the film during the 50 seconds of nonsynchronous operation and to obtain again contact drop curves similar to those of figure 2*c*.

## Ring Wear

The track produced on the surface of a copper ring by a carbon or graphite brush is definitely characteristic of the direction of current flow through the contact. If the current flows from the ring to the brush, the track has a light color and may even be bright and show signs of threading. If the current flows from the brush to the ring, the track is dull and in some cases seems to be covered with a thin film of carbon. These effects are generally observed on rings operated with direct current but it was discovered in the present investigation that they may be observed also with alternating current in the brushes. It will be recalled from the early part of this paper that during synchronous operation of the rings, certain parts of the ring surface always experienced current flow from the ring to the brush. These parts showed the typical brush track for this direction of current flow. Other parts of the ring surface always experienced current flow in the opposite direction and showed the characteristic track for that direction of current flow. The contrast was so sharp that one could determine by visual observation of the ring surface, the exact point at which the direction of current flow reversed.

This observation is of considerable importance for it establishes the fact that the nature of the track produced at one polarity or the other is effected by the direction of current flow across the contact (an instantaneous process) rather than by some condition of the brush face, such as fine copper picking or the loosening of carbon particles as is sometimes supposed.

Another interesting observation connected with the difference in ring surface over different parts of the ring after synchronous operation, was the occasional appearance of burned spots or brush photographs on the ring surface. These generally occurred only with a hard brush grade which did not ride well on the ring surface. This is such a common phenomenon that it would not be worth mentioning except for the fact that these spots always occurred at points of zero current on the slip-ring surface. This is not so surprising when it is remembered that just at the point of zero current there is an abrupt change in the

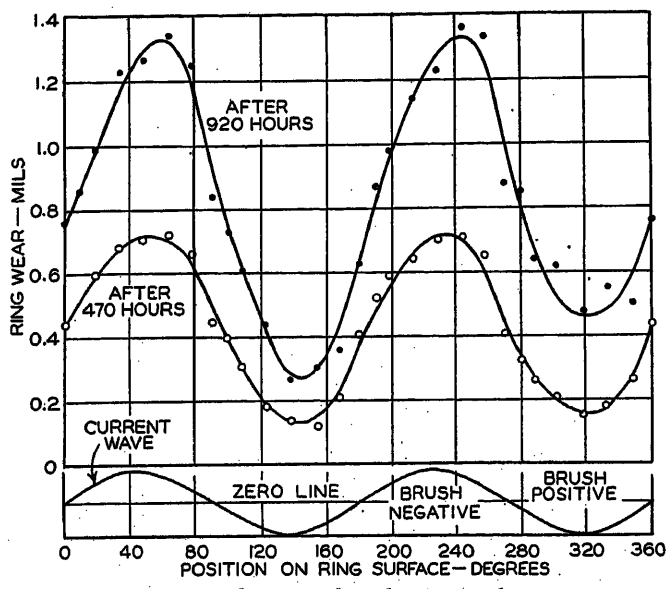



**Fig. 5. Curves showing that the wear of rings is in synchronism with the brush current**

"Brush negative" indicates current flow from ring to brush
"Brush positive" indicates current flow from brush to ring

appearance of the ring surface. This abrupt change in appearance is probably associated with a change in friction which causes the brush to dance just a little and burn the ring at this point.

The appearance of brush tracks, which already has been discussed at some length, is closely related to ring wear. The negative ring (current flow from ring to brush), which usually exhibits a bright clean-looking track, is the one which always shows rapid wear. The positive ring on the contrary usually shows a dull track and very much less wear. This is true when the rings operate with either graphite or metal-graphite brushes, although the wear is usually much more rapid with metal-graphite brushes than with graphite brushes.

The synchronous ring arrangement used throughout this set of experiments seemed likely to show some interesting facts regarding ring wear if enough wear could be produced to be measurable at all points around the ring. Since all values of current and both polarities would

be represented on the one ring surface, a single set of wear measurements should give a fairly complete story.

A test was made using metal-graphite brushes containing about 80 per cent of copper by weight. The brushes carried 35 amperes of 60-cycle alternating current. The rings ran synchronously at 1,800 rpm throughout the test.

The rings were measured at the beginning of the test, at the end of 470 hours, and again at the end of 920 hours. A special device was used to measure the ring wear with an accuracy of plus or minus 0.00002 inch.

The results of the test are shown in figure 5. The current wave shows the distribution of current around the ring surface, or more exactly, the current carried by each section of the ring surface as this section passed under the brush. The wear curves indicate the ring wear, measured at various angular positions around the ring. These curves show at once that the total wear of the ring surface is made up of 2 components, the one constant around the ring and the other alternating and almost exactly in phase with the distribution of current around the ring. Apparently the constant component of ring wear is caused by mechanical abrasion of the ring surface by the brush, while the alternating component is caused by the transportation of material across the contact by the current. The fact that the material transferred is roughly proportional to the current, indicates that the transfer might occur by an electrolytic process. Whether or not this is true is not definitely known. It is interesting however, to calculate what current, flowing electrolytically in parallel with the main brush current, would be required to transfer the amount of material indicated by the wear curves of figure 5. A simple calculation shows that if only 0.004 per cent of the total brush current flowed across the contact by electrolytic conduction, the material transfer would be sufficient to explain the wear curves obtained.

The results of this experiment show that a large percentage of the ring wear commonly observed with direct current in the brushes is due to an instantaneous process associated with the transfer of current across the contact. The curves of figure 5 show greater ring wear at the points of zero current than at the points of maximum current where the direction of flow is from the brush to the ring. Apparently metal is in some way picked up from one part of the ring surface and put down at another to bring about this result.

The maximum ring wear occurs on those sections of the ring where the current flows from the ring to the brush; the minimum wear occurs on those sections where the current flows from the brush to the ring. These observations agree with the fact that in direct current operation, the wear of the negative ring is much greater than that of the positive ring. As shown by figure 5, the ratio of maximum wear to minimum wear on the synchronous rings was 5.4 after 470 hours operation and 5.7 after 920 hours operation. This leads one to believe that if the rings had been operated with direct current in the brushes, the wear of the negative ring would have been about 5.5 times as rapid as that of the positive ring.

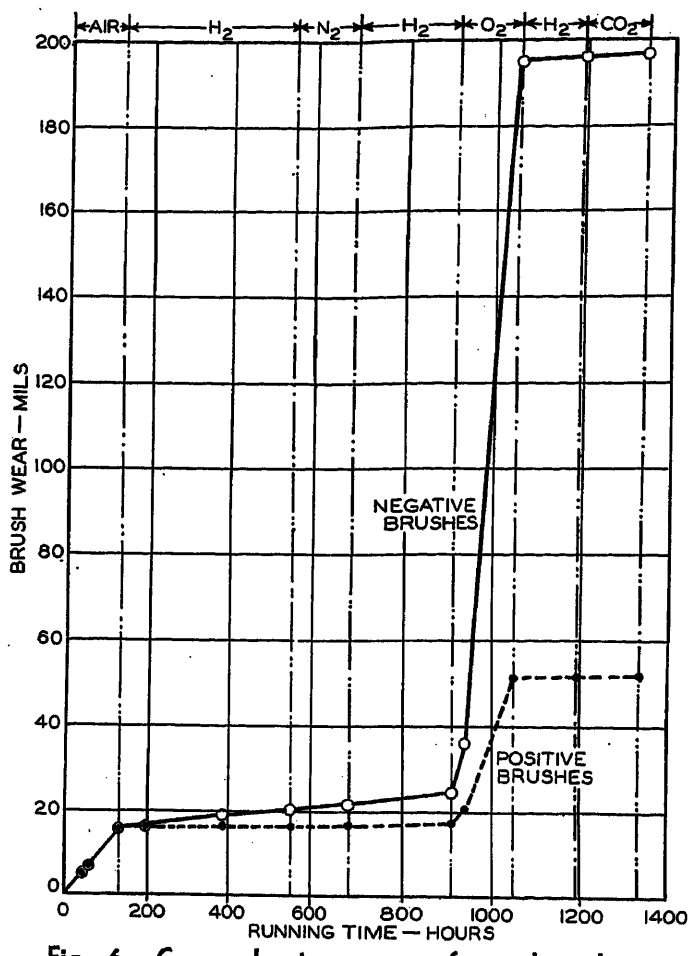



**Fig. 6. Curves showing wear of metal-graphite brushes in various gases**

However other factors which cannot be discussed here would probably make this ratio considerably greater if the test operated 1,000 hours or more.

## Brush Wear in Various Gases

Previous experiments[4] have shown that carbon brushes wear very slowly when operating in an atmosphere of hydrogen. This observation led to the belief that oxygen in the atmosphere around the brushes was responsible for the brush wear commonly observed in service and that this wear could be greatly reduced if the brushes were surrounded by some oxygen-free atmosphere. The greater demand for a longer life of metal-graphite brushes led to the choosing of this type of brush for a special test which will be described below.

Copper slip rings and a driving motor were inclosed in a gastight housing which could be filled with any gas desired. The rings were 9.5 inches in diameter and operated at a speed of 1,750 rpm. Each ring carried 2 metal-graphite brushes, $1/2$ inch wide by $1\,3/4$ inches thick. The brushes operated on direct current, 160 amperes per ring (80 amperes per brush). The current flowed into one ring and out the other. The temperature of the gas inside the housing was about 55 degrees centigrade.

The results of a series of tests are shown in figure 6. These curves show brush wear plotted as a function of

running time, so the slope of the curves at any point is an indication of the rate of wear. The brushes and rings operated in room air, in hydrogen, in nitrogen, in hydrogen again, in oxygen, in dry hydrogen, and finally in dry carbon dioxide. This series of tests shows that the rate of brush wear for the particular brush grade tested is about 10 times as rapid in air as in any of the commercial oxygen-free gases. It also shows that the brush wear is more rapid in oxygen than in air. Most of the tests were made with commercially pure gases taken directly from the high pressure cylinders. Only in the last 2 tests (figure 6), one in hydrogen and one in carbon dioxide, were the gases especially dried. It will be noticed that the rate of wear is still further reduced by drying the gases.

It is important to make one more comparison in order to show that brush wear is greatly reduced by the removal of oxygen even when the brushes carry no current.

A test made in dry oxygen with no current in the brushes indicated a brush wear of 8 inches per year or a greater rate of wear than was observed in commercial oxygen with current flowing. This high wear was due apparently to the extreme dryness of the oxygen for when some moisture was purposely introduced, the coefficient of friction decreased about 50 per cent and the rate of wear became 2.8 inches per year. In dry carbon dioxide the rate of brush wear with current flowing (last test, figure 6) was only 0.028 inches per year. Since it is unlikely that the brush wear in carbon dioxide with no current flowing is any greater than the rate of brush wear with current flowing, it appears that the brush wear with no current in the brushes is about 100 times greater in oxygen, under the most favorable conditions, than it is in dry carbon dioxide.

The noticeable effect of moisture in reducing wear of the brushes during operation in oxygen is just opposite to the effect observed during operation in the oxygen-free gases. The evidence is that moisture is beneficial during oxygen operation and perhaps also during air operation, for it results in a decreased friction and a lower rate of brush wear. This is in line with field experience, where short brush life is often associated with low air humidity.

Although no actual measurements of ring wear were made, visual observation indicated that the ring wear during tests in oxygen-free gases was extremely low and that this wear was rapid (especially on the negative ring) when air or oxygen was introduced. This was also observed on another test in which graphite brushes operated on copper-alloy rings.

The brushes used to study brush wear in various gases contained 70 per cent copper and 30 per cent graphite by weight and were bonded with pitch. This specification is given because another grade bonded with bakelite showed less improvement with the introduction of an oxygen-free gas.

The results of the experiments described in this paper have been interpreted in so far as it was consistent with the limitations of space and our present knowledge. For the most part the results agree well with the ideas and experimental evidence presented in previous works to which the reader was referred in the introduction.

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# A New Electrostatic Precipitator

(*Continued from page 163*)

$V_d$ = velocity of drift of a charged particle through the gas under the influence of the electrostatic force
$V_g$ = velocity of the gas parallel to the electrode face
$A$ = spacing between parallel electrodes
$L$ = length of parallel dust-collecting electrodes
$t_A$ = time required for a charged particle to drift hrough the gas a distance $A$
$t_g$ = time required for the gas to travel the length of the parallel dust collecting electrodes
$r$ = radius of the dust particle assuming that an actual irregular particle can be represented by a sphere of equivalent radius
$K$ = dielectric constant of the dust particle

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# Watt-Hour Meter Bearings

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J. H. GOSS
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**Bearings for the moving element in watt-hour meters have received considerable study in recent years in order that maintenance might be reduced. The requirements for the bearing, the materials available and their characteristics, lubricants, and the various designs of bearings are discussed in this paper.**

A GREAT DEAL of interest has always been exhibited in watt-hour meter design by the users as well as the manufacturers, because the watt-hour meter is so vital a factor in the sale of electrical energy. The emphasis has gradually shifted from one part of the meter to another as each has been perfected in turn to a high degree, until within the last few years much attention has been focused on the subject of bearings. Interest in meter bearings has been accentuated due to the tendency to increase the length of periodic test intervals and the necessity of eliminating as much servicing and as many replacements as possible. There are so many factors involved and it is so difficult to obtain conclusive data, that it is not surprising that there has existed a divergence of opinion on the part of many who have studied the problem.

The purpose of this article is to analyze the many factors that bear upon the design and operation of watt-hour meter bearings and to attempt to consolidate and clarify fundamental information on this subject. In searching for a complete explanation and evaluation of the various factors and their relative importance, a large amount of work has been done. The results of much of this work will be covered in this article, and it is the hope of the authors that it will assist in making a more complete understanding of the subject possible.

## Historical Review

The groundwork of bearing design for electrical instruments and meters was, no doubt, laid by the designers of chronometers. For centuries prior to the birth of the electrical industry, builders of clocks and watches were faced with the problem of building rugged low-friction bearings to carry the weight of moving parts and to have long life. Much work had been done on the geometry of bearings as well as on the component parts to select the best combination of materials available.

With the advent of the electrical industry in the latter part of the 19th century, it was only natural that the builders of electrical instruments and meters turned to the watch industry as a guide in selecting materials and designs of bearings to carry the moving systems. A wide variety of bearings has been proposed and used in various instruments, meters, and measuring devices. Figure 1 shows a number that are, in general, applicable to watt-hour meters, but are also applicable to some forms of instruments. All of these arrangements can be resolved into either the pivot or the ball type, and for a theoretical consideration of the friction of the bearings the ball type and the pivot type lend themselves to the same analysis.

## Important Considerations in Bearing Design

There are 2 bearings that are of primary importance from the standpoint of design and operation of a watt-hour meter. These are the top and bottom bearings of the moving element. The lower bearing carries the weight and the top bearing maintains the vertical alignment of the shaft.

For clarity of treatment this discussion will be divided as follows:

*A.* Mechanical design
*B.* Materials
*C.* Lubrication

Each of these factors will be examined in turn in relation to the lower bearing, as it is really the essence of successful long time operation of a watt-hour meter. A brief discussion of the top bearing will follow since it also performs an important function.

## Mechanical Design

### Friction Torque

The primary consideration in the design of a watt-hour meter lower bearing is the reduction of friction to a minimum value that can be maintained. If the weight of the moving system is designated by $W$ and the coefficient of friction by $\mu$, then from the definition of the coefficient of friction the frictional force of the bearing will be proportional to $W\mu$. It has been shown that the friction torque $T_f$ is proportional to $WR\mu$, where $R$ is the lever arm at which the force acts.[28] If it were possible to reduce $R$ to zero which could be done if a true point contact could be provided, then the friction torque would be zero and there would be no friction effect. Unfortunately, this would require the bearing material to carry or sustain an infinite stress which is impossible. All materials deform under load until the area in contact is sufficient to carry the load. The contact area then has an equivalent $R$ that determines the friction torque ($T_f$) of the bearing. As $R$ cannot be reduced to zero, the next best

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28. For all numbered references see list at end of paper.

thing is to make it as small as possible which can be done by carrying the load of the moving element on a pivot point of small radius or ball of small radius in contact with a flat plate or a cupped jewel of a larger radius of curvature than the ball or pivot. As pointed out in a previous article[1] due to wear the initial condition cannot be maintained throughout the useful life of a watt-hour meter bearing. The friction torque is made low so that an increase of several times the initial value will not materially affect the meter calibration. Figure 2 shows the initial error due to friction that must be compensated for, as a function of the radius of the pivot point. The values shown in figure 2 have been confirmed experimentally both by V. Stott[2] and by the authors.

### Rate of Wear and Shock Resistance

There are 2 important considerations aside from the fact that the geometrical requirement is that the contact area should be as small as possible for minimum initial friction. One of these is that the rate of increase of this area should be reduced to a minimum, and the other is that the bearing should have sufficient strength to withstand installation abuse and service abuse.

Figure 3 shows the manner in which the friction torque varies as a function of pivot radius for a given decrease in pivot length resulting from wear. The friction increases rapidly with an increase in the radius. This curve was drawn assuming the pivot in contact with a flat plate. V. Stott[2] has shown that little error is introduced by this assumption if the area in contact is small. The method of computing the friction torque as a percentage of the watt-hour meter load torque is given in a previous article.[1]

Figure 4 shows the relative shock resistance as a function of the radius of curvature for glass-hard steel pivots running in sapphire jewels. It is evident from a study of this curve that the shock resistance of a pivot falls off rapidly below 0.0175-inch radius and that in order to reduce impact failures under severe conditions to a minimum, a pivot should not have a radius below this value. The method of test will be discussed later in relation to the required shock resistance of bearing material.

A further treatment of the mechanical design of the types of bearings shown in figure 1 will be deferred until after materials and the subject of lubrication have been considered.

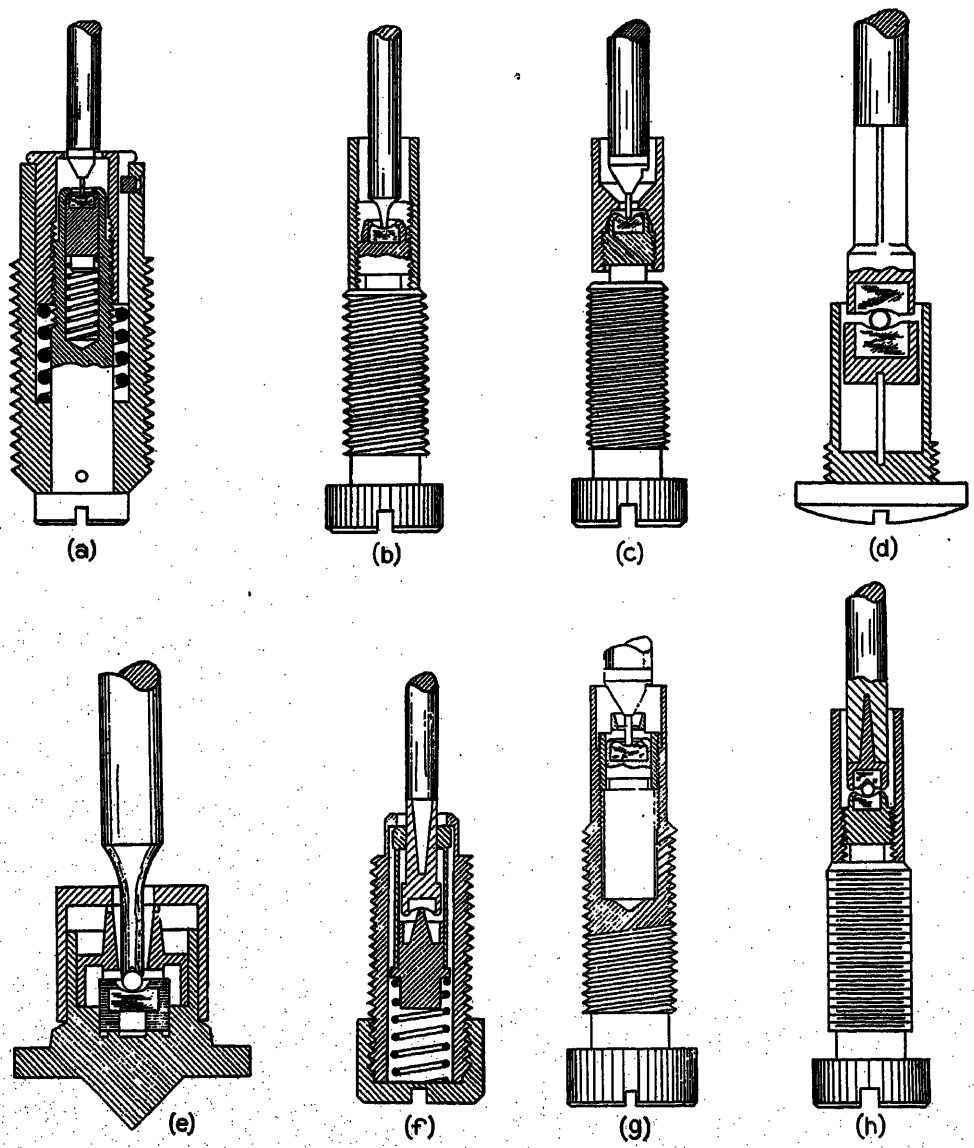



Fig. 1. Typical bearings for watt-hour meters

## Materials

The material for any of the bearing designs shown in figure 1 must meet practically the same requirements and as the geometry of a watt-hour meter pivot is limited to a ball or spherical point, improved materials offer the best possibilities in developing bearings with increased life.

### Jewel Material

The material for the jewel cup should have the following characteristics:

1. Hardness—That gives high resistance to wear.
2. Toughness—That will protect the surface against shattering under shock.
3. Low coefficient of friction—Should have a low friction coefficient in contact with the pivot or ball.
4. Workability—Should be such that the jewel cup can be produced at a cost which will not be prohibitive.

It is extremely difficult to give quantitative data of the above requirements for a given material, due to the lack of an accurate method of measuring perform-

ance. In the past hardness has been measured in accordance with the Moh scale which is based on the ability of one material to scratch another. . This scale makes no allowance for the toughness of the material which is also a factor in wear resistance just as hardness is a factor in protecting the surface against shattering.

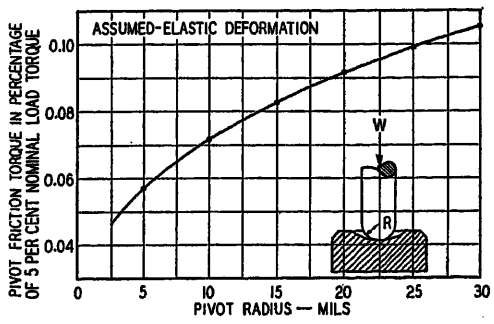



**Fig. 2. Calculated friction torque as a function of pivot radius**

Recently work has been done[3] and results published that have given an illuminating picture of the Moh scale when applied to bearing material. Instead of the scratch hardness, the ability of a given material to resist abrasion was taken as a measure of its hardness. This is precisely the thing of interest in a bearing material. The Moh scale and the new wear hardness scale are plotted in figure 5.

It is evident from this curve that the Moh scale of hardness gives erroneous results when used as a basis for

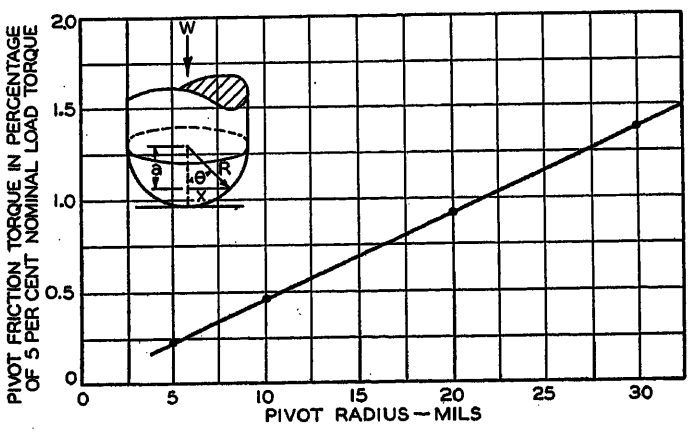


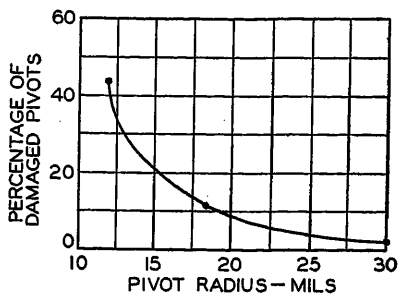

**Fig. 3. Friction torque as a function of radius for a given decrease in length of the pivot due to wear**

Decrease in length is $(R - a)$

judging the relative wear resistance of materials. The new scale based on abrasion resistance gives a much better indication of the relative performances of the materials as is borne out by the results obtained in service with diamond jewels for severe applications as compared with sapphire jewels. The Moh scale if assumed to be linear would indicate a small difference between sapphire and diamond (sapphire 9, diamond 10), while on the scale of wear hardness the diamond is superior in the ratio of over 4 to 1.

**Fig. 4. Curve showing the variation of pivot shock resistance as a function of pivot radius**

Data obtained from short-circuit test using high carbon steel pivots and natural sapphire jewels




Diamond, according to figure 5, should be the most desirable material to satisfy specification 1, and if it is assumed that wear hardness is also a measure of toughness diamond is the most desirable from specification 2. Both diamond and sapphire take a good polish and satisfy specification 3. It is, however, difficult to grind a cup into diamond, and the cost of the raw material plus the high cost of working it into cups makes the cost prohibitive except for meters yielding a large revenue.

Silicon carbide and boron carbide are seen to be between diamond and sapphire on the wear hardness scale. Jewel cups made from these materials are not commercially available although much work has been done to investigate their properties. Present practice, the outgrowth of long experience, shows that sapphire approaches nearer to the perfect material as defined by the specifications than any other material and is the best available.

### Pivot or Ball Material

Glass-hard steel approximately 1.25 per cent carbon, running in a polished sapphire jewel cup, has from the beginning of meter and instrument manufacture been the most widely used combination of materials. A large amount of operating data has been obtained on meters operating with bearings of these materials both with and without lubrication. Based on these data certain specifications have been drawn up as desirable for a pivot material.

1. Non-corrosive—Material should not corrode under operating conditions.

2. Non-abrasive—Products of wear should be non-abrasive. (Most important when pivot operates on a sapphire without lubrication.)

3. Wear-resistive—Should have a low rate of normal wear. (To be considered with and without lubrication.)

4. Shock-resistive—Should be capable of resisting high impact loads caused by rough handling of the watt-hour meter during transportation and installation and impact loads imposed by short circuits while in service.

5. Low coefficient of friction—Initial friction should be low in combination with sapphire.

6. Workable—Should be capable of being produced in the form of pivots and balls at a reasonable price.

Table I shows some of the more promising pivot materials rated in accordance with the above specifications.

To check materials to this set of specifications, one test was to run the bearings in meters at an accelerated speed without lubrication to see how well they stood up

**Table I—Properties of Pivot Materials**

| Material | Corrosive | Non-abrasive | Wear-Resistive | Shock-Resistive | Workable | Low Coefficient of Friction | |
|---|---|---|---|---|---|---|---|
| Steel (1.25 per cent carbon) | Yes. | Poor | Good. | Good. | Satisfactory | Satisfactory | |
| Nitralloy | Yes. | Poor | Good. | Good. | Satisfactory | Satisfactory | |
| Chromium plated steel | No. | Poor | Good. | Good. | Probably satisfactory. | Satisfactory. | Initially wears well with or without lubrication but plate wears off |
| Cyanided stainless steel (18–8) | No. | Poor | Good. | Fair. | Probably satisfactory. | Satisfactory | |
| Tantalum | No. | Fair. | Fair. | Poor. | Probably satisfactory. | Satisfactory. | Hard outer shell breaks down under impact |
| Beryllium copper | No. | Poor | Fair. | Poor. | Satisfactory | Satisfactory | |
| Beryllium nickel | No. | Fair. | Fair. | Fair. | Satisfactory | Satisfactory | |
| Cobalt-tungsten | No. | Good. | Good. | Good. | Satisfactory | Satisfactory | |

in comparison with high-carbon steel. The high-carbon steel and even alloys with a small percentage of iron were found to form appreciable quantities of iron oxide which, due to its highly abrasive character, rapidly wore away the pivot point. It is interesting to note that a bearing that is adequately lubricated with the proper lubricant does not form this oxide. The formation of the iron oxide has been investigated by Shotter[6] and has been shown to be dependent upon the presence of a certain amount of water vapor which may in a measure serve to explain why a bearing that is properly lubricated does not form the abrasive oxide.

In table I the material approaching nearest to the requirements is an alloy of cobalt and tungsten (75 per cent cobalt and 25 per cent tungsten). This alloy is the development of Sykes[4,5] who has applied it for wire-drawing dies to resist the high temperatures necessary for the drawing of tungsten wire for lamp filaments. The material belongs to the group of precipitation-hardening alloys. Figure 6 shows a typical hardening curve for actual pivot samples.

## Accelerated Tests of Cobalt-Tungsten

It is very valuable to be able to check a material against the specifications in terms of values obtained by actual measurements. This can be done under stated conditions as there are several methods of obtaining data on watt-hour meter bearings.[1] In the preparation of the results for table I and figure 7, an accelerated test was used.

Figure 7 shows the results of the test run to compare the wear rate of the cobalt-tungsten material with that of high-carbon steel and to check the abrasion characteristics of the wear products in accordance with specification 2. The worn area on the end of the pivot is approximately circular in shape and its diameter can be measured readily by means of a microscope with a calibrated eye-piece. From time to time as the test progressed the pivots were removed and the diameter of the worn area was measured. These measurements as a function of revolutions of the watt-hour meters are shown in figure 7.

Without lubrication the cobalt-tungsten pivots averaged $34 \times 10^6$ revolutions for a worn area diameter of 0.003 inch as compared to $12 \times 10^6$ for high carbon steel. This shows a ratio of 2.8 to 1 for cobalt-tungsten over steel. The mean diameter of the worn area of the jewels run with the steel pivots and the jewels run with the cobalt-tungsten pivots were as shown in table II.

These results show definitely that the cobalt-tungsten material has a life well over twice that of steel when run without lubrication and that the jewel wear is approximately $1/8$ as much with cobalt-tungsten as with steel based on this test.

Figure 7 also shows the worn area of cobalt-tungsten in a well lubricated bearing tends to approach a limiting value and become stable. While it is difficult to measure the small amount of wear of the jewels with the 2 materials running in well lubricated bearings, the cobalt-tungsten definitely showed less wear on the jewels than did the steel pivots. Further tests made on a large number of watt-hour meters in actual service have confirmed the conclusions drawn from the accelerated test. For example, a field test in which 175 steel pivots and 153 cobalt-tungsten pivots operated with lubricated bearings for a one year

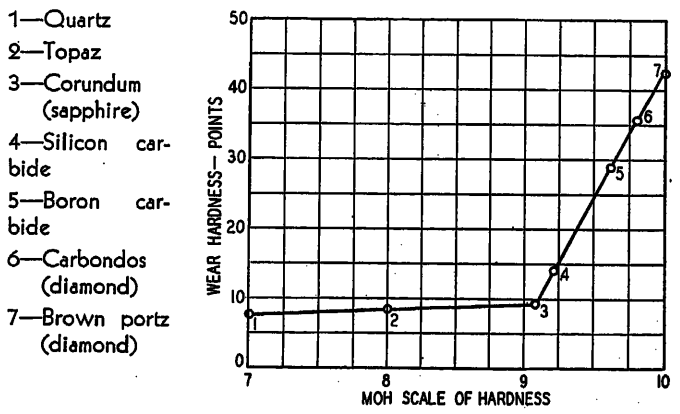



**Fig. 5. Curve showing relation between Moh hardness scale and wear hardness scale**

period showed an average jewel wear area diameter of 0.004 inch for cobalt-tungsten as compared to 0.0084 inch for steel.

## Shock Resistance of Pivot Materials

In order to check the shock resistance of different materials, 2 watt-hour meters rated at 5 amperes, 115 volts were connected in series with a 30-ampere fuse and the load side was short-circuited with a heavy knife switch. An oscillogram was taken to determine the point on the wave at which the switch was closed and the magnitude of the short-circuit current. It was found that a peak value of 1,500 amperes was obtained. Further tests showed that currents under 1,000 amperes were not suffi-

cient to crack jewels or damage the steel pivots used. The 1,500 ampere value was selected as a reasonable one to use as it represents a value that is likely to be obtained in service.

The disk is thrown upward when the short circuit is applied and springs between the damping magnets and the driving element so that energy is stored elastically in the deformed aluminum disk. When the short circuit is removed, the pivot is driven downward like an arrow from a bow and strikes a sharp impact blow upon the jewel.

Figure 8*a* shows the disk, damping magnet, and driving element in the normal position, and figure 8*b* shows the deformed disk under short-circuit conditions. An attempt was made to study the energy of the blow with which the jewel was struck by the pivot by replacing the sapphire jewel with a polished brass plug and observing the depth of the indentation made by the pivot.

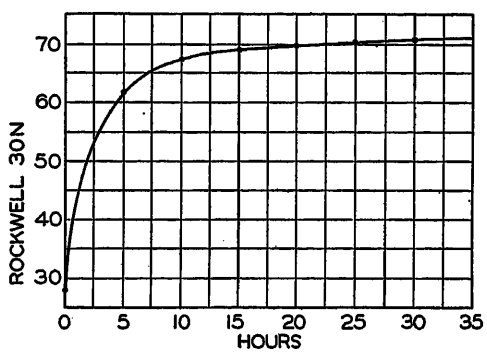



**Fig. 6. Age hardening of cobalt - tungsten pivot material at 650 degrees centigrade**

After one short circuit which was opened within 1/4 cycle after its occurrence, the brass plug showed *seven* indentations. This shows that a condition of oscillation existed after the release of the short circuit, resulting in a multiple hammering of the plug.

The data to plot the curve, shown in figure 4, were obtained with steel pivots and solidly mounted sapphire jewels using short circuits having a peak value of 1,500 amperes. These tests were made, as previously mentioned for the purpose of evaluating the effect of pivot radius on shock-resistance and show conclusively that shock-resistance increases very rapidly with increase in radius.

In making the tests to obtain the data for figure 4, 13 per cent of the jewels were damaged by steel pivots of 0.0185-inch radius. The tests were repeated using 0.0185-inch radius cobalt-tungsten pivots and no jewels were damaged. The cobalt-tungsten pivots are softer than steel pivots and in this test tended to flatten slightly, thereby reducing the stress on the jewel and preventing damage to the jewel surface. The extent of the flattening was not sufficient, however, to measurably increase the friction of the bearing.

## Lubrication

It was shown by Abbott and Goss[1] that the most successful operation of a pivot type bearing is obtained when the bearing is properly lubricated, but the provision of a good lubricant is not a simple matter. The requirements for a lubricant are exacting due to the fact that a small quantity put into the bearing at the time of installation is expected to last for periods up to 10 years. Based on experience and tests on watt-hour meter bearing lubricants over a period of years, the following empirical set of specifications has been developed to serve as a criterion for judging a lubricant for this application:

1. Low evaporation—The evaporation loss shall not exceed 20 per cent in a dry atmosphere at 75 degrees centigrade after 50 days. Free circulation of air shall be provided. The evaporation shall be tested in glass dishes approximately 2 inches in diameter and the depth of oil shall not exceed 1/8 inch or an equivalent ratio of area to volume shall be maintained.

2. Stable viscosity—The viscosity during the evaporation test shall not change more than 10 per cent and no gummy deposits or precipitates shall be formed.

3. Wide temperature range—The viscosity of the oil shall not affect the calibration of a standard watt-hour meter more than 0.10 per cent between +25 and −40 degrees centigrade. The test shall be made with 5 per cent nominal load on the watt-hour meter.

4. High chemical stability—The oxidation or acid forming properties of the oil shall be checked by the following method: 500 cubic-centimeters of oil shall be placed in a 1,000-cubic-centimeter glass beaker which also contains 40 inches of number 18 iron wire and 40 inches of number 18 copper wire. The beaker shall be placed in

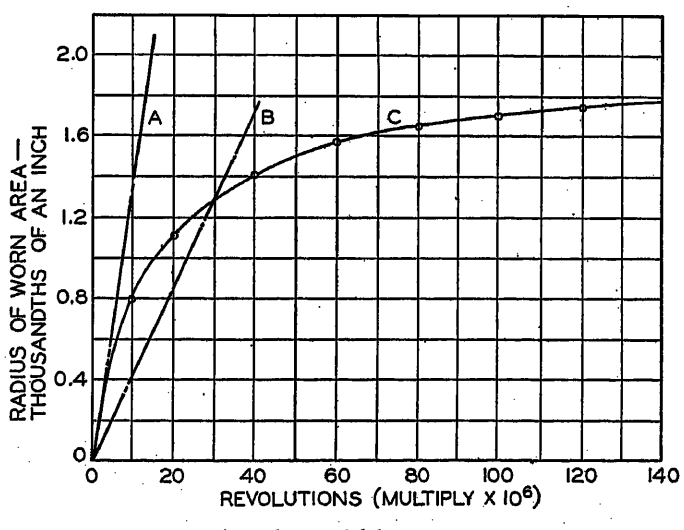



**Fig. 7. Accelerated life test wear curves**

*A*—Standard steel pivot without lubrication; 12 × $10^6$ revolutions for a worn area radius of 0.0015 inch

*B*—Cobalt-tungsten pivot without lubrication; 34 × $10^6$ revolutions for a worn area radius of 0.0015 inch

*C*—Cobalt-tungsten pivot with ideal lubrication

Pivot radius 0.0185 inch

**Table II—Wear in Pivot Material**

| Material | Number of Meters | Number of Revolutions | Mean Diameter of Worn Area, Inches |
|---|---|---|---|
| Steel (1.25 per cent carbon) | 4 | 62.9 × $10^6$ | 0.031 |
| Cobalt-tungsten | 4 | 63.8 × $10^6$ | 0.0113 |

a water bath at 75 degrees centigrade and an excess of free oxygen bubbled through the oil. The initial acidity shall not be over 0.50 per cent and at the end of 500 hours on this test it shall not exceed 1.0 per cent.

5. Low creepage—The oil should have low creepage tendencies.

6. Corrosion protection—The oil should not corrode steel or the other bearing materials used and should also afford good corrosion protection to the pivots.

Over 60 different oils were checked to these specifications during a recent investigation and table III gives the results of a few typical oils.

The literature contains an abundance of material on the properties of different mineral oils, fish oils, animal, and vegetable oils. This information is not, however, of particular value in selecting an oil or the components of an oil to meet the above set of specifications because of the fact that the evaporation requirement is particularly exacting when combined with the low temperature requirement. This subject has been treated by Holtz[7] for the mineral oils. The mineral oils in general are too volatile at the upper temperature (75 degrees centigrade) if they will meet the low temperature viscosity requirements, and too viscous at low temperatures if they will meet the evaporation requirement. There are exceptions, however, as shown by mineral oil *E* in table III.

The fish oil *F* has the unusual property of combining low evaporation with good low temperature performance and meets the specifications very well. The acidity is high, however, and as seen from the table when blended with mineral oil *E* an oil was obtained which fulfilled the requirements satisfactorily. Figure 9 shows the evaporation loss curve for this oil and figure 10 shows the increase in acidity on the oxidation test. Certain inhibitors can be added to oils as shown by Dornte[8] that will materially retard the rate of oxygen absorption in an oil. The chemistry of the reaction of oxygen with oil is complex, but by adding the proper inhibitor, as was done in the case of the blend *A*, the rate of acid formation can be reduced to a very low value.

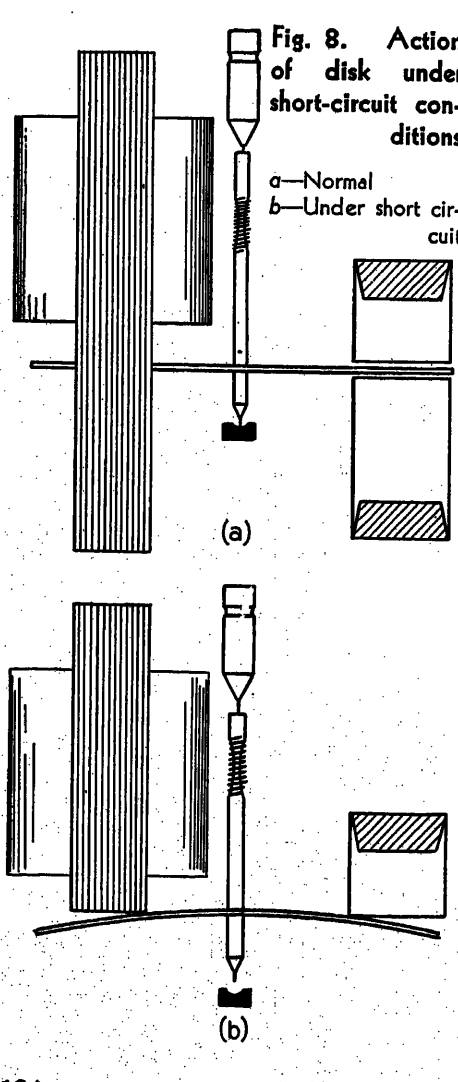



**Fig. 8. Action of disk under short-circuit conditions**

*a*—Normal
*b*—Under short circuit

Table III shows that oil *A* meets all of the specifications by a liberal margin. It represents a good balance between evaporation rate and temperature range so that it can be safely used for the wide temperature range to which outdoor metering subjects the bearing. Ordinary lubricants and many special blends of expensive ingredients will not meet these specifications which are so important to long bearing life. This oil meets the need for a lubricant that can be used in modern watt-hour meter bearings to give the full advantages of reduced wear and long life that good lubrication can produce.

## Top Bearing

Figure 11 shows a typical top bearing for a watt-hour meter. As previously stated, the load this bearing must carry is small and the bearing is subject to little wear for this reason. At the present time a brass washer and steel pivot lubricated with petroleum jelly are the most widely used combination of materials.

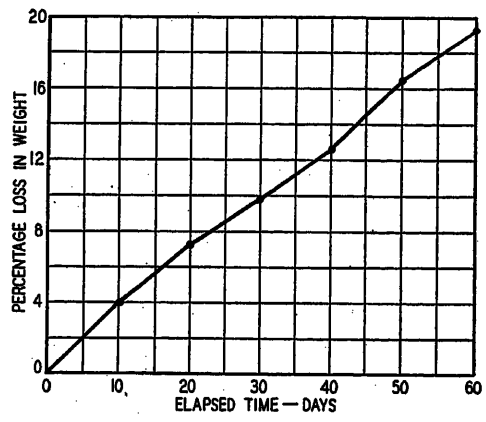



**Fig. 9. Evaporation loss of jewel oil A at 75 degrees centigrade**

Induction-type watt-hour meters require that the clearance between the pivot and washer be kept small in order to provide accurate alignment of the moving element, and to minimize the bearing noise set up by vibration. The addition of the lubricant also serves to reduce this noise as well as to provide the necessary lubrication to the bearing.

This discussion of the top bearing may be summed up by saying that while some improvements may be made in the top bearing by the use of new materials and by improved design, little trouble is experienced at the present time with millions of meters in service.

## Discussion of Typical Bearing Designs

It is evident from the discussion of friction and impact considerations that the radius of curvature for a pivot or ball must be a compromise between initial friction, rate of increase of friction, and impact strength. Figure 12

shows the range within which the radius of curvature for pivots and balls shown in figure 1 falls. These limits have been selected by the different manufacturers of watt-hour meters, based on years of experience, as being a suitable compromise among the various factors for their particular watt-hour meter design.

Too much emphasis should not be placed on the initial or elastic conditions of pivot or ball deformation because it is almost impossible to maintain them due to wear. This was shown by Abbott and Goss[1] for the pivot-type bearing with lubrication and is shown in figure 7 for the pivot-type bearing without lubrication.

Up to this point the design requirements have been considered without reference to any of the particular bearing arrangements shown in figure 1. It will be of value to consider some of the design details together with the advantages and disadvantages of the 3 principal designs.

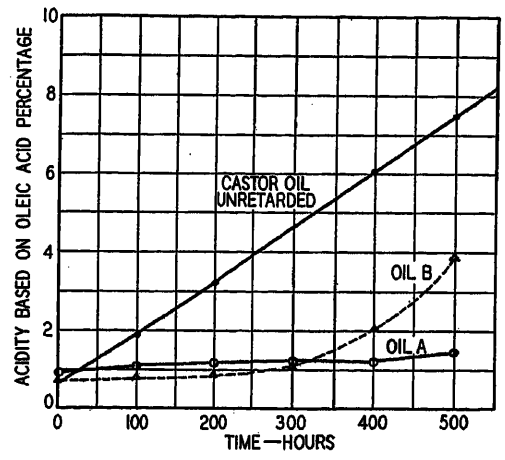



**Fig. 10. Oxidation of oils in stability test**

## Pivot Type Bearing

A typical example of a pivot-type bearing is shown in figure 1*c*. The radius of curvature of the pivot point is 0.0185 inch and the radius of the jewel is 0.035 inch.

The metal guide bearing shown in the figure is to limit the side motion of the pivot and shaft as the load on the meter is increased above a given value. This side motion is due to the combined action of the driving force and the damping force of the meter acting to move the disk out of the meter air gap. Were the side thrust bearing not provided, the meter element shaft would eventually come in contact with the sleeve and the resulting friction would be much greater due to the greatly increased lever arm at which the friction would act. The necessity for such a bearing comes from the wide range over which modern watt-hour meters hold their calibration accuracy and over which they may be used without exceeding their thermal rating. It is possible for a modern watt-hour meter to operate for long periods at 400 per cent to 500 per cent of rated nominal load with good accuracy and no damage to the meter.

*Interchangeability.* In order to insure interchangeability of the pivot and jewel without appreciably affecting the watt-hour meter calibration, it is necessary that the position of the disk in the air gap shall not be materially altered when the bearing is changed. The distribution of the fluxes in the gap is such that both the driving torque and the damping torque vary with the vertical position of the disk in the gap. The speed of the watt-hour meter on a given load will therefore vary with the vertical position of the disk. Figure 13 shows an actual curve taken on a standard make of watt-hour meter rated 5 amperes, 115 volts. It will be noted that as the disk moves down from the top of the air gap, the meter speeds up. For an extreme case this change may be well over 1 per cent.

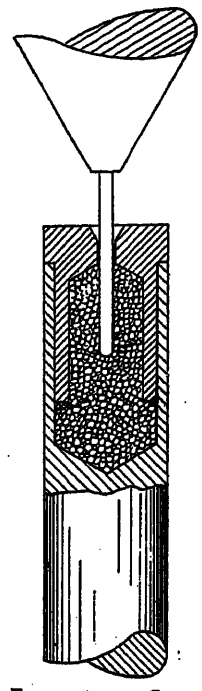


**Fig. 11. Cross section of top bearing**

The control of the position of the disk in the gap necessitates the manufacture of the jewel screw and pivot to within a few one-thousandths of an inch. The sapphire jewel is subject to dimensional variations due to the method of manufacture that makes it necessary to take it into account in the manufacture of the brass screw.

*Lubrication.* The pivot type bearing requires lubrication for the best operation[1] and provision must be made for an adequate supply of the proper lubricant and the retention of this lubricant. The jewel screw shown in figure 1*g* provides a deep reservoir for this purpose.

At low temperatures all oils that are suitable for watt-hour meter bearing lubricants increase in viscosity and

**Table III—Properties of Oils**

| Oil | Composition | (1)* Evaporation Loss, Per Cent | (2)* Viscosity After Evaporation at 75 Deg C | (3)* Viscosity at −40 Deg C | (4)* Percentage Acidity Final | (4)* Percentage Acidity Per Cent of Initial | (5)* Creepage Property | (6)* Corrosion Protection |
|---|---|---|---|---|---|---|---|---|
| *A* | Mineral and fish oil | 16.4 | Unchanged | Satisfactory | 0.09 | 167.0 | Medium | Satisfactory |
| *B* | Castor oil** | 1.0 | Solid | Solid | 0.75 | 3,850.0 | Low | Fair |
| *C* | Castor oil** and fish oil | 16.0 | Solid | Solid (−18 deg C) | 0.33 | 185.0 | Medium | Satisfactory |
| *D* | Mineral oil** | 26.0 | Tacky and gummy | Solid | 0.10 | 100.0 | High | Fair |
| *E* | Mineral oil | 13.4 | Unchanged | Satisfactory | 0.25 | 153.0 | Medium | Satisfactory |
| *F* | Fish oil** | 14.0 | Substantially unchanged | Satisfactory | 0.38 | 240.0 | Medium | Satisfactory |

* See specifications for details of test method. ** Retarded.

tend to retard the rotation of the moving element. By the proper choice of a lubricant and by minimizing the area of the moving parts (such as the pivot) in contact with the oil, the viscous drag can be reduced to the point where the operation of the watt-hour meter is not affected over a wide range of temperature.

### Ball Type Bearing

Figure 1*d* shows a good example of a bearing using 2 cup jewels and a small ball instead of one cup jewel and a pivot. The jewel radius is the same for this construction as for the pivot construction but the radius of the balls used is approximately 0.030 inch which as shown by figure 12 is the upper limit of radius of curvature for watt-hour meter bearings.

The side thrust for this bearing must of necessity be taken by the shaft and sleeve. It is necessary to make the parts so they will not come in contact until the watt-hour meter is operating under a load sufficiently great to make the effect of the side thrust bearing friction negligible and at the same time not allow the ball to ride out of the jewel cup.

*Lubrication.* This bearing is operated without lubrication as the ball is free to move with the sudden application of load or mechanical vibration and constantly presents new points of contact to the jewel surface. The use of a lubricant in this type of construction is not recommended because it introduces an appreciable viscous drag at low temperatures which slows down the watt-hour meter and is, therefore, objectionable for installations where low temperatures are encountered.

### Cup and Cone Type Bearing

Figure 1*h* shows a modification of the pivot type and the ball type which combines some of the advantages of each. The cone is either metal, or sapphire set into a metal plug. The friction between the ball and cone is greater than between the ball and the lower jewel but still is not great enough to prevent the shifting of the position of the ball with changes in load and with vibration. Added rigidity of the system is obtained by the use of the cone and the construction also makes it possible to take the overload side thrust on a thrust bearing of small radius.

*Lubrication.* This bearing should not be lubricated because of the viscous drag introduced by the oil at low temperatures just as with the ball type with 2 cup jewels. Dependence must be placed on the movement of the ball to distribute the wear over the surface of the ball rather than to rely upon lubrication to reduce the wear to a low value. An alloy ball that will meet the specifications that have been set up for a pivot or ball material should materially increase the life of the bearing over that obtained with a steel ball.

## Field Tests

Based on the material covered under the headings of the component parts of watt-hour meter top and lower bearings, the question naturally arises as to the improvement in bearing life that is to be obtained by carrying out the improvements in construction, materials, and design.

Figure 7 shows the results of accelerated tests on one bearing combination consisting of the jewel screw shown in figure 1*g*, the lubricant oil *A*, and cobalt-tungsten pivots. Figure 7 also shows results for the same combination except without the oil run in comparison with high-carbon-steel pivots. Many accelerated tests of this nature have been run. It is realized, of course, that tests of this nature are not the final method of evaluating any bearing combination and that actual field tests under service conditions offer the final basis for judgment of the true value of a bearing. Hundreds of bearings have been studied that were placed in meters in actual service and the results obtained verify the statements made in this paper. While tests have been for but one and 2 year periods, high-carbon-steel pivots and old designs of jewel screws that did not provide oil reservoirs were run in comparison and served as controls. The indications are that improved lubrication and improved pivot materials have added years to the life of the bearings by reducing wear and maintaining more nearly constant values of friction.

While all tests definitely show that proper lubrication increases the life of bearings, it has also been shown that cobalt-tungsten performs exceptionally well even without oil. Experience may prove that cobalt-tungsten pivots running on sapphire jewels will give entirely satisfactory service without lubrication, but much service data will have to be obtained before this question can be answered.

## Summary


1. It has been shown that the meter bearing problem can be rationalized and simplified by careful analysis and that specific requirements or specifications can be formulated for each component part.

2. Definite limitations on the mechanical design result from the requirements of low initial and sustained friction of the bearing

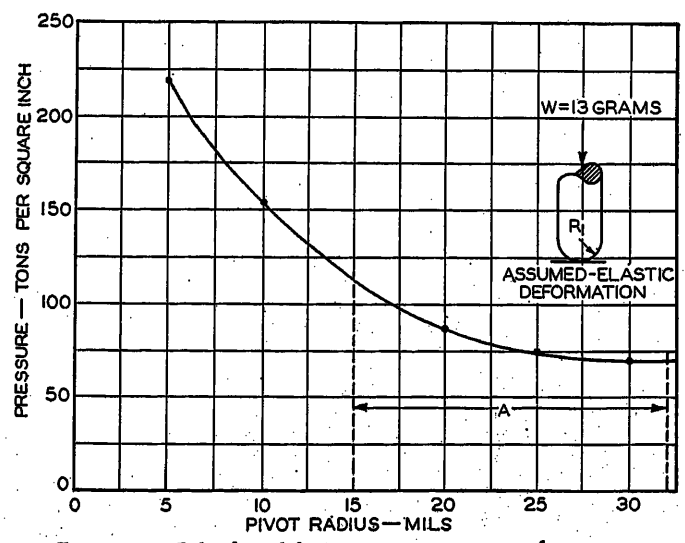




**Fig. 12. Calculated bearing pressure as a function of pivot radius**

*A*—Present range of watt-hour meter bearings

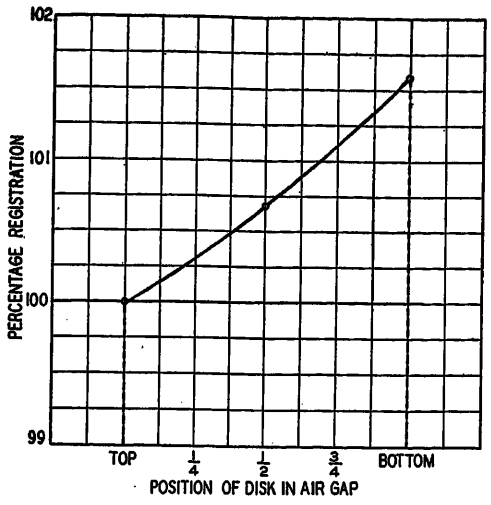



**Fig. 13. Variation of meter calibration as a function of vertical position of the disk in the air gap**

and the shock resistance requirements. Improved materials, therefore, offer the best possibilities for increased bearing life.

3. Although the hardness of sapphire is considerably lower than that of diamond on the new scale of hardness, the high cost and the difficulty of working the latter leave sapphire the best material available for jewel cups.

4. Various alloys offer possibilities of improved bearing life but an alloy of cobalt and tungsten very definitely shows all around superiority to all other materials tested.

5. Research and development work on watt-hour meter bearing oils has resulted in improvements which have made possible a wide temperature-range oil with a low evaporation rate for outdoor meter installations.

6. For pivot bearings, tests indicate that best results are obtained with a jewel screw that maintains a liberal supply of oil in the jewel cup. This is not true for the ball type for which lubrication is not recommended.

7. Improved materials and design may make possible some improvements in watt-hour meter top bearings, but little trouble is experienced with them at the present time.

8. The maximum service for the pivot type bearing is obtained by adopting the 3 improvements mentioned in paragraphs 3 to 5 inclusive of this summary, namely:

(*A*) A jewel screw designed to provide a liberal oil reservoir.

(*B*) Improved oil suitable for a wide temperature range.

(*C*) Cobalt-tungsten pivots which reduce jewel breakage under impact, decrease jewel wear, and reduce abrasion in the event of the loss of the lubricant.

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# Trends in Distribution Overcurrent Protection

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**The provision of suitable overcurrent protection for distribution systems at low cost is an important problem, for upon the satisfactory solution of that problem depends the continuity of service of a great many consumers of electric energy; consequently, the relations of a public utility company with its customers also depend upon adequate overcurrent protection. This paper presents a discussion of the various trends in overcurrent protection, with the aim of providing for the distribution engineer some basis for selecting the particular protective system best suited to his particular requirements.**

LOW-COST overcurrent protection on distribution systems has commanded the attention of the utility industry. New devices and applications have opened new avenues of thought on this phase of distribution problems. It is proposed to make an impartial presentation of the facts pertaining to the problem of overcurrent protection, from the plug or cartridge fuse on the meter board on the consumer's premises to the co-ordination of the main feeder breaker relays with those on the transmission system. This presentation, by correlating the various trends of thought as they are related to the whole overcurrent protection program, should assist utility engineers in choosing the one best suited to their present and future requirements.

Continuity and quality of service, protection of equipment, and low initial and maintenance costs are often divergent factors governing the application of overcurrent protective apparatus on distribution systems. Where the stressing of one necessitates sacrificing another, it is important to know all the facts so the most efficient balance can be secured. The facts governing such a balance will differ somewhat on urban, suburban, and rural systems. Of first importance is a knowledge of the causes of outages evaluated for different parts of the distribution system in terms of some unit for measuring the service being rendered the consumer.

## Review of the Causes and Evaluation of Outages

Protection of consumer service is of fundamental importance. There is little duplication of equipment on the distribution system for reducing consumer outage, and so the equipment must be used with the greatest possible efficiency. Thus, the protection problem involves the handling of fault conditions more with the idea of minimizing consumer outage rather than from the standpoint of protecting the equipment. In analyzing the effect of troubles with the idea of using an overcurrent protective device to improve the continuity of service, it is necessary to know the duration of the fault, how often it is likely to occur, and the number of consumers affected.

Consumer minutes of outage, which is conventionally used as a measure of continuity is determined from the number of consumers affected by any particular outage and the length of time for which the service is interrupted. The importance of including time is, of course, obvious, although there may be some question as to whether it is correct to say that a 60-minute outage for one consumer is equally undesirable as a one-minute outage for 60 consumers.

When considering consumer outage, attention cannot be confined to the outage of any one particular consumer or group of consumers, but must be given to all the outages of all the consumers. For instance, it might be possible to reduce the outages of a small group of consumers at the expense of increasing the outages for a larger group of consumers. This, of course, would be generally undesirable but nevertheless it can easily happen if one does not have a thorough knowledge of all the factors involved or if one places emphasis on just one part of the system without correlating it with the whole system.

A major factor in the efficient application of protective equipment is the relative percentage of temporary versus permanent outages which occur on that particular part of the system. Temporary outages usually refer to fault conditions which will clear themselves with the interruption of power and before the first or second reclosing of the breaker or fuse cutout, whereas permanent outages are those which require the attention of a line crew. Temporary outages would ordinarily be of less than one minute duration, whereas a study of the records of a number of operating companies shows that faults which require the attention of a line crew last anywhere from several minutes up to several hours and average something like 45 minutes.

## Outage Records

Outage information is an indication of the type of service being rendered. However, to be usable in system design, the outage data should be segregated into those parts of the distribution circuit which might be sectionalized, such as main feeder, branch feeder, distribution transformer, and secondary. Another important segregation should correspond to the nature of the area and the load served. For instance, line outage data on rural

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1. For all numbered references, see list at end of paper.

feeders should be kept separate from that on suburban or urban feeders.

Line data are usually given in terms of outages per hundred miles per year. Transformer and secondary outages, on the other hand, are given as the per cent of the number of transformer installations or as the number per 100 transformers per year.

An analysis of the outage data of a number of operating companies, some of which is given in table I, shows that the number of outages on primary lines varies from only a few to as high as 70 or 80 per hundred miles per year. The per cent of these faults which are temporary also varies over a wide range. Trees are a very important cause of line outage. Conditions between various localities differ greatly in the possibility to trim or avoid trees, which accounts for the smaller number of outages per hundred miles on many rural lines as compared with urban or suburban feeders on the same system.

Lightning is still of major importance as a cause of distribution-transformer outage due to the large number of older transformers still in service, to the omission of lightning arresters, etc. Fuse blowing and transformer burnouts due to lightning have been greatly reduced by

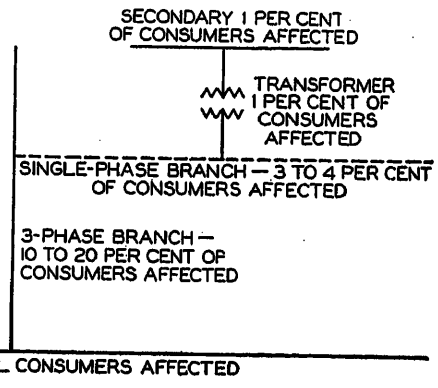



**Fig. 1. Diagram of distribution circuit, showing average percentage of all consumers on the circuit affected by an outage confined to the portion of the line on which the fault occurs**

the interconnection of the lightning arrester grounds with the secondary neutral. This, and the present trend toward connecting the lightning arrester so the discharge currents do not pass through the fuse link, has tended to improve the undesirable situation in which the prevalence of lightning dictated the use of fuse-link ratings larger than might otherwise have been selected.

In analyzing the distribution transformer and secondary outage data from which table I was obtained, it is found that the number of outages accompanied by transformer burnouts is relatively small. For instance, of the distribution transformer and secondary outages tabulated, the transformer burnouts occurred with only 12.5 per cent of the total outages due to lightning (0.256 per 100 transformers average), 6.4 per cent of the total outages due to secondary faults and miscellaneous (0.255 per 100 transformers average), and 30 per cent of the total outages due to overload (0.091 per 100 transformers average). These figures demonstrate the overcurrent protection afforded the distribution transformer by the primary fuse.

As is to be expected, there is a wide variation in the frequency and nature of outages for the various companies which emphasizes the necessity of each company maintaining outage records for its own particular use. If a company attempts to make use of an average value as indicated from a study of the records of other companies, a type of design might result which would not be at all suitable for the particular condition under which the system operates.

## Consumers Affected

The number of consumers affected by a fault accompanied by the functioning of some overcurrent protective device varies from one to all those on a feeder or perhaps even more if the feeder breaker relay is not properly coordinated with devices between it and the source of supply. With the usual type of construction, trouble occurring anywhere from the consumer service fuses to the transformer primary fuses involves all the consumers on the particular transformer. This varies from one consumer in the case of rural areas to over a hundred, and averages from 25 to 40 for the usual type of urban residential construction. The number of transformers on any particular primary branch varies from one or more, in the case of single-phase branches, up to 100 in the case of 3-phase branches. Trouble on branch circuits may, therefore, involve from one up to 1,000 or more consumers. In the case of feeders and branches having a higher percentage of residental consumers, fairly accurate estimates of the actual number of consumers can be obtained by multiplying the peak load in kilowatts by 4. This applies when the kilowatt consumption of the consumers in the area considered averages 600 kw or 700 kw per year.

In studying a distribution system with the idea of reducing the consumer minutes of outage, it is usually important to know the relative importance of troubles on the primary lines, in the distribution transformer, and on the secondary lines; with respect to which causes most of

**Table I—Outage Data for 2,400/4,160 Y Volt Distribution Circuits**

| Company | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | Average |
|---|---|---|---|---|---|---|---|---|---|---|
| Total outages due to line troubles (urban) per 100 miles of line | 29.1 | 13.5 | 41.6 | 53.7 | 20.2 | 13.4 | 40.1 | 29.3 | 2.5 | 27.04 |
| Total outages due to distribution transformer and secondary troubles (per 100 distribution transformers) | 7.2 | 4.1 | 8.7 | 5.6 | 8.1 | 0.9 | 7.8 | 3.0 | 11.6 | 6.3 |
| Total outages due to lightning (per 100 transformers) | 2.02 | 0.86 | 2.53 | 1.34 | 4.05 | 0.298 | 1.67 | 0.09 | 5.57 | 2.05 |
| Total outages due to secondary faults and miscellaneous (per 100 transformers) | 4.54 | 3.08 | 6.0 | 3.64 | 3.48 | 0.612 | 6.11 | 2.70 | 5.68 | 3.98 |
| Total outages due to overloads (per 100 transformers) | 0.065 | 0.16 | 0.17 | 0.62 | 0.57 | 0.0 | 0.02 | 0.21 | 0.35 | 0.304 |

the consumer minutes of outage. Figure 1 shows graphically the probable range in percentage of consumers affected by faults on the various parts of the system for the more generally used types of radial feeders.

Table II, lines 1 and 2 show a study of the ratios of permanent line outages to distribution transformer and secondary outages for the various companies whose outage data are given in table I. The number of transformers per mile is also given in line 3 of table II, so that a direct comparison may be made between them on the same basis as in lines 4 and 5. These point conclusively to the importance of primary line trouble as a cause of consumer minutes of outage. This is confirmed by figure 2 which gives the actual records in percentage of consumer minutes outage for the different parts of two utility companies' systems. The comparisons of lines 4 and 6 show that a reduction of one-half the length of line decreases the effect of permanent line faults in transformer outages to $^1/_4$, whereas lines 5 and 7 show it only decreases the effect of transformer and secondary faults on transformer outages to $^1/_2$.

Therefore branch-line fusing or other sectionalizing of the line to confine the effect of faults to smaller areas, not only attacks the problem at one of the most important causes of consumer minutes outage, but also produces a greater reduction per protective unit installed. The growing interest in the co-ordination of line protection is a natural outcome of an understanding of these facts.

## Time-Current Characteristics

The co-ordination of overcurrent protective apparatus to reduce to a minimum the number of consumer-minutes outage on distribution circuits, is based on the correlation of their time-current characteristics. These are usually plotted as curves so as to show the variations in the shape for different types and ratings of apparatus. This is important as the comparison of one or 2 points may not insure proper co-ordination over the complete range of fault currents that can occur in the section protected. The fault currents will vary with the total impedance of the line, the connected apparatus and the fault.

The total time to clear the circuit is comprised of 2 parts for most protective apparatus: For circuit breakers these parts are (1) the time to complete the electrical cycle of the relay and (2) the time for the breaker to open mechanically and extinguish the arc (see figure 3 $E^{2\prime} - E^{2\prime\prime}$); for fuse links (more especially those used on the primary lines) they are (1) the time to melt the fuse link and (2) the time to extinguish the arc (see figure 3 $B'' - B'''$). Both are essential for the proper co-ordination of protective apparatus. The device farthest out on the line must clear the circuit (total clearing time figure 3 $B'''$, $C'''$, $D'''$) before the fuse link between it and the source of supply melts or the electrical cycle of the relay is completed (figure 3 $E'$, $E^{2\prime}$, $E^{3\prime}$).

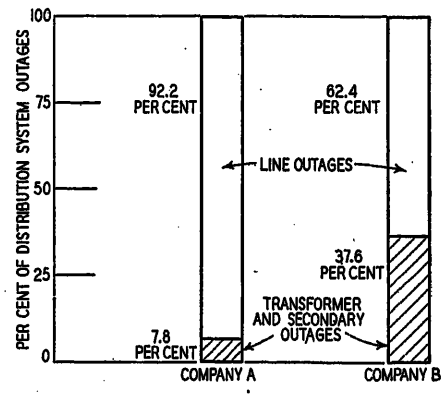



**Fig. 2. Diagrammatic representation of the outage record of 2 companies**

### Circuit-Breaker Relays

The earlier designs of relays of the plunger type functioned almost instantaneously or with a slight time delay where a bellows attachment was provided. The induction relay was developed at a comparatively early date in order to meet operating requirements, necessitating greater time delay to permit a wider range for co-ordination with the current-carrying and current-interrupting characteristics of other apparatus further out on the line. These have been adopted quite universally. The induction relay curves have the inverse time-current characteristic of figure 3 $E'$ or the very inverse time-current characteristic of figure 3 $E^{2\prime}$. The latter provides a sharper knee which is especially valuable at the low time lever settings, where the less inverse curves tend to approach the fuse link curves at the low currents.

Attachments are available for induction relays to permit instantaneous completion of the electrical cycle at any desired current. The use of this attachment allows

**Table II—Comparison of Permanent Primary Line Outages With Distribution Transformer and Secondary Outages**

| | Company | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | Permanent line outages (per 100 miles of lines) | 18.65 | 8.3 | 2.54 | 35.0 | 14. | 1.0 | 34. | 1.7 | 4.0 |
| 2 | Distribution transformer and secondary outages (per 100 distribution transformers) | 7.2 | 4.1 | 8.7 | 5.6 | 8.1 | 0.9 | 7.8 | 3. | 11.6 |
| 3 | Transformers per mile | 11.9 | 9.5 | 13.5 | | 10.7 | | 7.9 | | 8.9 |
| 4 | Transformer outages for one mile of line due to permanent line faults | 1.22 | 0.79 | 3.43 | | 1.5 | | 3.58 | | 0.36 |
| 5 | Transformer outages for a one-mile line due to transformer and secondary faults | 0.86 | 0.39 | 1.73 | | 0.87 | | 0.63 | | 1.03 |
| 6 | Transformer outages for a $^1/_2$-mile line due to permanent line faults | 0.305 | 0.20 | 0.83 | | 0.38 | | 0.69 | | 0.09 |
| 7 | Transformer outages for a $^1/_2$-mile line due to transformer and secondary faults | 0.43 | 0.20 | 0.86 | | 0.44 | | 0.31 | | 0.52 |

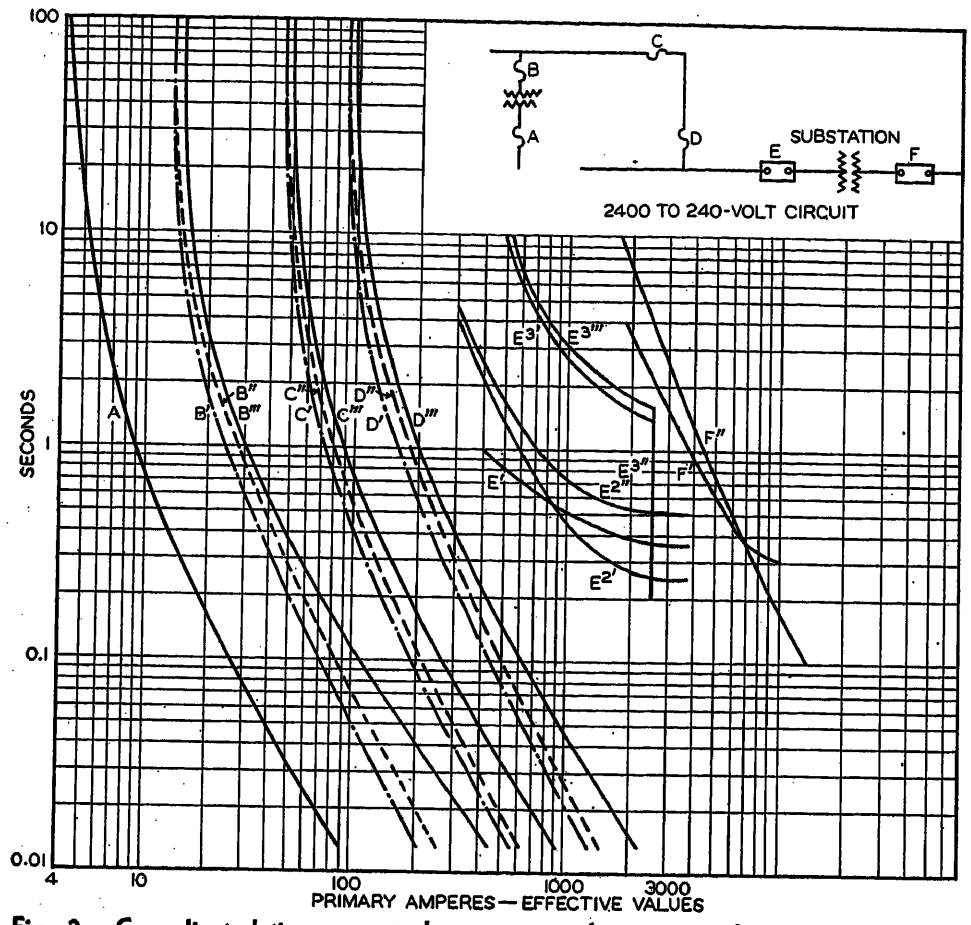



**Fig. 3. Co-ordinated time-current characteristics of protective devices on a typical distribution circuit**

*A*—Household plug or cartridge fuse rated at 30 amperes
*B*—Fuses rated at 10 amperes in primary leads of a distribution transformer
*B'*—Time-current characteristic curve for 75 per cent of melting time to factor operating and manufacturing variables
*B''*—Melting time-current characteristic curve
*B'''*—Total clearing time-current characteristic curve
*C*—Branch line sectionalizing fuse rated at 30 amperes
*C', C'', C'''*—Same as *B', B'', and B'''*, respectively
*D*—Branch line sectionalizing fuse rated at 50 amperes
*D', D'', D'''*—Same as *B', B'' and B'''*, respectively
*E*—Feeder oil circuit breaker and relay (minimum pick-up, 200 amperes)
*E'*—Inverse relay (number 1 time lever setting)
$E^{3'}$—Very inverse relay (number 1 time lever setting)
$E^{3''}$—Opening of oil circuit breaker
$E^{3'}$—Very inverse relay (number 10 time lever setting)
$E^{3''}$—Instantaneous attachment on relays function
$E^{3'''}$—Opening of oil circuit breaker
*F*—Protective device on incoming transmission lines
*F'*—Very inverse relay (number 1 time lever setting)
*F''*—Fuse

higher time lever settings (figure 3 $E^{3'}$), which makes possible a greater time-current range for other protective apparatus on the distribution system. The instantaneous pick-up at high currents (figure 3 $E^{3''}$), will prevent distribution system faults from blowing the fuses of figure 3*F''* or operating the relays of figure 3 *F'* on the transmission side of the substation.

### Primary Fuse Cutouts and Fuse Links

As one phase of the marked improvement that has been incorporated in primary fuse cutouts and fuse links[1,2], the time-current characteristic curves for fuse links were made more inverse so as to permit closer co-ordination with the induction relay. Of more recent date, a further improvement figure 4 has resulted from an engineering study that took into consideration the 100 per cent continuous current carrying ability of the fuse links and cutouts, the motor starting demand currents figure 4*A*, the plunger type and the induction relay characteristics figure 4*E* and *D*, and the current-interrupting ability of the fuse cutouts.

### Secondary Fuse Cutouts and Fuse Links

The use of secondary fuse cutouts while not new, has only very recently come into prominence because of the improvement made in the designs available. A large part of this improvement has resulted from making the time-current characteristics of the fuse links identical

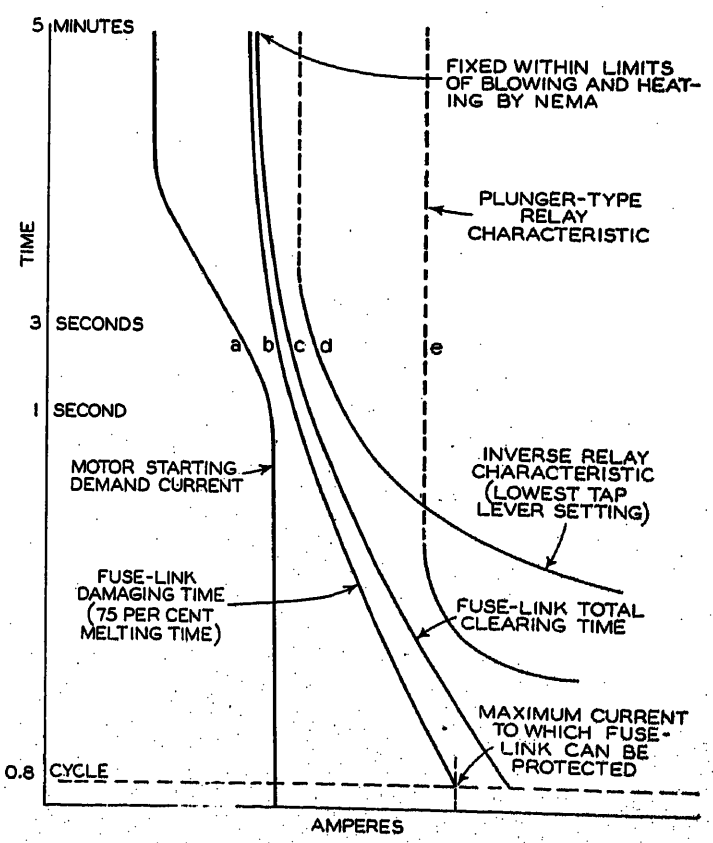



**Fig. 4. Curves showing scientific development of universal cable-type fuse links**

to those for the latest designs of primary fuse links figure 4. This similarity enables a closer co-ordination between the secondary and primary.

### Plug and Cartridge Fuse Characteristics

The household plug and cartridge fuse, commonly used at the meter boards on the consumer's premises, has been a merchandised product that rarely entered into the distribution engineer's problems. The rapid increase in residential loads, especially due to ranges and water heaters, has so raised the ratings of these fuses used with the relatively low kva transformer ratings, that a knowledge of their time-current characteristics has become a vital factor. To date, the different manufacturers of plug or cartridge fuses, of the renewable or nonrenewable type, have complied with the specifications of the National Electric Code and the Fire Underwriters' Laboratories which state:

"*Rating.* Fuses shall be so constructed that with the surrounding atmosphere at a temperature of 24 degrees centigrade they will carry indefinitely 110 per cent current without causing the tubes to char or externally visible soldered connections to melt.

"Temperature and 110 per cent current tests shall be made simultaneously.

"With a room temperature between 18 and 32 degrees centigrade, fuses starting cold shall blow on 150 per cent current, without causing the tubes to char or externally visible soldered connections to melt, within the times specified below.

| | |
|---|---|
| 0– 30 amperes | 1 minute |
| 31– 60 amperes | 2 minutes |
| 61–100 amperes | 4 minutes |
| 101–200 amperes | 6 minutes |
| 201–400 amperes | 12 minutes |
| 401–600 amperes | 15 minutes |

"In the 150 per cent rating test, only one fuse shall be tested at a time."

Except for these specifications, as quoted, no other published information has been available.

Recent studies have shown a rather wide variation between the curves of fuses of different manufacture.

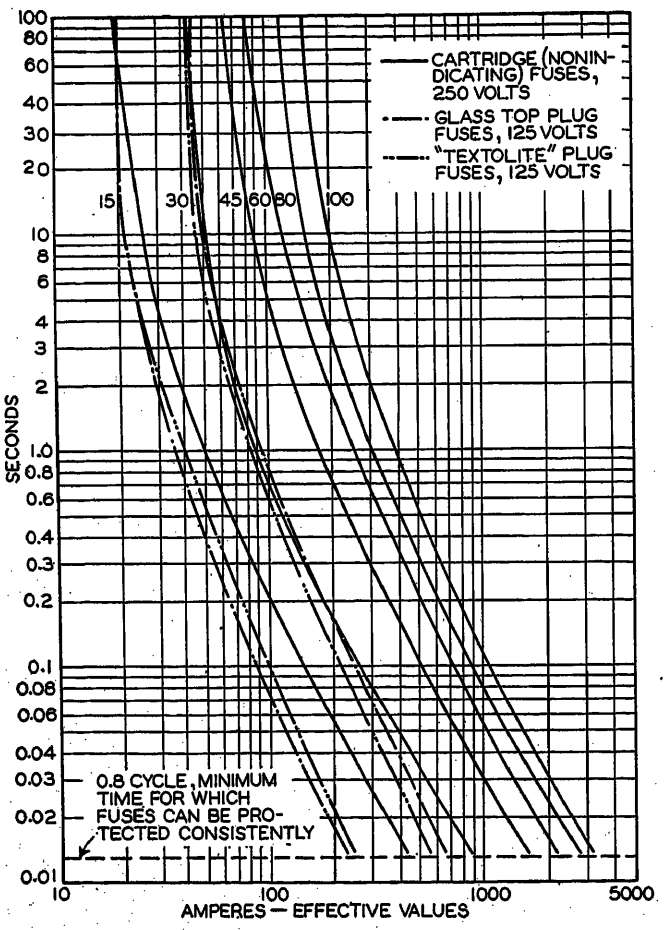


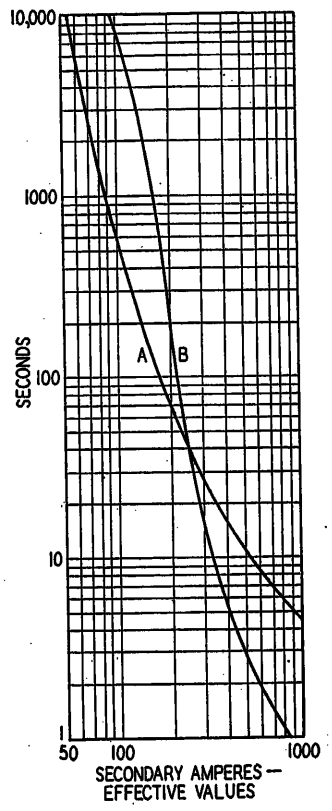

**Fig. 5. Total clearing time-current characteristics of typical plug and cartridge fuses**

Curves are based on tests at normal rated voltage

**Fig. 6. Transformer and internal breaker time-current characteristic curves**

*A*—Recommended time-load curve for a 10-kva transformer

*B*—Secondary breaker curve, with breaker mounted in transformer oil (setting similar to that used in practice)




However, generally these all have an inverse-time-current characteristic, figure 5, quite similar to that of the fuse links and induction relays used on the primary and secondary lines.

## Transformer Time-Load Characteristics

Heretofore transformer protection has been a problem of overvoltage rather than overcurrent. The interconnection of the lightning arrester ground and secondary neutral has so greatly reduced the failures caused by overvoltage, that those caused by overcurrent appear more important. This is accentuated in some places by the desire to increase the average loading of the transformers.

A recommended time-load curve for distribution transformers has been prepared by the AIEE and ASA as a guide (see figure 6*A* plotted for a 10-kva transformer).

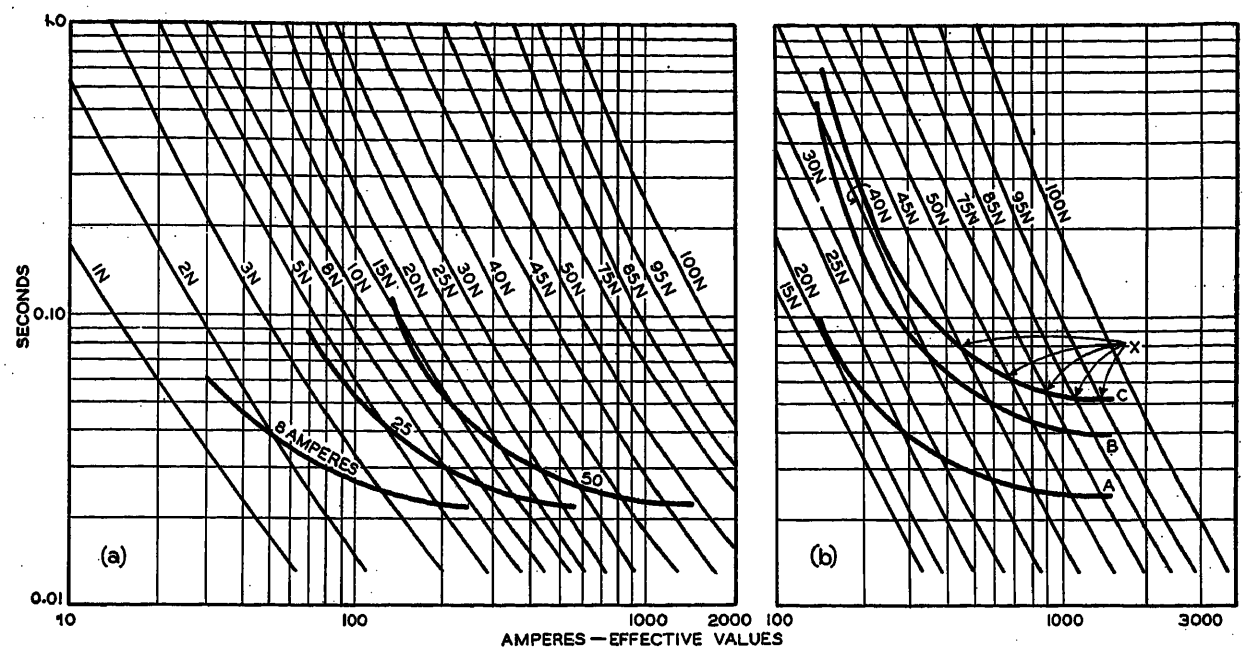



**Fig. 7. Time-current characteristics of recloser and fast-blowing universal cable-type fuse links for enclosed, open, and drop-out cut-outs rated at from 50 to 100 amperes and from 5 to 15 kv**

(*a*)—First opening of recloser and total clearing time for fuse links (fuse link curve must be to left of recloser curve for proper co-ordination)

(*b*)—Curves for 50-ampere recloser and melting time of fuse links

*A*—First opening of a typical recloser

*B*—Equivalent heating of fuse link by current during all operations to lock-out of the recloser, and taking into account the cooling for that part of the cycle during which no current flows

*C*—Equivalent heating, but including a factor for operating variables

This curve has the backing of a large group of utility and manufacturing engineers. In this analysis we are more interested in the shape rather than the exact positioning of this curve with respect to current and time.

The recommended transformer time-load curve (figure 6*A*) has an inverse time-current characteristic. The curve has much less slope, especially at the low-current long-time end, than is provided by the induction relay, the primary and secondary fuse links, or the household plug and cartridge fuses.

## The Low Voltage Breaker

The time-current characteristic curve for the low-voltage breaker recently developed for household application is slightly less inverse than the induction relay and the fuses whose characteristics have to be co-ordinated with it. The breaker characteristics were made to co-ordinate with the fusing of the wire used in buildings so as to afford the maximum fire protection.

### Secondary Breakers in Distribution Transformers

A breaker has been developed for use inside the tank of distribution transformers. It is mounted so as to obtain some of the heating characteristics of the transformer and has a time-current characteristic curve figure 6*B* that approaches the transformer time-load curve at the low-current, long-time end and is more inverse (much faster) at the high-current short-time end. The average slope is less than for induction relays and the fuses.

### Characteristics of Circuit Reclosers

The circuit recloser is a recent development designed to provide low-cost reclosing circuit breaker operation for rural or troublesome branch lines where there are a high percentage of temporary faults. The time-current characteristic curves figure 7*A* for the recloser are similar to the characteristics of plunger-type relays.

Another factor is introduced by the recloser, namely, that of the time to reclose. During the interval after the arc has been extinguished and until the contacts have reclosed, relays connected in series will partially or completely reset to the normal position and fuse links will tend to cool. Thus the resultant effect of the periods when current flows and no current flows must be considered in co-ordinating the recloser with other protective apparatus so as to permit the recloser to lock out before the relay functions or the fuse links are partially melted. The curves figure 7*B* and 7*C* factor the cumulative heating of fuse links.

### The Problem of Co-ordinating the Characteristics

In most cases, existing conditions impose a definite range of time-current characteristics within which all overcurrent protection on the distribution system must be obtained. The curves figure 3 represent the condition in existence on a high percentage of distribution systems in the country. The maximum limit is the highest possible setting of the feeder breaker relay *E* that will permit co-ordination with the relay *F'* or fuse *F''* on the transmission

side of the substation. Quite often the range can be increased by the use of the instantaneous attachment on the induction relays of the feeder breakers set to trip at currents $E^{3}''$ below those which will trip the transmission relay $F'$ or blow the fuse $F''$. In order to confine the effect of faults to the minimum number of consumers, the time-current characteristics of the fuses at the sectionalizing points $C$ and $D$, at the transformer installation $B$, at the meter board on the consumer's premises $A$, and at any other points on the system, have to be squeezed in the range to the left of the feeder breaker relay curve $E$, so that each is co-ordinated with the other. It is frequently found that there is not a sufficiently wide range to the left of the feeder breaker relay curve $E$ to permit the installation of all the protective devices desired on the distribution system. It, therefore, becomes a matter of choosing the ones which will provide the greatest reduction in average consumer minutes outage for the whole system, with, of course, the economics of the particular circuit kept fully in mind.

## The Household Fuse and Breaker

The plug and cartridge fuses located on the meter board of the consumer's premises are becoming a factor to be considered. Their time-current characteristics may determine the lower side of the range available for distribution overcurrent protection. This has become increasingly true where the higher rated household fuses are used for installations supplied through the smaller sizes of distribution transformers. For instance, the 60-ampere cartridge fuse, figure 8$A''$, usually used on services feeding ranges and hot-water heaters requires 2 times the full-load secondary current of a 10-kva transformer (220- to 250-volt winding), 4 times the full load current of a 5-kva transformer, and 7 times the full-load current of a 3-kva transformer to blow within 2 minutes. To co-ordinate the primary fuse links with this 60-ampere household fuse, without any other secondary protective devices in the circuit, necessitates the use of minimum primary fuse-link ratings of approximately 15 amperes for transformers having a 10 to 1 ratio, 5 amperes for transformers with a 20 to 1 ratio, and 3 amperes for transformers having a 30 to 1 ratio, regardless of whether the rating of the transformer is 3, 5, or 10 kva. Figure 8 shows the effect of superimposing the 60-ampere cartridge fuse and the 15-ampere primary fuse link on the curves of figure 7 shaded. As a high percentage of urban distribution circuits use 2,400 to 120 and 240-volt distribution transformers for serving residential loads, this may present an overcurrent protection problem for a great many systems. A factor in this problem is the

$A$—Household plug and cartridge fuses
$A'$—30-ampere rating
$A''$—60-ampere rating
$B$—Fuses in primary leads of distribution transformer
$B^{s}$—$10N$ ampere rating
$B'$—Time-current characteristic curve for 75 per cent of melting time to factor operating and manufacturing variables
$B''$—Melting time-current characteristic curve
$B'''$—Total clearing time-current characteristic curve
$C$—Branch line sectionalizing fuse rated at 30 amperes
$D$—Branch line sectionalizing fuse rated at 50 amperes
$E$—Feeder oil circuit breaker and relay
$E^{s}'$—Very inverse relay (number 1 time lever setting)
$E^{s}'$—Very inverse relay (number 10 time lever setting)
$E^{s}''$—Instantaneous attachment on relay functions
$F$—Protective device on incoming transmission lines
$F'$—Very inverse relay (number 1 time lever setting)
$F''$—Fuse

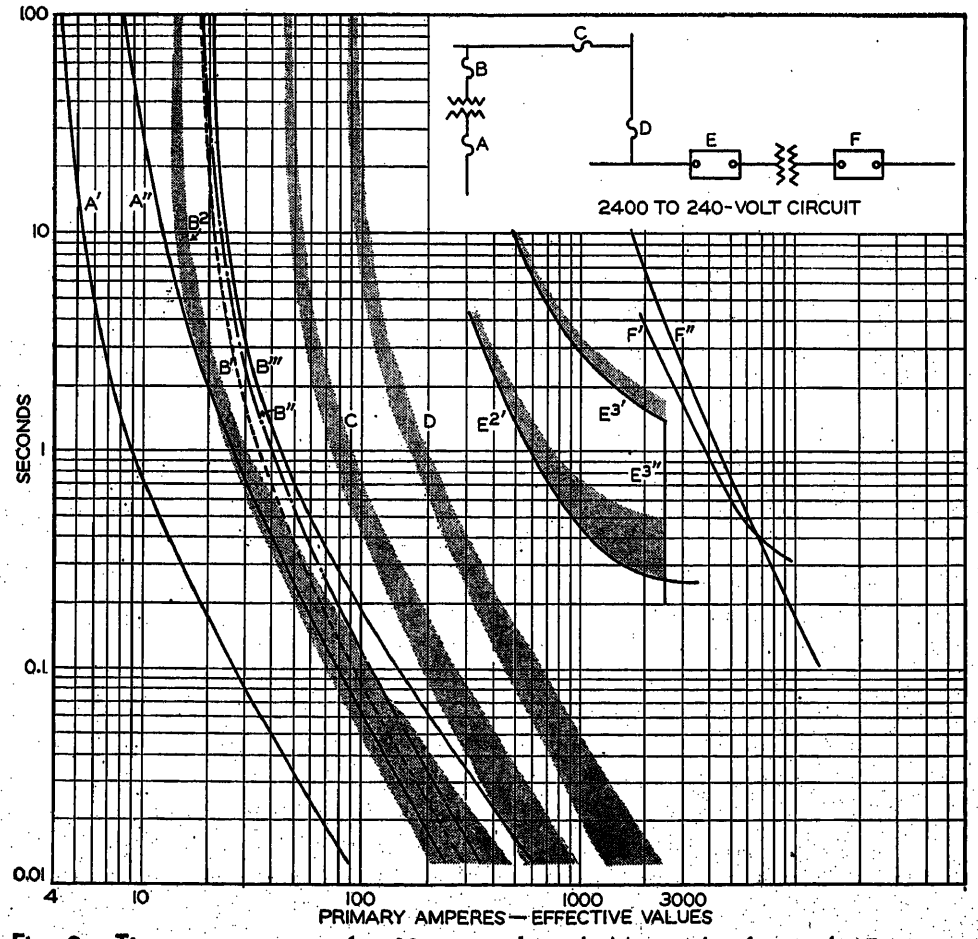



**Fig. 8. Time-current curves for 60-ampere household cartridge fuse and 15-ampere primary fuse link superimposed on curves of the conventionally co-ordinated system of figure 3**

*A*—Household plug and cartridge fuses
*A'*—30-ampere rating
*A''*—60-ampere rating
*B*—Fuses rated at 15 amperes, in primary leads of distribution transformer
*C*—Branch line sectionalizing fuse rated at 30 amperes
*D*—Branch line sectionalizing fuse rated at 50 amperes
*E*—Feeder oil circuit breaker and relay
$E^{3}'$—Very inverse relay (number 1 time lever setting)
$E^{3}'$—Very inverse relay (number 10 time lever setting)
$E^{3}''$—Instantaneous attachment on relay functions
*F*—Protective device on incoming transmission lines
*F'*—Very inverse relay (number 1 time lever setting)
*F''*—Fuse
*G*—Recommended transformer time-load curve
*H*—Internal secondary breaker
*H'*—Overload indicator lights
*H''*—Breaker opens
*I*—Internal "weak link" or fuse in primary leads
*I'* and *I''*—Available designs

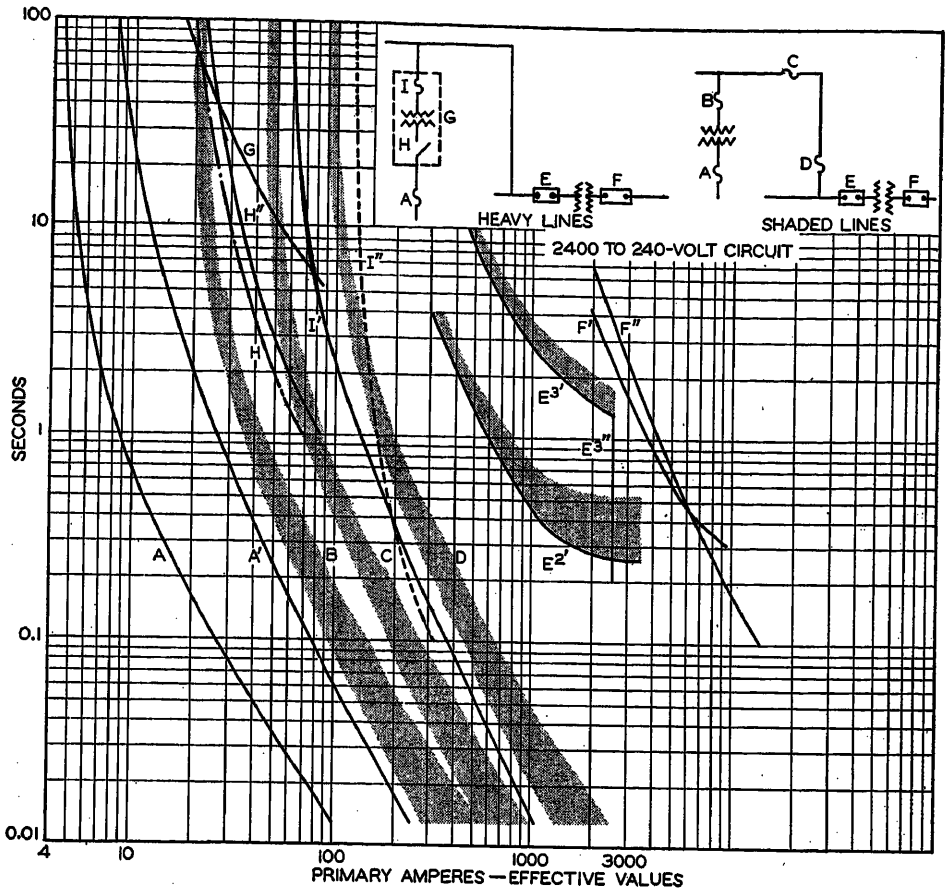



**Fig. 9. Time-current curves for unit-type distribution transformer superimposed on curves of the conventionally co-ordinated system of figure 1, showing comparative use of range available for distribution protection**

probable frequency of faults, occurring, now and later, on the short comparatively new wiring or in the range or water heater fed directly through the 60-ampere fuse. A large majority of the faults should occur on the other house wiring, and should be isolated by lower rated branch fuses, provided these fuses are not short-circuited malicious or otherwise. On the higher-voltage systems, the 60-ampere cartridge fuse or equivalent breaker is not such a limiting factor, except in cases where other secondary protection is introduced into the problem.

## Protection on Secondary Circuits

The protection on secondary circuits from overcurrent faults involves a number of different factors including not only the continuity of service, but the quality and the protection of equipment. Overcurrent protective devices, such as fuses, are installed at the points where the individual service entrances are connected to the main secondary circuit, so as to:

1. Isolate old and faulty installations.
2. Protect against outages from services through buried cable.
3. Isolate services where pennies are inserted behind plug fuses.

The insertion of an overcurrent protective device at the individual service entrance may or may not necessitate using more than a justifiable share of the range available for protection on the whole system. This depends upon several factors. A low rated household plug or cartridge fuse and/or a high transformation ratio makes available a greater range for protection at the service entrances. It will be readily apparent that a protective device such as a fuse, having a time-current characteristic similar in shape to the household fuse and the fuse link on the primary of the transformer permits the closest co-ordination and thus requires the least range for its insertion. If the introduction of a protective device in the service entrance lead necessitates increasing the fusing on the primary of the transformer, an analysis may show the advantages secured for a few consumers have increased the average consumer minutes outage for the whole system.

For example, if the insertion of a secondary fuse cutout in the service leads to confine outages to individual consumers necessitates substituting a $20N$ ampere primary fuse link for the $15N$ ampere rating, figure 8*B*, it cannot be co-ordinated with the $30N$ ampere sectionalizing fuse link, figure 8*C*. Substituting any higher rating for the $30N$ ampere link, in turn, requires the replacing of the $50N$ ampere rating, figure 8*D*, with a larger fuse link which then cannot be co-ordinated with the relay, figure 8*E*. If the relay setting cannot be changed, either the $30N$ or the $50N$ ampere sectionalizing fuse links must be omitted. Then each fault on that portion of the primary line will cause an outage to a larger number of consumers, totaling a great many times those securing

improved service. The average consumer minutes outage for the whole system will, therefore, be increased.

The improved lightning protection afforded by the interconnection of the lightning arrester ground with the secondary neutral has greatly increased the relative importance of overcurrent protection for distribution transformers. Augmenting this relative importance is the desire in some places for higher loading of distribution transformers. New applications of overcurrent protective devices are involved in attempts to meet these changing conditions and requirements. Three major trends in thinking have developed as a result:

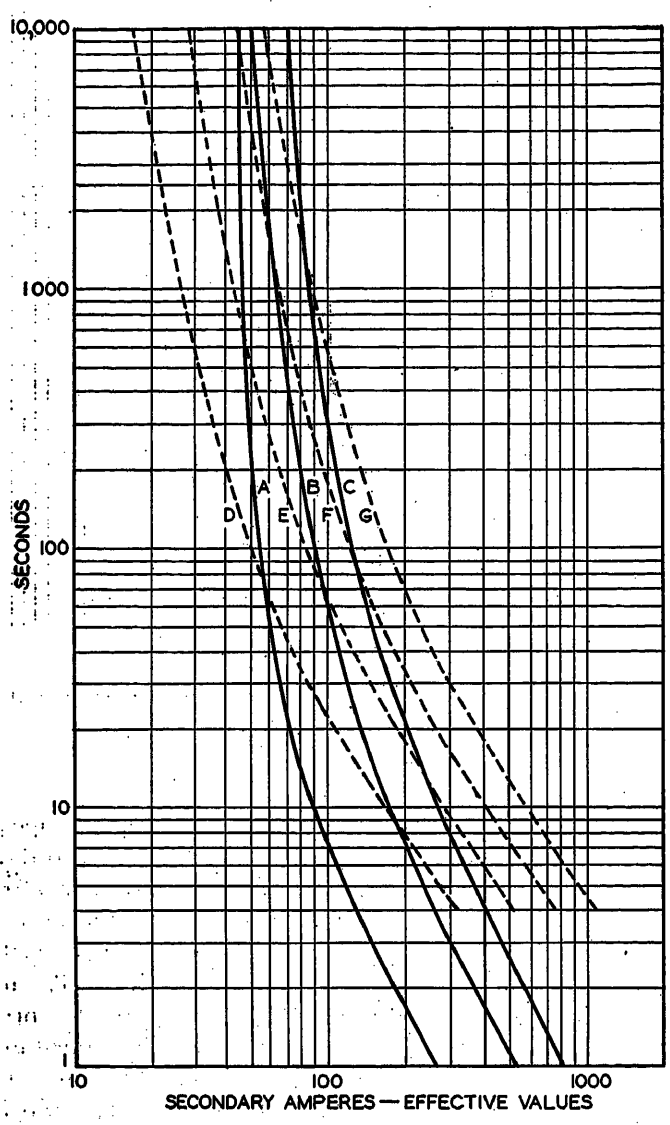



**Fig. 10. Co-ordination of time-current curves for 30-, 45-, and 60-ampere household fuses with those for the time load of 3-, 5-, 7.5-, and 10-kva distribution transformers**

*A*—30-ampere plug or cartridge household fuse
*B*—45-ampere plug or cartridge household fuse
*C*—60-ampere plug or cartridge household fuse
*D*—3-kva transformer time load
*E*—5-kva transformer time load
*F*—7.5-kva transformer time load
*G*—10-kva transformer time load

### 1. Use of Secondary Protection for Higher Loading

Much attention has been and is being given to the use of a secondary protective device supplemented by an overload indicator, to serve as a stop gap against excessive decrease in the life of the transformer so as to permit increased loading at distribution transformers. Such protection must be over the complete range of excessive currents. These vary from long-time, overload currents which are repeated often to the less frequent short-time high short-circuit currents.

In figure 9, the transformer time-load curve *G* is drawn with the corresponding internal secondary breaker *H* and the internal fuse *I* superimposed on the (shaded) curves of figure 8. In studying the effect of time-load curve *G* on the whole protection problem, the important consideration is the flatter slope of the curve, which may make the protective devices curves *H* and *I* co-ordinated with it, occupy too great a portion of the available range for protection on the entire distribution system. If protection is afforded the transformer by a secondary protective device having a time-current characteristic curve identical to or at least closely approximating the transformer time-load curve *G*, the internal primary fuse *I'* or *I''* must be rated much higher than the normal fusing practice *B* so the breaker *H''* will open first and without damage to the fuse *I'* or *I''*. The attendant decrease in the available range may prevent any sectionalizing of the primary lines as indicated in figure 9. The economics of this situation depend wholly upon the degree of protection which can be afforded transformers and the actual number of transformer burnouts saved thereby. Against this must be balanced the increase—or the inability to effect future decreases—in the consumer minutes outage resulting from the utilization of a major portion of the available range for protection on the whole distribution system for protecting the transformer.

For example, consider the degree of protection which can be afforded transformers using as a basis the recommended transformer time-load characteristic curves, figure 10*D*, *E*, *F*, and *G* (for the 3, 5, $7\frac{1}{2}$, and 10-kva ratings, respectively). As shown in figure 10, these curves cross the curves for the household fuses *A*, *B*, and *C* (30-, 45-, and 60-ampere ratings, respectively) due to the dissimilarity in the slopes. Thus any attempt to secure complete protection involves having the secondary protective device interrupt service for all the consumers fed by the transformer for any fault on individual consumer's premises of such magnitude and duration that when plotted on figure 10 the point lies to the left of the fuse curves *A*, *B*, or *C* and to the right of the transformer curves *D*, *E*, *F*, or G.

Complete protection involves a further increase in consumer minutes outage. Any lesser degree of protection means some decrease in the life of the transformer. Therefore, using the recommended transformer time-load curves figure 10 as a basis, it is necessary to strike

a balance between the permissible increase in outages and the degree of protection deemed necessary for the transformer, just as has been done for years in choosing the primary fusing practice.

There is another factor entering the problem; namely, the equipment available and its ability to afford protection to the transformer. Breakers are mounted internally in transformers below the oil level to obtain a portion of the heating characteristic of the transformer. However, curve $C''$, figure 11*a* approaches but does not quite equal the flatter transformer time-load curve $B$, figure 11*a*, at the low current long-time end. The breakers are usually set to trip so the curve $C''$ is well to the right of the transformer time-load curve $B$ at the low current long-time end. Even the overload indicator trips on curve $C'$, to the right of the time-load curve $B$.

The primary and secondary fuse links have more inverse time-current characteristics $D$, $E$, $F$, figure 11*b*, than the transformer curve $B$, figures 11*b* and *c*, and the breaker curve $C''$, figures 11*a* and *c*. Thus in general the primary or secondary fuse link affords a slightly lesser degree of protection to the transformer than the breaker at the low current long-time end as shown by the shaded portion $X$ of figure 11*c*. An exception to this is shown by the shaded portion $Y$, figure 11*c*, indicating a range where the fuse link affords better protection. Comparing the curves $D$ and $F$, figure 11*b* with the curve $E$ shows that the primary and secondary fuse links, respectively, will afford an equal degree of protection to the transformer assuming both halves of the secondary are equally loaded. The secondary fuse link or protective device can be used to afford a greater degree of protection without decreasing service continuity only where it can be co-ordinated with the household fuse and the primary fuse link without increasing the fusing practice on the primary.

### 2. Better Primary Fuse Protection With Increased Transformer Capacity

Some distribution engineers are giving consideration to the economics of affording complete, or very nearly complete, protection to the transformer by installing larger transformers and fusing on the primary at a minimum value which will not cause unnecessary outages from overcurrent surges. They are thinking in terms of having the improved regulation and the saving due to decreased transformer burnouts and the omission of extra protective devices pay the interest on the increased investment for the greater installed transformer capacity.

### 3. Use of Protective Devices and Secondary Banking for Higher Loading

Increasing attention is being given to the protection of the transformer with normal low primary fusing practice and with the banking of transformers to take advantage of the diversity of loads on individual transformers to reduce extremes of loading which also improves the instantaneous regulation.

The protective devices are connected in the secondary lines at sectionalizing points between adjacent transformers, which are tied solidly to these lines. Outages

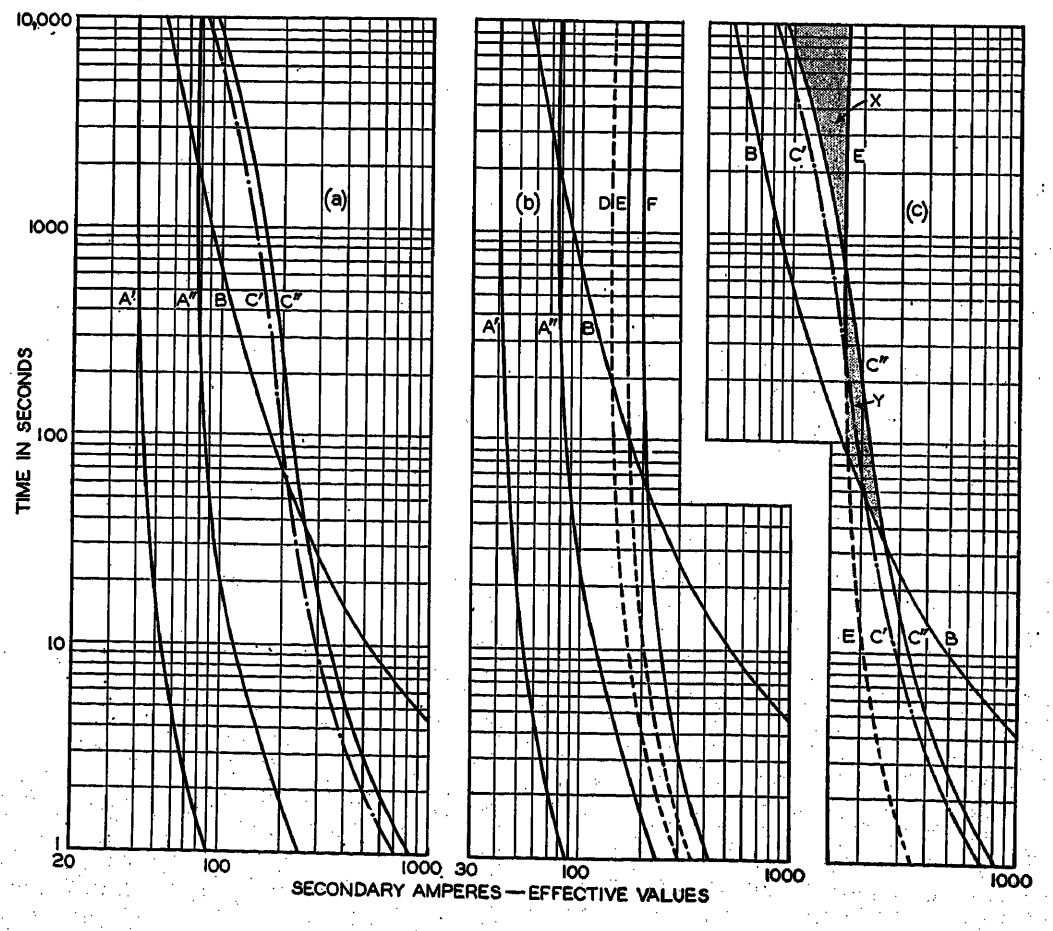



**Fig. 11. Curves showing relative degree of protection afforded distribution transformer by secondary breaker, secondary fuse, or primary fuse on a 2,400 to 240-volt circuit**

*A*—Household plug or cartridge fuse
*A'*—30-ampere rating
*A''*—60-ampere rating
*B*—Recommended transformer characteristic curve
*C*—Secondary breaker and overload indicator
*C'*—Overload indicator lights
*C''*—Breaker opens
*D*—Primary fuse rated at 15 amperes, with no secondary protective device
*E*—Secondary fuse rated at 85 amperes
*X*—Shaded portion showing degree of improved protection afforded by secondary breaker
*Y*—Shaded portion showing degree of improved protection afforded by secondary fuse

from transformer or secondary faults are isolated to the consumers fed by the one transformer. It is not fundamentally important to burn off secondary faults in order to obtain successful operation. The resulting permissible low rating of the secondary and primary protective devices affords generally normal overload protection to the transformer and no decrease in the range available for protection on the primary lines. The co-ordination of the household and secondary fuses can be close since only a maximum of approximately 50 per cent of the current through the household fuse passes through the secondary fuse link.

In some cases the protective devices are placed in the transformer secondary leads and the secondaries of adjacent transformers are tied solidly together to isolate faulty transformers without interrupting service. Faults on the secondary lines or service leads then affect all the consumers on the particular secondary circuit by causing low voltage or the complete loss of service, due to the opening of the secondary protective devices on several or all of the transformers banked on the circuit, known as cascading. The successful operation of banking through protective devices in the transformer leads requires that the majority of the secondary faults clear themselves.

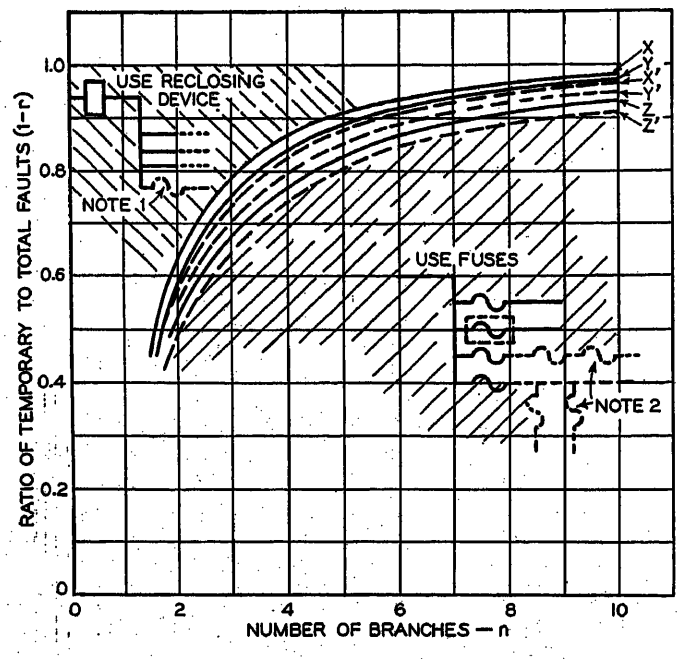



**Fig. 12. Curves showing dividing line above which reclosing equipment, and below which branch line fuses, will reduce consumer minutes of outage for the whole system**

Note 1—Isolating branches on which permanent faults predominate may raise the percentage of temporary faults for the remainder of the system, above the curves

Note 2—Fusing sub-branches or several sectionalizing points will raise the temporary percentage values of the curves

| | X | Y | Z | X' | Y' | Z' |
|---|---|---|---|---|---|---|
| Minutes to go to location ($a$) | 30 | 30 | 30 | 60 | 60 | 60 |
| Minutes per branch to locate fault ($b$) | 10 | 5 | 0 | 10 | 5 | 0 |
| Minutes duration of temporary fault ($c$) | 1 | | | | | |

Burning a fault clear, demands that secondary and primary protective devices allow the full use of the transformer thermal capacity which involves all of the problems just discussed as attendant upon the use of secondary protection for the higher loading of individual transformer. A similar compromise must be made between overload protection and service continuity. The higher rating of the protective devices reduces the available range for the protection on the primary lines.

The foregoing consideration of the trends in thinking on solutions for the overcurrent protection of distribution transformers has shown that it evolves into a decision on the relative value of protection to the transformer versus present and future improvements in service continuity for the system as a whole. The success of an operating practice intended to reduce the number of consumers affected by each fault and decrease the length of each outage, centers about the ratings of the fuses required on the primary of the distribution transformers. Schemes for reducing outages due to secondary faults, decreasing transformer burn-outs with increased loading, and improving regulation, should be used with caution if they require increasing the primary fusing practice. Where higher rated fuse links are necessitated in the primary leads of the transformer, the available range is decreased for existing or future protection on the primary lines against the major causes of consumer minutes outage.

## Fusing Transformer Primaries

Among the various trends in thinking, consideration is being given as to whether transformer primaries should be fused with nonrenewable fuses mounted inside the transformer case or with external renewable fuse cut-outs, or whether they should be fused at all.

Nonrenewable fuses, so called "weak links," are mounted inside transformer cases to permit connecting internal gaps on the line side of the fuses and/or to make the transformer and its protective apparatus one unit. Because they are nonrenewable and in blowing will carbonize the insulating oil, the rating of the fuses must be greatly increased, see curves $I'$ or $I''$, figure 9. Internal fuses should blow only in the case of a transformer failure. Fuse blowing otherwise would damage and necessitate the removal of good transformers. The higher primary fusing may decrease the range available for protection on the primary lines as in figure 9, $I'$, $I''$. The lack of a secondary protective device requires the moving of the curves $I'$ and $I''$ still further to the right to prevent unnecessary blowing. This may even prevent proper coordination with the fuses or breaker relay on the primary lines, especially where the fuse ratings or relay settings for line protection are very low on long rural circuits so as to interrupt the flashover of external gaps installed on the transformers for lightning protection. In either case, a probable increase—or prevention of future decrease—in the average consumer minutes outage should be anticipated.

Modern distribution fuse cutouts and renewable fuse links with their background of over 14 years of intensive

*A*—Household plug and cartridge fuses
*A'*—30-ampere rating
*A''*—60-ampere rating
*B*—Fuses rated at 15 amperes in primary leads of distribution transformer
*B'''*—Total clearing time-current characteristic curve
*C*—Branch line sectionalizing fuse rated at 30 amperes
*D*—Branch line sectionalizing fuse rated at 50 amperes
*E*—Feeder oil circuit breaker and relay
$E^{3}$'—Very inverse relay (number 1 time lever setting)
$E^{3}$'—Very inverse relay (number 10 time lever setting)
$E^{3}$''—Instantaneous attachment on relay functions
*F*—Protective device on incoming transmission lines
*F'*—Very inverse relay (number 1 time lever setting)
*F''*—Fuse
*G*—Sectionalizing fuse rated at 45*N* amperes, to clear fault currents below minimum pick-up of recloser
*G'*—Total clearing time
*G''*—Melting time
*H*—Recloser
*H'*—First opening (should be to the right of curve *B''*; fuse cut-out or link having mechanical means for separating burned ends should help to secure successful operation when curve *B''* crosses *H'* as shown)
*H''*—Equivalent heating of fuse (factors cooling of fuses while recloser is open)
*H'''*—Equivalent heating of fuse, with 25 per cent factor added to permit direct comparison with melting-time curves for fuse *G*
*X*—Maximum current up to which recloser will lock out before fuse link melts

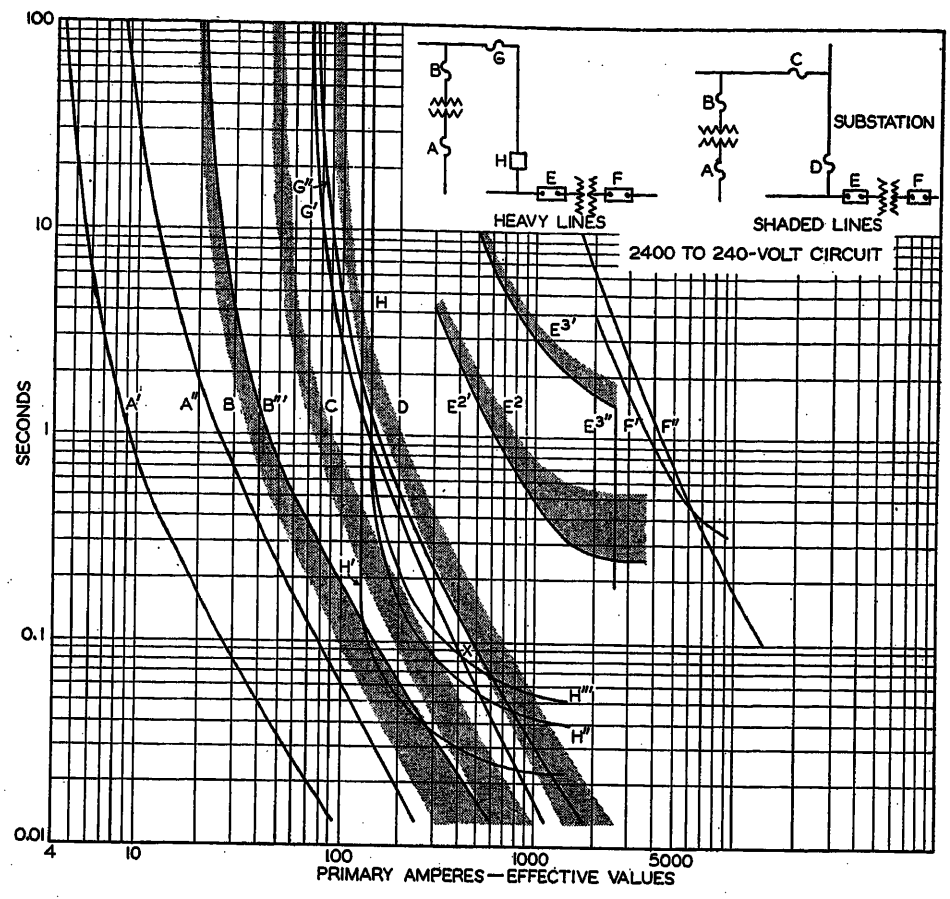



**Fig. 13. Time-current curves for a recloser protecting part of a long line and a fuse cut-out protecting the rest, superimposed on the curves for a conventionally co-ordinated system as shown in figure 3, showing the comparative use of the rangeavail able for distribution protection**

research and engineering development permit the utility engineer to choose the lowest primary fusing practice with assurance of a successful operating record. This cannot be said of some of the earlier designs upon which much of the present-day service data are based. The primary fuse link rating is usually chosen so as to provide a balance between unnecessary fuse blowing and protection afforded the apparatus, and/or proper co-ordination with protective devices on the secondary of the transformer. A fuse cutout provides an easy means for manually disconnecting transformers and for easily and quickly locating those which are damaged.

The prevalence of lightning in some localities makes it desirable to limit the size of transformer primary fuse links to a certain minimum in order to take advantage of the ability of the larger links to more successfully withstand lightning impulses. This is especially true where the lightning arrester is connected on the load side of the fuse cutout. A minimum rating of 10 amperes will generally eliminate the majority of unnecessary fuse blowing and will not ordinarily interfere greatly with proper primary co-ordination. Saving one fuse replacement trip will usually more than pay for the installation of secondary fuses on the smaller sizes of transformers to provide the same overload protection as would be given by the smaller primary fuse link that would normally be used.

The omission of fuses on the primary of distribution transformers is virtually the same as adding miles of exposure to the primary lines. A service interruption to all the consumers on such a line may result from a line fault or a transformer flashover or burnout; or a secondary line fault if no secondary protective device is employed. The cause of each outage must be sought among every one of these possibilities, thus greatly increasing the length of each interruption. The use of secondary fuses or breakers while affording a degree of protection to the transformer, merely removes the secondary line as a possible cause of trouble. Therefore, where primary fuses are omitted, a marked increase in consumer minutes outage can be anticipated over that occurring where protection is afforded the individual transformer by modern fuse cut-outs and renewable fuse links.

## Primary Line Faults

With the fuse link on the primary of distribution transformers kept as small as possible, the effect of faults on

the primary lines can be reduced by the introduction of the properly located protective devices. The choice between fuses and automatic reclosing devices is largely dependent upon the ratio of temporary faults to permanent faults on the whole and each portion of the distribution system. Of course, there is also the question of economics and the importance of loads. Superior service continuity can be secured by the use of fuses at a number of sectionalizing points on the primary lines especially where a fairly high percentage of the faults are permanent. Automatic reclosing equipment will reduce the average consumer minutes outage where temporary faults predominate. This equipment may be a breaker or a recloser which reset themselves after interrupting temporary fault currents, or a reclosing fuse cutout which requires periodic inspection and renewal of blown fuse links.

The dividing line between the percentage of temporary versus permanent faults above which reclosing equipment located either in the station or at branch lines, and below which sectionalizing fuses, will reduce the consumer minutes outage is shown in figure 12. These values were derived using the following formula, with the indicated assumptions as to the times required to restore service.

$r$ = ratio of permanent to total number of faults
$1 - r$ = ratio of temporary to total number of faults
$P$ = faults per branch
$a + nb$ = duration of permanent fault
$a$ = minutes to go to location
$b$ = minutes to locate fault per branch
$n$ = number of branches
$e$ = duration of temporary fault
$N$ = number of consumers per branch

Total consumer minutes outage per year with reclosing device = $nPr\,(a + nb)\,(nN) + Pn\,(1 - r)\,(e)\,(nN)$
Total consumer minutes outage per year with sectionalizing fuses at each branch or sub-branch = $nP\,(a + b)\,N$

$$\text{ratio} = \frac{\text{minutes outage with reclosing device}}{\text{minutes outage with sectionalizing fuse}}$$

$$= \frac{n^2 PN[r\,(a + nb) + e\,(1 - r)]}{nPN\,(a + b)}$$

$$= \frac{n\,(ra + rnb + e - er)}{a + b}$$

The lower cost, nonreclosing fuse cutout can perform a real service for reducing consumer minutes outage both as to the effect and the length of outages. The curves figure 12 show the advantage of connecting fuse cutouts and fuse links in several branch lines. The use of additional fuses at sub-branches or in series at various sectionalizing points, will raise the curves figure 12. For example, with 3 fused branches each having one fused sub-branch, curve $x$ figure 12 will be raised from 79.1 per cent to 84.7 per cent and with 2 sub-branches each to 89.2 per cent. Connecting one and 2 fuses in series with each branch line fuse will raise curve $x$ figure 12 from 79.1 per cent to 84.7 per cent, respectively. In addition to those greater benefits due to the confinement of the effect of faults to fewer consumers, the time to locate the faults will be reduced and the curves figure 12 raised, for example, the 89.2 per cent and 84.7 per cent values given above will be raised to 91.2 per cent and 86.9 per cent, respectively, with a proportionate reduction in time to the length of line affected.

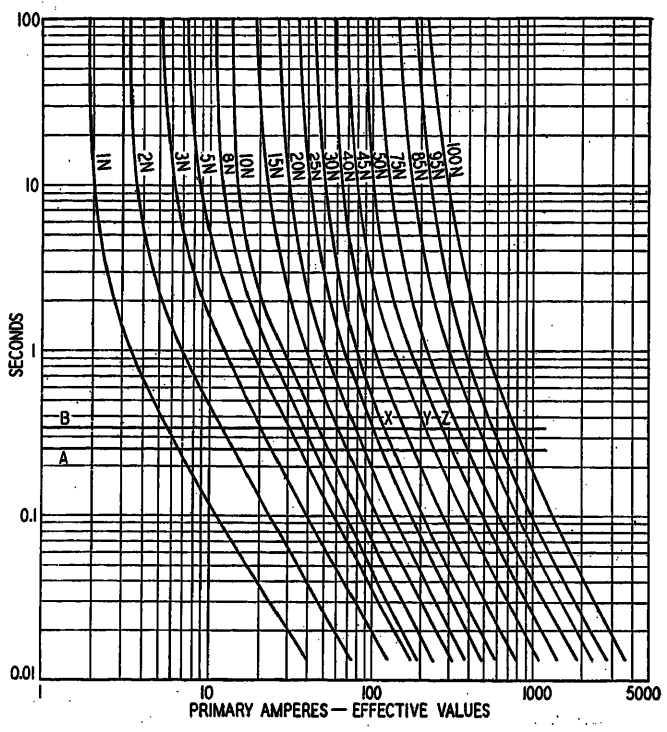



**Fig. 14. Melting time-current characteristic curves for fuse links with lines A and B showing time required to open the feeder breaker, the limiting factor for co-ordinating so that the first opening of the breaker is ahead of the fuse link**

*A*—Time required for instantaneous ground relay and breaker to open
*B*—Factor of 25 per cent added to curve A to permit direct comparison with melting-time curves of fuse links
*X*—Maximum current up to which breaker will clear ahead of 30*N* ampere fuse link
*Y*—Maximum current with 45*N* ampere fuse link
*Z*—Maximum current with 50*N* ampere fuse link

The effectiveness of reclosing fuse cutouts depends on the periodic inspection and replacement of blown fuse links before an outage occurs. If they are not refused until both or all 3 fuse links have blown, their use should tend to raise the curves figure 12 up to which they will improve service continuity. If periodically inspected and a majority of the blown fuse links are replaced before an outage occurs, their performance approximates the reclosing devices indicated on the curves, figure 12.

Both conventional reclosing oil circuit breakers and the lower cost mechanical breakers known as circuit reclosers, are available for use at sectionalizing points. The relay actuating the conventional oil circuit breaker functions with the induction relay characteristics which are similar to those for the modern distribution fuse links, figure 8*B*, *C*, and *D*. Thus the introduction of this equipment permits reasonably close co-ordination with the fuse links at transformer installations and at any desirable sectionalizing point.

The instantaneous plunger type relay characteristics of the circuit recloser figure 13*H'* definitely limit the rating of fuse links which will blow before the first opening

of the recloser, to low values (the fuse link curves which are to the left of the respective recloser curves figure 7*a*). The ratings of practically all internal fuses, or "weak links," are too high to blow soon enough to prevent lockout of the recloser. If the fuses further out on the system are too large to blow before the recloser locks out, a fuse cutout can be connected across the recloser to permit manually by-passing it through a fuse after the recloser locks out. The fuse link in the cutout should be large enough to allow the internal fuses or sectionalizing fuses beyond the recloser to blow first, so as to indicate the location of the fault.

On long lines the recloser can be used for that portion where the fault currents will be greater than the minimum current required to pick up the contact so that it actuates the lockout mechanism. A fuse cutout, installed within this portion, can be fused, figure 13*G*, so as to permit the recloser to lock out on fault currents above the minimum pick-up. The location of the cutout should be such that the maximum fault current available at the point of installation does not exceed the value at which the melting time current curve 13*G'* crosses the recloser curve, figure 13*H'''*, at *X*. Then the fuse cutouts will afford protection for all fault currents below the minimum pick-up of the recloser; in most cases reaching out to the end of a long line. The fuse link can also be co-ordinated with the relay on the main feeder breaker, figure 13*F'* and *F''*.

Automatic reclosing oil circuit breakers are more generally installed at the substation to improve continuity of service to the more important consumers on the main feeder and larger branches. By fusing branches of the circuit where permanent faults predominate, the percentage of temporary faults on the important parts may be raised so the reclosing breakers will reduce the consumer minutes outage for the whole system, note 1, figure 12, as well as for the important loads.

Several large utility companies report an improvement in service continuity resulting from the combination of branch line fusing and automatic reclosing breakers at the substation. Their scheme is applicable on grounded neutral systems where the instantaneous relay, connected to operate on ground and/or neutral currents, can be set to pick up at very low currents for the initial opening of the breaker. A grounding bank can be used to provide the neutral on delta systems. After the first opening, the instantaneous relay locks out and the induction relays, connected in the phase wires are automatically switched on for the subsequent operations to the lockout of the breaker. However, in the case of a permanent fault on a branch line the fuse links and induction relays are coordinated so a time delay is provided and the fuse links clear ahead of the second relay operation. The ground relay is automatically reconnected in the case of a temporary fault or after the fuse disconnects the branch. A practical set-up for the fusing of branch lines in this way automatically differentiates between temporary and permanent faults to neutral and ground.

The successful functioning of such an arrangement depends on the time required for the breaker to open and interrupt the fault current, after the instantaneous ground relay has closed the trip circuit. For example, a relay and breaker requiring a total time of 15 cycles (0.25 second) to clear the circuit, will successfully clear temporary faults up to 125 amperes without damaging a 33*N* ampere branch line sectionalizing fuse link of the design for which the curves figure 14 are plotted. This is indicated by the point *X*, figure 14, where the melting time curve for the fuse link crosses the curve *B* plotted so as to allow a 25 per cent factor for operating and manufacturing variables above line *A* drawn at 0.25 second. Under similar conditions, a 45*N* ampere fuse link will not be damaged up to 205 amperes, and a 50*N* ampere fuse link up to 270 amperes (points *Y* and *Z*, figure 14, respectively). If the short-circuit current available at the point of installation for the sectionalizing fuse cutout exceeds these values, the fuse link may be partially melted. If it is not replaced subsequent melting on load currents may cause arcing which will not clear and will burn the fuse tube of cutouts that provide no mechanical means for separating the burned ends of the fuse link.

One utility company reports that it has been their experience based on observations of actual operating conditions, as well as field tests, that those circuits which are fused with the 30*N* ampere fuse links usually have shorts which range between 100 and 150 amperes, while the circuits on which the 50*N* (60) ampere fuse links are used, run between 200 and 300 amperes. In the cases where it is definitely known a heavy phase short circuit has taken place, it is the operating practice to replace both fuses. From this it would appear practical to secure the combined advantages of automatic reclosing for temporary line-to-ground or line-to-neutral faults and fused sectionalizing for isolating permanent line-to-ground and line-to-neutral and line-to-line faults to small areas. Such a practice should afford a marked decrease in the consumer minutes of outage.

## Summary

In the foregoing an attempt has been made to make an impartial study of the various trends in thinking with respect to the overcurrent protection on distribution systems. This has been done from the standpoint of the effect of each on the service continuity, the protection to apparatus, and the system economy. Major emphasis has been given to service continuity as present-day consumer requirements have increased the utility companies' interest in reducing outages to a minimum. A number of pertinent factors have been brought out which are generally applicable to any such studies that might be made on specific systems. A tabulation of these without doubt, will be of value.

1. Actual operating records on the system in question are essential.
2. The data in such records will be enhanced in value if selected to show the differences,

*a*. On urban, suburban, and rural sections,

*b*. On main feeders, branch feeders, distribution transformers, and secondary lines,

*c*. Between causes of faults such as lightning, short circuits, overloads, etc.,

*d.* Between types of faults, temporary vs. permanent,

*e.* Between modern and old equipment.

3. Such records will show that one permanent fault on the primary lines will cause upward to 100 times as many consumer minutes outage as one fault in a transformer or on the secondary lines, and that generally a greater percentage of faults occur on the primary lines.

4. Secondary protection to continuity and/or apparatus which can be secured without increasing the normal fusing practice on the primary of the distribution transformer (generally 2 or 3 times the full load current of the transformer) will improve service continuity.

5. Conversely, any increasing of the normal primary fusing practice to secure other advantages very likely will increase—or prevent future decreases in—the average consumer minutes outage for the whole system.

6. The use of the external fuse cutout with renewable fuse links enables the use of the lowest possible fusing practice, spoken of as normal. Modern equipment insures an improved service record.

7. The normal fusing practice while termed short-circuit protection, affords a fairly high degree of protection to the transformer as indicated by operating records; such as those where higher internal fusing has been employed with no secondary protection.

8. The use of nonrenewable internal fuses necessitates increasing the primary fusing practice, and without a secondary fuse or breaker affords no protection to the transformer.

9. The omission of fuses on the primary virtually adds miles of exposure to cause and on which to locate, trouble on the primary lines.

10. The ratio of temporary to permanent faults on the whole and various parts of the system governs the benefits in improved continuity of service rendered by fuse cutouts at sectionalizing points and by automatic reclosing equipment.

*a.* Fusing sectionalizing points on the primary lines to confine the effect of outages to small areas will reduce the average consumer minutes outage even with high ratios of temporary to permanent faults (see figure 12).

*b.* Automatic reclosing equipment or reclosers at the substation or in branch lines will reduce the consumer minutes outage where the percentage of temporary faults is high. This percentage in some instances can be improved by fusing branches where permanent faults predominate.

*c.* A practical arrangement for automatically combining sectionalizing fuse and automatic reclosing protection so as to differentiate between temporary and permanent faults will produce the best results.

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## Expansion Theorems for Ladder Networks

(*Continued from page 158*)


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## A New Service Restorer

(*Continued from page 182*)

Film *B* shows the record of 2 interruptions with 12,000 volts across the terminals, the current being 960 and 880 amperes, respectively. Film *C* shows 4 interruptions (3 reclosures and a final lockout) of 400 amperes at 12,000 volts. Reclosure is immediate after each opening, the average reclosing time from the instant the fault occurs until the device recloses being 31 cycles.

The service restorer was developed primarily for low-capacity low-revenue lines and it is hoped that it will be a real contribution toward the improvement of electric power service by providing an economical and efficient automatic reclosing device for such applications. It should be ideally suited for sectionalizing lines and protecting feeders in rural and suburban districts as well as for use at small isolated industrial and mining properties where a continuous power supply is important.

# Expansion Theorems for Ladder Networks

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**The well-known expansion theorem of Heaviside applies to circuits whose current-electromotive force relations may be expressed through differential equations, whereas in some networks such as filters and artificial lines, in which the network consists of a repeated pattern or mesh, the relations give what are known as difference equations. These are equations involving the mesh number of the network. The solutions of such networks are given in this paper in the form of expansion theorems similar to Heaviside's expansion theorem and its extensions.**

THE current-electromotive force relations of filter circuits, artificial lines, and other ladder networks lead to difference equations whose solutions have been given by Pupin,[1] Rüdenberg,[3] Wagner,[4–6] Rogowski,[7,8] Carson,[9–11] Zobel,[11–13] Cauer,[21–23] Alford,[25] and others.[2,14–20,24,26,27] Mathematical work on difference equations has been going on since the days of Newton, Laplace, and Gauss (18th century). Treatises on difference equations have been written by Nörlund,[31] Batchelder,[32] and F. Bleich[29] and E. Melan.[29]

Although Laplace transformations have been used in the treatment of linear difference equations with constant coefficients, particularly by Bochner,[30] the authors do not know of any results which parallel Heaviside's expansion theorem and its extensions for differential equations.[28] The object of this paper is to develop such expressions by the use of Laplace transformations.

## 1. Solution of a Difference Equation

Consider the following linear difference equation of the $n$th order with constant coefficients $a_k$:

$$a_0 f(x) + a_1 f(x+1) + \ldots + a_n f(x+n) = \phi(x) \tag{1}$$

In equation 1, $a_0 \neq 0$, $a_n \neq 0$. This does not detract from the generality of equation 1 because if $a_0 = 0$, then substituting $x$ for $x + 1$ reduces equation 1 to a difference equation of lower order. On the other hand if $a_n = 0$ then again the order of equation 1 is reduced.

Again $\phi(x)$ is a given function which satisfies the following conditions:

1. $\phi(x)$ is of bounded variation in any finite interval
2. $\phi(x) \equiv 0$ for $x < 0$
3. $\phi(x) = [\phi(x+0) + \phi(x-0)]/2$ for every $x$
4. $\int_0^\infty | \phi(x) \epsilon^{-ux} | \, dx$ converges if the real part of $u$ is sufficiently large.

It may be here observed that all functions encountered in engineering practice do satisfy these conditions.

In addition to equation 1 certain boundary conditions must be given. As boundary conditions we shall assume that $f(x)$ is known over the interval $0 \leqq x < n$ and that in this interval $f(x)$ is of bounded variation and $f(x) = [f(x+0) + f(x-0)]/2$. The solution of equation 1 consists in determining $f(x)$ which

1. Satisfies equation 1 for all $x \geqq 0$;
2. Is equal to the given boundary function for $0 \leqq x < n$

Multiply both sides of equation 1 by $\epsilon^{-ux} dx$ and integrate between zero and infinity thus:

$$\sum_{k=0}^{n} \int_0^\infty a_k f(x+k) \epsilon^{-ux} dx = \int_0^\infty \phi(x) \epsilon^{-ux} dx \tag{2}$$

where $u$ is any complex number whose real part is positive and sufficiently large.

Consider a typical term of the sum in equation 2. Let $x + k = y$ then $dx = dy$, $x = y - k$. When $x = 0$, $y = k$ and when $x = \infty$, $y = \infty$. Substitute these relations in the left side of equation 2 and obtain:

$$\sum_{k=0}^{n} a_k \epsilon^{ku} \int_k^\infty f(y) \epsilon^{-uy} dy = \int_0^\infty \phi(x) \epsilon^{-ux} dx \tag{3a}$$

or

$$\sum_{k=0}^{n} a_k \epsilon^{ku} \left[ \int_0^\infty f(x) \epsilon^{-ux} dx - \int_0^k f(x) \epsilon^{-ux} dx \right] = \int_0^\infty \phi(x) \epsilon^{-ux} dx \tag{3b}$$

Since $f(x)$ is known for $0 \leqq x < n$ and since $k \leqq n$, therefore the second integral in each term of the sum to the left of equation 3$b$ is known. Again since $\phi(x)$ is known the integral to the right of equation 3$b$ is also known. Let:

$$\Psi(u) = \sum_{k=0}^{n} a_k \epsilon^{uk} \int_0^k f(x) \epsilon^{-ux} dx \tag{4a}$$

$$\Phi(u) = \int_0^\infty \phi(x) \epsilon^{-ux} dx \tag{4b}$$

Substitute equation 4 in 3$b$ and obtain:

$$\sum_{k=0}^{n} a_k \epsilon^{uk} \int_0^\infty f(x) \epsilon^{-ux} dx = \Phi(u) + \Psi(u) \tag{5a}$$

or

$$\int_0^\infty f(x) \epsilon^{-ux} dx = F(u) \tag{5b}$$

where

$$F(u) = [\Phi(u) + \Psi(u)] \Big/ \sum_{k=0}^{n} a_k \epsilon^{ku} \tag{5c}$$

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1. For all numbered references see list at end of paper.

Equation 5*b* is a well-known integral equation whose solution is:

$$f(x) = \frac{1}{2\pi j}\int_{b-j\infty}^{b+j\infty} F(u)\epsilon^{ux}du \tag{6}$$

where $b$ is a sufficiently large positive number.

Equation 6 is the solution of equation 1. It is given in the form of a complex integral which may be readily evaluated (see section 3).

## 2. Solution of a System of Difference Equations

Consider the following system of linear difference equations of the $n$th order with constant coefficients $a_{lrk}$:

$$\sum_{r=1}^{m}\sum_{k=0}^{m_r} a_{1rk}f_r(x+k) = \phi_1(x) \tag{7a}$$

$$\sum_{r=1}^{m}\sum_{k=0}^{m_r} a_{2rk}f_r(x+k) = \phi_2(x) \tag{7b}$$

.....

$$\sum_{r=1}^{m}\sum_{k=0}^{m_r} a_{mrk}f_r(x+k) = \phi_m(x) \tag{7m}$$

where $\phi_l(x)$ are given functions which satisfy the conditions imposed on $\phi(x)$ in section 1; $f_r(x)$ are unknown functions. As to the boundary conditions we shall assume that $f(x)$ is known over the interval $0 \leqq x < m_r$ and that in this interval $f_r(x)$ is of bounded variation and $f_r(x) = [f_r(x+0) + f_r(x-0)]/2$. The problem is to determine $f_r(x)$ which satisfy the system of difference equations 7 for all $x \geqq 0$ and the boundary conditions for $0 \leqq x < m_r$.

Multiply both sides of each of equations 7 by $\epsilon^{-ux}dx$ and integrate between zero and infinity. Then a typical equation becomes:

$$\sum_{r=1}^{m}\sum_{k=0}^{m_r}\int_0^\infty a_{lrk}f_r(x+k)\epsilon^{-ux}dx = \int_0^\infty \phi_l(x)\epsilon^{-ux}dx \tag{8}$$

where $l = 1, 2, 3, \ldots m$.

Substitute $x + k = y$ in equation 8 and obtain as in equation 3*b*:

$$\sum_{r=1}^{m}\sum_{k=0}^{m_r} a_{lrk}\epsilon^{uk}\left[\int_0^\infty f_r(x)\epsilon^{-ux}dx - \int_0^k f_r(x)\epsilon^{-ux}dx\right] = \int_0^\infty \phi_l(x)\epsilon^{-ux}dx \tag{9}$$

Since $f_r(x)$ is known for $0 \leqq x < m_r$ and since in each inner sum $k \leqq m_r$, therefore the second integral to the left in equation 9 is known. Again, since each $\phi_l(x)$ is known, the integral to the right of equation 9 is also known. Let:

$$\Psi_l(u) = \sum_{r=1}^{m}\sum_{k=0}^{m_r} a_{lrk}\epsilon^{uk}\int_0^k f_r(x)\epsilon^{-ux}dx \tag{10a}$$

$$\Phi_l(u) = \int_0^\infty \phi_l(x)\epsilon^{-ux}dx \tag{10b}$$

Substitute equations 10 in 9 and obtain:

$$\sum_{r=1}^{m}\sum_{k=0}^{m_r} a_{lrk}\epsilon^{uk}\int_0^\infty f_r(x)\epsilon^{-ux}dx = \Phi_l(u) + \Psi_l(u) = M_l(u) \tag{11}$$

Let:

$$\sum_{k=0}^{m_r} a_{lrk}\epsilon^{uk} = A_{lr}(\epsilon^u) \tag{12a}$$

$$\int_0^\infty f_r(x)\epsilon^{-ux}dx = F_r(u) \tag{12b}$$

Substituting equations 12 in equation 11 and remembering that we have $m$ such equations because $l$ assumes all integer valves between 1 and $m$, we have:

$$\sum_{r=1}^{m} A_{1r}(\epsilon^u)F_r(u) = M_1(u) \tag{13a}$$

$$\sum_{r=1}^{m} A_{2r}(\epsilon^u)F_r(u) = M_2(u) \tag{13b}$$

.....

$$\sum_{r=1}^{m} A_{mr}(\epsilon^u)F_r(u) = M_m(u) \tag{13m}$$

Expanding equations 13 we obtain

$$A_{11}(\epsilon^u)F_1(u) + A_{12}(\epsilon^u)F_2(u) + \ldots + A_{1m}(\epsilon^u)F_m(u) = M_1(u) \tag{14a}$$

$$A_{21}(\epsilon^u)F_1(u) + A_{22}(\epsilon^u)F_2(u) + \ldots + A_{2m}(\epsilon^u)F_m(u) = M_2(u) \tag{14b}$$

.....

$$A_{m1}(\epsilon^u)F_1(u) + A_{m2}(\epsilon^u)F_2(u) + \ldots + A_{mm}(\epsilon^u)F_m(u) = M_m(u) \tag{14m}$$

Solving equations 14 simultaneously for $F_r(u)$ we have:

$$F_r(u) = [\Delta_{1r}(\epsilon^u)M_1(u) + \Delta_{2r}(\epsilon^u)M_2(u) + \ldots + \Delta_{mr}(\epsilon^u)M_m(u)]/\Delta(\epsilon^u) \tag{15}$$

where

$$\Delta(\epsilon^u) = \begin{vmatrix} A_{11}(\epsilon^u) & A_{12}(\epsilon^u) & \ldots & A_{1m}(\epsilon^u) \\ A_{21}(\epsilon^u) & A_{22}(\epsilon^u) & \ldots & A_{2m}(\epsilon^u) \\ \ldots & \ldots & \ldots & \ldots \\ A_{m1}(\epsilon^u) & A_{m2}(\epsilon^u) & \ldots & A_{mm}(\epsilon^u) \end{vmatrix} \tag{16}$$

and $\Delta_{pq}(\epsilon^u)$ is the minor of $\Delta$ obtained by omitting the $p$th row and $q$th column and multiplying the determinant so obtained by $(-1)^{(p+q)}$.

Substituting equation 15 in 12*b* we have

$$\int_0^\infty f_r(x)\epsilon^{-ux}dx = F_r(u) = \sum_{l=1}^{m}\Delta_{lr}(\epsilon^u)M_l(u)/\Delta(\epsilon^u) \tag{17}$$

Equation 17 is of the same form as 5*b*. Hence its solution is:

$$f_r(x) = \frac{1}{2\pi j}\int_{b-j\infty}^{b+j\infty} F_r(u)\epsilon^{ux}du \tag{18}$$

## 3. Evaluation of the Integrals of Equations 6 and 18

The complex integrals given in equations 6 and 18 are not usable in their present form. They must be evaluated before the functions $f(x)$ and $f_r(x)$ can be computed in any engineering problem. These integrals have, accord-

ingly been evaluated by us. The actual evaluation is of mathematical interest only. We therefore give here the results.

Referring to the difference equation 1 let:

$$P(\epsilon^u) = \sum_{k=0}^{n} a_k \epsilon^{ku} \tag{19a}$$

$$Q_s(\epsilon^u) = \sum_{k=0}^{n-s} a_{(k+s)} \epsilon^{ku} \tag{19b}$$

If the polynomial $P(\epsilon^u)$ has distinct (unequal) roots $\alpha_k$ then by decomposition into partial fractions we obtain:

$$1/P(\epsilon^u) = \sum_{k=1}^{n} B_k/(\epsilon^u - \alpha_k) \tag{20a}$$

$$Q_s(\epsilon^u)/P(\epsilon^u) = \sum_{k=1}^{n} B_{ks}/(\epsilon^u - \alpha_k) \tag{20b}$$

where

$$B_k = 1/P'(\alpha_k); \qquad B_{ks} = Q_s(\alpha_k)/P'(\alpha_k) \tag{21}$$

On the other hand if the polynomial $P(\epsilon^u)$ has $\lambda$ roots $\alpha_k$, each repeated $n_k$ times, then decomposition into partial fractions gives:

$$1/P(\epsilon^u) = \sum_{k=1}^{\lambda} \sum_{r=1}^{n_k} B_{kr}/(\epsilon^u - \alpha_k)^r \tag{22a}$$

$$Q_s(\epsilon^u)/P(\epsilon^u) = \sum_{k=1}^{\lambda} \sum_{r=1}^{n_k} B_{krs}/(\epsilon^u - \alpha_k)^r \tag{22b}$$

where

$$B_{kr} = [\psi_k^{(n_k-r)}(\alpha_k)]/(n_k - r)! \tag{23a}$$

$$B_{krs} = [\psi_{ks}^{(n_k-r)}(\alpha_k)]/(n_k - r)! \tag{23b}$$

$$\psi_k(\epsilon^u) = [\epsilon^u - \alpha_k]^{n_k}/P(\epsilon^u) \tag{23c}$$

$$\psi_{ks}(\epsilon^u) = Q_s(\epsilon^u)[\epsilon^u - \alpha_k]^{n_k}/P(\epsilon^u) \tag{23d}$$

With these notations the integral equation 6 becomes, for distinct and repeated roots respectively of $P(\epsilon^u)$:

$$f(x) = \sum_{k=1}^{n} B_k \sum_{c=0}^{[x]-1} \alpha_k^c \phi(x - c - 1) + \sum_{s=1}^{n} \sum_{k=1}^{n} B_{ks} \alpha_k^{[x]} f(x - [x] + s - 1) \tag{24a}$$

$$f(x) = \sum_{k=1}^{n} \sum_{r=1}^{n_k} B_{kr} \sum_{c=0}^{[x]-r} \binom{r+c-1}{c} a_k^c \phi(x - r - c) + \sum_{s=1}^{n} \sum_{k=1}^{\lambda} \sum_{r=1}^{n_k} B_{krs} \binom{[x]}{[x]-r+1} \alpha_k^{([x]-r+1)} f(x - [x] + s - 1) \tag{24b}$$

In equations 24:

1. $\binom{a}{b} = 0$ if $b < 0$
2. $x$ is a positive non-integer
3. If $x$ is a positive integer then $f(x) = [f(x + 0) + f(x - 0)]/2$ and $f(0) = f(0 + 0)/2$

Equation 24*a* may be termed Heaviside's expansion theorem for difference equations; while equation 24*b* is

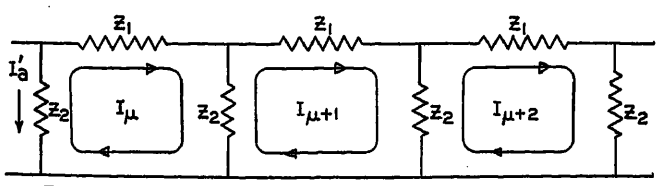



**Fig. 1. Schematic diagram of a ladder network**

the extension of that theorem to the case of repeated roots[28] of $P(\epsilon^u)$.

Next referring to the system of difference equations 7 let:

$$\Delta(\epsilon^u) = \sum_{k=0}^{n} b_k \epsilon^{ku}, \quad \Delta_{lr}(\epsilon^u) = \sum_{\nu=0}^{q_{lr}} b_{lr\nu} \epsilon^{\nu u} \tag{25a}$$

$$Q_{lrps}(\epsilon^u) = \sum_{k=s}^{m_p} a_{lpk} \epsilon^{ku} \Delta_{lr}(\epsilon^u) = \sum_{\nu=0}^{m_p+q_{lr}} \beta_{lrps\nu} \epsilon^{\nu u} \tag{25b}$$

Then the expansion of $1/\Delta(\epsilon^u)$ in partial fractions is given by equations 20*a* and 22*a* respectively where $\Delta(\epsilon^u)$ replaces $P(\epsilon^u)$. With these notations the integral in equation 18 becomes:

$$f_r(x) = \sum_{l=1}^{m} [f_{lra}(x) + f_{lrb}(x)] \tag{26}$$

where

(*a*) *For distinct roots of* $\Delta(\epsilon^u)$

$$f_{lra}(x) = \sum_{\nu=0}^{q_{lr}} b_{lr\nu} \sum_{k=1}^{n} B_k \sum_{c=0}^{\nu+[x]-1} \alpha_k^c \phi_l(\nu + x - c - 1) \tag{27a}$$

$$f_{lrb}(x) = \sum_{p=1}^{m} \sum_{s=1}^{m_p} \sum_{\nu=0}^{m_p+q_{lr}} \beta_{lrps\nu} \sum_{k=1}^{n} B_k \alpha_k^{[x]} f_p(x - [x] + s - 1) \tag{27b}$$

(*b*) *For repeated roots of* $\Delta(\epsilon^u)$

$$f_{lra}(x) = \sum_{\nu=0}^{q_{lr}} b_{lr\nu} \sum_{k=1}^{\lambda} \sum_{r=1}^{n_k} B_{kr} \sum_{c=0}^{\nu+[x]-r} \binom{r+c-1}{c} \times \alpha_k^c \phi_l(\nu + x - r - c) \tag{28a}$$

$$f_{lrb}(x) = \sum_{p=1}^{m} \sum_{s=1}^{m_p} \sum_{\nu=0}^{m_p+q_{lr}} \beta_{lrps\nu} \sum_{k=1}^{\lambda} \sum_{r=1}^{n_k} B_{kr} \times \binom{[x]}{[x]-r+1} \alpha_k^{([x]-r+1)} f_p(x - [x] + s - 1) \tag{28b}$$

In equations 27 and 28:

1. $\binom{a}{b} = 0$ if $b < 0$
2. $x$ is a positive non-integer
3. $\Delta(\epsilon^u)$ has no zero roots

If $\Delta(\epsilon^u)$ has a zero root of the $n_0$th order then $x$ in equations 27 and 28 should be replaced by $x - n_0$ and $\Delta(\epsilon^u)$ in 25, 20*a*, and 22*a* should be replaced by $\Delta_1(\epsilon^u)$ where

$$\Delta(\epsilon^u) = \epsilon^{n_0 u} \Delta_1(\epsilon^u) \tag{29}$$

Equations 26, 27, and 28 correspond to the extensions of Heaviside's expansion theorem[28] to systems of differential equations.

## 4. Application to Ladder Networks

Consider the ladder network figure 1. Writing Kirchhoff's equations for any one element we have:

$$Z_1 I_{\mu+1} + Z_3(I_{\mu+1} - I_{\mu+2}) + Z_3(I_{\mu+1} - I_\mu) = 0 \tag{30a}$$

or

$$Z_3 I_\mu - (Z_1 + 2Z_3) I_{\mu+1} + Z_3 I_{\mu+2} = 0 \tag{30b}$$

Equation 30*b* is a difference equation of the second order similar to equation 1 where:

$$f(x) = I_\mu \text{ for } \mu - 1 < x < \mu \tag{31a}$$

$$a_0 = Z_3, \qquad a_1 = -(Z_1 + 2Z_3), \qquad a_2 = Z_3 = a_0 \tag{31b}$$

$$\phi(x) \equiv 0, \qquad n = 2 \tag{31c}$$

From equations 19 we have

$$P(\epsilon^u) = \sum_{k=0}^{2} a_k \epsilon^{ku} = a_0 + a_1 \epsilon^u + a_2 \epsilon^{2u} \tag{32a}$$

$$Q_1(\epsilon^u) = \sum_{k=0}^{2-1} a_{(k+1)} \epsilon^{ku} = a_1 + a_2 \epsilon^u \tag{32b}$$

$$Q_2(\epsilon^u) = \sum_{k=0}^{0} a_{(k+2)} \epsilon^{ku} = a_2 \tag{32c}$$

The roots of $P(\epsilon^u)$ are:

$$\alpha_1 = \left[-a_1 + \sqrt{a_1^2 - 4a_0a_2}\right]/2a_2; \qquad \alpha_2 = \left[-a_1 - \sqrt{a_1^2 - 4a_0a_2}\right]/2a_2 \tag{33}$$

We shall assume that $\alpha_1 \neq \alpha_2$. It must be also noted that:

$$\alpha_1\alpha_2 = 1 \tag{34}$$

Equations 21 reduce, in this case, to:

$$B_1 = 1/(a_1 + 2a_2\alpha_1) \qquad B_2 = 1/(a_1 + 2a_2\alpha_2) \tag{35a}$$

$$B_{11} = (a_1 + a_2\alpha_1)/(a_1 + 2a_2\alpha_1) \qquad B_{12} = a_2/(a_1 + 2a_2\alpha_1) \tag{35b}$$

$$B_{21} = (a_1 + a_2\alpha_2)/(a_1 + 2a_2\alpha_2) \qquad B_{22} = a_2/(a_1 + 2a_2\alpha_2) \tag{35c}$$

Substituting equations 31 to 35 in 24*a* and remembering that $\phi(x) \equiv 0$ and that (see equation 31*a*) $f(x - [x] + s - 1) = I_s$ and $[x] = \mu - 1$ we have:

$$I_\mu = \sum_{s=1}^{2}\sum_{k=1}^{2} B_{ks}\alpha_k^{(\mu-1)} I_s \tag{36a}$$

$$= (B_{11}I_1 + B_{12}I_2)\alpha_1^{(\mu-1)} + (B_{21}I_1 + B_{22}I_2)\alpha_2^{(\mu-1)} \tag{36b}$$

$$= K_1\epsilon^{\mu \ln \alpha_1} + K_2\epsilon^{\mu \ln \alpha_2} \tag{36c}$$

Equation 36*c* is the form generally encountered in engineering literature.

One more fact might be brought out before leaving this illustrative problem. Quite often the boundary conditions relate not to 2 successive elements but to the 2 ends of a line (say $I_1$ and $I_N$ are given). Such cases could be readily worked out by the use of equation 36*b* or equation 36*c*. Thus in equation 36*b*, substitute $\mu = N$ and solve for $I_2$ thus reducing the problem to the given boundary conditions. On the other hand, if we assume both

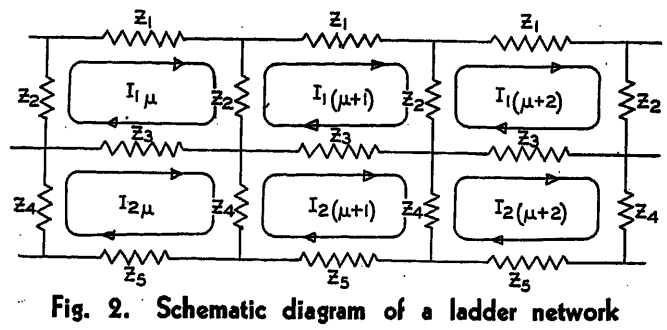



**Fig. 2. Schematic diagram of a ladder network**

$K_1$ and $K_2$ in equation 36*c* to be unknown, then by substituting $\mu = 1$ and $\mu = N$ in equation 36*c* we obtain 2 equations with 2 unknowns. The latter is the classical mode of procedure.

In order to illustrate the use of the solution for systems of difference equations consider the ladder network figure 2. Writing Kirchhoff's equations we have:

$$Z_1 I_{1\,(\mu+1)} + Z_2(I_{1\,(\mu+1)} - I_{1\,(\mu+2)}) + Z_3(I_{1\,(\mu+1)} - I_{2\,(\mu+1)}) + Z_2(I_{1\,(\mu+1)} - I_{1\mu}) = 0 \tag{37a}$$

$$Z_3 I_{2\,(\mu+1)} + Z_4(I_{2\,(\mu+1)} - I_{2\,(\mu+2)}) + Z_3(I_{2\,(\mu+1)} - I_{1\,(\mu+1)}) + Z_4(I_{2\,(\mu+1)} - I_{2\mu}) = 0 \tag{37b}$$

whence:

$$Z_3 I_{1\mu} - (Z_1 + 2Z_2 + Z_3) I_{1(\mu+1)} + Z_2 I_{1\,(\mu+2)} + Z_3 I_{2\,(\mu+1)} = 0 \tag{38a}$$

$$Z_4 I_{2\mu} - (Z_3 + 2Z_4 + Z_5) I_{2\,(\mu+1)} + Z_4 I_{2\,(\mu+2)} + Z_3 I_{1\,(\mu+1)} = 0 \tag{38b}$$

Equations 38 are a system of difference equations of the second order similar to equation 7 where

$$I_{1\mu} = f_1(x) \text{ for } \mu - 1 < x < \mu \tag{39a}$$

$$I_{2\mu} = f_2(x) \text{ for } \mu - 1 < x < \mu \tag{39b}$$

$$\phi_k(x) \equiv 0, \qquad m_1 = m_2 = m = 2 \tag{39c}$$

In order to obtain a clearer insight into the correspondence of equations 38 and the system of difference equations 7 we shall write 7 more explicitly for the case at hand. Thus:

$$a_{110}f_1(x) + a_{111}f_1(x+1) + a_{112}f_1(x+2) + a_{120}f_2(x) + a_{121}f_2(x+1) + a_{122}f_2(x+2) = 0 \tag{40a}$$

$$a_{210}f_1(x) + a_{211}f_1(x+1) + a_{212}f_1(x+2) + a_{220}f_2(x) + a_{221}f_2(x+1) + a_{222}f_2(x+2) = 0 \tag{40b}$$

Comparing equations 40 with equations 38 we have:

$$a_{110} = Z_3 \tag{41a}$$ $$a_{210} = a_{212} = 0 \tag{41a'}$$

$$a_{111} = -(Z_1 + 2Z_2 + Z_3) \tag{41b}$$ $$a_{211} = Z_3 \tag{41b'}$$

$$a_{112} = Z_2 \tag{41c}$$ $$a_{220} = Z_4 \tag{41c'}$$

$$a_{120} = a_{122} = 0 \tag{41d}$$ $$a_{221} = -(Z_3 + 2Z_4 + Z_5) \tag{41d'}$$

$$a_{121} = Z_3 \tag{41e}$$ $$a_{222} = Z_4 \tag{41e'}$$

Referring to equations 12 we have

$$A_{11}(\epsilon^u) = \sum_{k=0}^{2} a_{11k}\epsilon^{ku} = a_{110} + a_{111}\epsilon^u + a_{112}\epsilon^{2u} \tag{42a}$$

$$A_{12}(\epsilon^u) = \sum_{k=0}^{2} a_{12k}\epsilon^{ku} = 0 + a_{121}\epsilon^u + 0 \tag{42b}$$

$$A_{21}(\epsilon^u) = \sum_{k=0}^{2} a_{21k}\epsilon^{ku} = 0 + a_{211}\epsilon^u + 0 \tag{42c}$$

$$A_{22}(\epsilon^u) = \sum_{k=0}^{2} a_{22k}\epsilon^{ku} = a_{220} + a_{221}\epsilon^u + a_{222}\epsilon^{2u} \tag{42d}$$

The determinant $\Delta(\epsilon^u)$ equation 16 is:

$$\Delta(\epsilon^u) = (a_{110} + a_{111}\epsilon^u + a_{112}\epsilon^{2u})(a_{220} + a_{221}\epsilon^u + a_{222}\epsilon^{2u}) - a_{211}a_{121}\epsilon^{2u} \tag{43a}$$

$$= b_0 + b_1\epsilon^u + b_2\epsilon^{2u} + b_3\epsilon^{3u} + b_4\epsilon^{4u} \tag{43b}$$

where:

$$b_0 = a_{110}a_{220} \qquad b_1 = a_{110}a_{221} + a_{220}a_{111} \tag{44a}$$

$$b_2 = a_{110}a_{222} + a_{111}a_{221} + a_{112}a_{220} - a_{211}a_{121} \tag{44b}$$

$$b_3 = a_{111}a_{222} + a_{112}a_{221} \qquad b_4 = a_{112}a_{222} \tag{44c}$$

Moreover:

$$\Delta_{11} = A_{22}, \quad \Delta_{12} = -A_{21}, \quad \Delta_{21} = -A_{12}, \quad \Delta_{22} = A_{11} \tag{45}$$

Finally the values of $\beta_{lr\,ps\nu}$ in equation 25*b* are given in table I.

**Table I—Values of $\beta_{lrps\nu}$**

| lrps | $\nu=0$ | $\nu=1$ | $\nu=2$ | $\nu=3$ | $\nu=4$ |
|---|---|---|---|---|---|
| 1111 | 0 | $a_{220}a_{111}$ | $a_{220}a_{112} + a_{221}a_{111}$ | $a_{221}a_{112} + a_{222}a_{111}$ | $a_{222}a_{112}$ |
| 1112 | 0 | 0 | $a_{220}a_{112}$ | $a_{221}a_{112}$ | $a_{222}a_{112}$ |
| 1121 | 0 | $a_{220}a_{121}$ | $a_{221}a_{121}$ | $a_{222}a_{121}$ | 0 |
| 1122 | 0 | 0 | 0 | 0 | 0 |
| 1211 | 0 | 0 | $-a_{111}a_{211}$ | $-a_{112}a_{211}$ | 0 |
| 1212 | 0 | 0 | 0 | $-a_{112}a_{211}$ | 0 |
| 1221 | 0 | 0 | $-a_{121}a_{211}$ | 0 | 0 |
| 1222 | 0 | 0 | 0 | 0 | 0 |
| 2111 | 0 | 0 | $-a_{121}a_{211}$ | 0 | 0 |
| 2112 | 0 | 0 | 0 | 0 | 0 |
| 2121 | 0 | 0 | $-a_{121}a_{221}$ | $-a_{121}a_{222}$ | 0 |
| 2122 | 0 | 0 | 0 | $-a_{121}a_{222}$ | 0 |
| 2211 | 0 | $a_{110}a_{211}$ | $a_{111}a_{211}$ | $a_{112}a_{211}$ | 0 |
| 2212 | 0 | 0 | 0 | 0 | 0 |
| 2221 | 0 | $a_{110}a_{221}$ | $a_{110}a_{222} + a_{111}a_{221}$ | $a_{111}a_{222} + a_{112}a_{221}$ | $a_{112}a_{222}$ |
| 2222 | 0 | 0 | $a_{110}a_{222}$ | $a_{111}a_{222}$ | $a_{112}a_{222}$ |

Assuming that the roots of $\Delta(\epsilon^u)$ are distinct and equal to $\alpha_1$, $\alpha_2$, $\alpha_3$, $\alpha_4$, and using equation 20*a* where $P(\epsilon^u)$ is replaced by $\Delta(\epsilon^u)$ we have:

$$1/\Delta(\epsilon^u) = \sum_{k=1}^{4} B_k/(\epsilon^u - \alpha_k) \tag{46}$$

where

$$B_k = 1/[b_1 + 2b_2\alpha_k + 3b_3\alpha_k^2 + 4b_4\alpha_k^3], \qquad k = 1, 2, 3, 4 \tag{47}$$

Substituting equations 39 to 47 in 27 and the result in 26 and remembering that $\phi_l(x) \equiv 0$ and that (see equation 39) $f_p(x - [x] + s - 1) = I_{ps}$ and that $[x] = \mu - 1$ we have:

$$I_{\mu r} = \sum_{l=1}^{2}\sum_{p=1}^{2}\sum_{s=1}^{2}\sum_{\nu=0}^{4}\beta_{lr\,ps\nu}\sum_{k=1}^{4}B_k\alpha_k^{\mu-1}I_{ps}, \text{ where } r = 1, 2 \tag{48}$$

This problem could, of course, have been solved by reducing, through elimination, the system of difference equations to 2 difference equations, each of the fourth order, and each involving only one unknown function. The choice between the 2 modes of solution is determined by the nature of the problem. The above example simply illustrates the applicability of our results and could have been solved through elimination.

## 5. Extension to Other Boundary Conditions

Quite often, in physical problems, the boundary conditions are not what we assumed in sections 1 and 2 of this paper. In fact, the boundary conditions are often specified at the beginning and end of a network. It needs but a slight addition to this theory, as indicated in the first illustrative problem, to obtain the solution for any boundary conditions whatever.

Consider equations 24 which are solutions of the difference equation 1. Let, for distinct and repeated roots, respectively:

$$A(x) = \sum_{k=1}^{n} B_k \sum_{c=0}^{[x]-1} \alpha_k^c \phi(x - c - 1) \tag{49a}$$

$$A(x) = \sum_{k=1}^{\lambda}\sum_{r=1}^{n_k} B_{kr} \sum_{c=0}^{[x]-r} \binom{r+c-1}{c} \alpha_k^c \phi(x - r - c) \tag{49b}$$

Let, for distinct and repeated roots, respectively:

$$H_s(x) = \sum_{k=1}^{n} B_{ks}\alpha_k^{[x]} \tag{50a}$$

$$H_s(x) = \sum_{k=1}^{\lambda}\sum_{r=1}^{n_k} B_{krs}\binom{[x]}{[x]-r+1}\alpha_k^{([x]-r+1)} \tag{50b}$$

Then equations 24 may be written in both cases as follows:

$$f(x) = A(x) + \sum_{s=1}^{n} H_s(x) f(x - [x] + s - 1) \tag{51}$$

In equation 51, $A(x)$ and $H_s(x)$ are both known functions. $f(x - [x] + s - 1)$ is the value of $f(x)$ in the interval $s - 1 < x < s$. In our solution $f(x - [x] + s - 1)$ is given for $s = 1, 2, \ldots n$.

It is our object to show that equation 51 gives an explicit solution even when the boundary values are not given for the first $n$ intervals but for any $n$ arbitrary intervals $k_1 - 1 < x < k_1$; $k_2 - 1 < x < k_2$, $\ldots$ $k_n - 1 < x < k_n$.

In the first place it must be observed that $f(x - [x] + s - 1)$ is periodic in one, or:

$$f((x+k) - [x+k] + s - 1) = f(x - [x] + s - 1) \tag{52}$$

Moreover:

$$x = x - [x] + k_r - 1 \text{ if } k_r - 1 < x < k_r \tag{53}$$

Substituting for $x$ its value from equation 53 in 51 for the various intervals where $f(x)$ is known and using the relation 52 we have:

$$f(x - [x] + k_1 - 1) - A(x - [x] + k_1 - 1) = \sum_{s=1}^{n} H_s(x - [x] + k_1 - 1) f(x - [x] + s - 1) \tag{54a}$$

$$f(x-[x]+k_2-1)-A(x-[x]+k_2-1)=\sum_{s=1}^{n}H_s(x-[x]+k_2-1)f(x-[x]+s-1) \quad (54b)$$

.....

$$f(x-[x]+k_n-1)-A(x-[x]+k_n-1)=\sum_{s=1}^{n}H_s(x-[x]+k_n-1)f(x-[x]+s-1) \quad (54n)$$

Equations 54 are $n$ equations with $n$ unknowns, the unknowns being the values of $f(x)$ for the first $n$ intervals, *viz.:*

$$f(x-[x]), \quad f(x-[x]+1), \quad \ldots \quad f(x-[x]+n-1)$$

The solutions of equations 54 give these values of $f(x)$ which can now be substituted back in 24. The process is the same for each $f_r(x)$ in a system of $n$ difference equations.

It should be here remarked that if, as is generally the case, some of the boundary values are given for the first $\beta$-intervals then the number of unknowns and therefore of equations in 54 is reduced to $(n-\beta)$.

## Summary

We have developed 2 expansion theorems applicable to difference equations and to systems of difference equations such as occur in ladder networks. These theorems are given by equations 24, 26, 27, and 28, respectively. The equations presuppose that the boundary conditions are given for the values of $f(x)$ in the first $n$ successive intervals. As, in physical problems, the boundary conditions vary widely, the theorems are adapted to any boundary conditions in section 5 of the paper. Finally 2 problems are worked out in section 4 to illustrate the use of these theorems.

## Notations

$a_k$ = constant coefficient in the difference equation 1
$a_{lrk}$ = constant coefficient in the system of difference equations 7
$A_{lr}$ = see equation 12*a*
$A(x)$ = a function defined by equations 49
$b_k$ = coefficient of the $k$th term of the polynomial $\Delta(\epsilon^u)$
$b_{lr\nu}$ = coefficient of the $\nu$th term in the polynomial $\Delta_{lr}(\epsilon^u)$ see equation 25*a*
$B_k$ = see equation 21
$B_{ks}$ = see equation 21
$B_{kr}$ = see equation 23*a*
$B_{krs}$ = see equation 23*b*
$\binom{a}{b}$ = $\begin{cases} a(a-1)(a-2)(\ldots)(a-b+1)/b! \text{ if } b \geqq 0,\ a \geqq 0 \\ 0 \text{ if } b<0,\ a \geqq 0 \end{cases}$
$c$ = any non-negative integer
$f(x)$ = The unknown function in the difference equation 1. See also equations 6 and 24
$f_r(x)$ = The unknown functions in the system of difference equation 7. See also equations 18, 26, 27 and 28
$f(x+0)$ = $\lim_{\delta \to 0} f(x+\delta)$, $\delta>0$
$f(x-0)$ = $\lim_{\delta \to 0} f(x-\delta)$, $\delta>0$
$f_{lra}(x)$ = see equations 27*a* and 28*a*
$f_{lrb}(x)$ = see equations 27*b* and 28*b*
$F(u)$ = see equations 5
$F_r(u)$ = see equations 12*b* and 15
$H_s(x)$ = a function defined by equations 50
$I_\mu$ = mesh current in the $\mu$th mesh of the ladder network figure 1
$I_{1\mu}$ = mesh current in the first row of the $\mu$th mesh of the ladder network figure 2
$I_{2\mu}$ = mesh current in the second row of the $\mu$th mesh of the ladder network figure 2
$k$ = any positive integer
$K_1, K_2$ = constants defined by equation 36*c*
$l$ = any non-negative integer
$m$ = number of difference equations in the system 7
$m_r$ = order of the difference equation involving $f_r(x)$ in the system of equations 7
$M_1(u)$ = see equation 11
$n$ = order of the difference equation 1
$n_k$ = multiplicity of the root $\alpha_k$ of $P(\epsilon^u)$ (see equation 22*b*) and of $\Delta(\epsilon^u)$
$p$ = any non-negative integer
$P(\epsilon^u)$ = see equation 19*a*
$q$ = any non-negative integer
$q_{lr}$ = the degree of the polynomial $\Delta_{lr}(\epsilon^u)$
$Q_s(\epsilon^u)$ = see equation 19*b*
$Q_{lrps}(\epsilon^u)$ = a polynomial defined by equation 25*b*
$r$ = any non-negative integer
$s$ = any non-negative integer
$t$ = a variable of integration
$u$ = any complex number whose real part is positive
$x$ = independent variable in a difference equation or a system of difference equations
$[x]$ = greatest integer which is equal to or less than $x$
$y$ = a variable of integration
$Z_k$ = an impedance in the ladder networks figures 1 and 2
$\alpha_k$ = roots of the polynomial $P(\epsilon^u)$ or of the polynomial $\Delta(\epsilon^u)$
$\beta_{lrps\nu}$ = coefficient of the $\nu$th term in the polynomial $Q_{lrps}(\epsilon^u)$
$\Delta(\epsilon^u)$ = see equation 16
$\Delta_{lr}(\epsilon^u)$ = the minor of $\Delta(\epsilon^u)$ obtained by omitting row $l$ and column $r$
$\Delta_1(\epsilon^u)$ = a polynomial having no zero roots (see equation 29)
$\epsilon$ = base of napierian logarithms
$\lambda$ = any positive integer
$\mu$ = any non-negative integer
$\nu$ = any non-negative integer
$\phi(x)$ = given function in the difference equation 11
$\phi_l(x)$ = given function in the system of difference equations 7
$\phi(x+0)$ = $\lim_{\delta \to 0} \phi(x+\delta)$, $\delta>0$
$\phi(x-0)$ = $\lim_{\delta \to 0} \phi(x-\delta)$, $\delta>0$
$\Phi(u)$ = see equation 4*b*
$\Phi_l(u)$ = see equation 10*b*
$\psi_k(\epsilon^u)$ = see equation 23*c*
$\psi_{ks}(\epsilon^u)$ = see equation 23*d*
$\Psi(u)$ = see equation 4*a*
$\Psi_l(u)$ = see equation 10*a*

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*(Concluded on page 152)*

# A New Electrostatic Precipitator

By G. W. PENNEY
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**The cleaning action upon gases of a corona discharge has been known since 1824; however, the technique of electrostatic precipitation has been improved slowly because of the inherent difficulties of the process and the somewhat limited field of its application. With accurately controlled industrial processes and delicate laboratory measurements came the necessary incentive for improving electrostatic precipitation equipment, and recently it has been applied in the field of medicine for the treatment of such maladies as hay fever. The theory of electrostatic precipitation is reviewed briefly in this paper, and a new precipitator is described.**

ELECTROSTATIC precipitation has long been recognized as the outstanding method of removing very fine particles from gases, especially at elevated temperatures.

The cleaning of gases by a corona discharge was observed by Hohlfield in 1824. His experiments were extended by Sir Oliver Lodge who made a working installation in a lead smelter in 1884. In 1906 Dr. Cottrell developed a practical form which has been very successful in handling difficult cleaning problems which could not be accomplished by other cleaning methods. The application of electrostatic precipitation has, however, been limited. The most serious factors limiting the use of electrostatic precipitation are as follows:

1. D-c voltages of from 30,000 to 100,000 and appreciable current are required.
2. The space required is large both for the precipitator proper as well as the high-voltage transformer and rectifier.
3. The corona discharge of the conventional precipitator generates so much ozone that the cleaned air, although free of dust, is too irritating to the nose and throat to be used for ventilation.
4. First cost and maintenance are both high as compared to other types of cleaning equipment.

In considering the field of gas purification, the larger particles (above 10 microns) are readily removed by various means, such as centrifugal devices, simple filters, washers, or by viscous coated devices which depend on impinging the particle onto the coated surface. Somewhat finer particles can be removed by the better grade of filters. However, in many cases the dust particles are only a fraction of a micron in diameter. Such particles approach the resolving power of the ordinary microscope. The diameter of these particles is comparable with the mean free path of air molecules. Such particles defy almost all air cleaning devices except precipitation, although in most cases this could not previously be used for the reasons given.

An analysis of the process of precipitation has pointed the way to the development of a new type of precipitator which reduces the size, voltage, power required, and ozone and compounds of nitrogen generated so that this new device can be applied in fields in which electrostatic precipitation was not previously practical.

## Generation of Ozone

In air, the generation of ozone by a given discharge current depends somewhat upon the geometry of the electrodes. By selecting a favorable design of electrode the generation of ozone per unit of current can be limited to a minimum value. The problem then becomes one of designing the precipitator to clean the air with the minimum discharge current. The analysis given in this paper has resulted in a precipitator which gives a generation of ozone which is small as compared with that found in outdoor air in bright sunlight and at the same time the space, voltage, and power required are small as compared to previous practice.

## Analysis of Electrostatic Precipitation

### The Corona Discharge

The conventional process of electrostatic precipitation uses a wire or system of points at high potential so that there is a corona discharge which carries the dust to the opposite electrode. The forces acting on the particles have been analyzed by R. Ladenburg.[1] The primary effect is an accumulation of charge on each dust particle. The particle is then acted upon by the electrostatic field which carries it toward the electrode of opposite polarity. There is another effect which Ladenburg refers to as the electrostatic wind. This electrostatic wind consists of a movement of air away from discharge points and carries dust toward the collecting electrode. However, the movement of air toward the electrode must also displace air

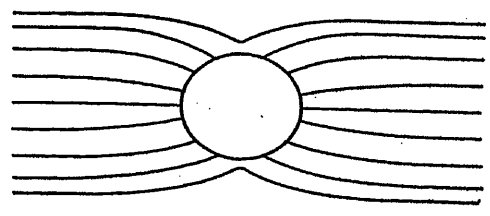


**Fig. 1. Sketch showing how an electrostatic field is distorted by a dust particle**

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1. For all numbered references, see list at end of paper.

away from the collecting electrode. The net result increases the precipitation of dust but it appears to be a very inefficient method. In this paper the electrostatic wind is ignored and an attempt made to develop the most efficient device for charging the particles and attracting them out of the air. The resulting device accomplishes results not considered possible in devices where the electrostatic wind is utilized.

### Effect of the Electrostatic Field

The particles are charged in the region of a corona discharge. Here a high local electrostatic field is produced by impressing a high voltage on points or a fine wire. This local voltage gradient is sufficiently high to produce ionization by collision and a self-maintaining discharge. If the point or wire is negative, the positive ions generated in the discharge are attracted to the negative electrode but the electrons are repelled and drift toward the large positive electrode. Probably most of the electrons quickly become attached to air molecules forming negative ions. This space charge forms a high opposing voltage which limits the current and produces a stable discharge.

The electrons or ions drifting through the gas tend to follow the electrostatic lines of flux. Dust particles usually have a dielectric constant greater than one and distort the field tending to concentrate the flux through the particle (figure 1). This drives the drifting charges toward the particle. Any charge on the particle exerts a force tending to repel ions from the particle. The maximum charge which the particle can attain is that at which this repulsive force cancels the effect of the main electrostatic field. Ladenburg's equation expressing the balance of forces acting on an electron just outside the dust particle at this limiting charge is

$$e\left(1+2\frac{k-1}{k+1}\right)E_0-\frac{ne^2}{r^2}=0 \qquad (1)$$

Solving for $n$,

$$n=E_0\left(1+2\frac{k-1}{k+1}\right)\frac{r^2}{e} \qquad (2)$$

This equation gives the maximum number of electrons which can be collected by a dust particle of radius $r$ and dielectric constant $k$ in a field strength $E_0$. Experiments

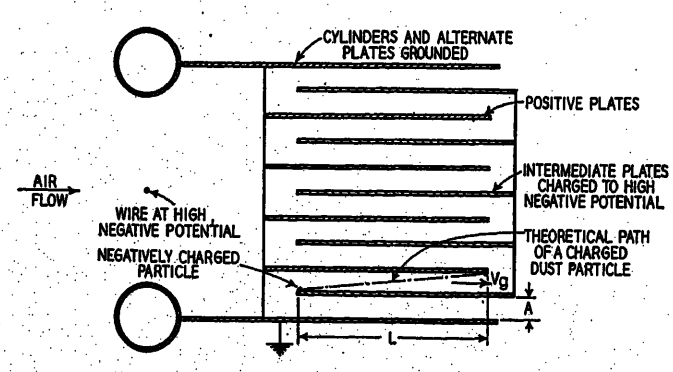



**Fig. 2. Cross section of the ionizing unit and parallel dust-collecting plates of an electrostatic precipitator, showing the path of a dust particle**

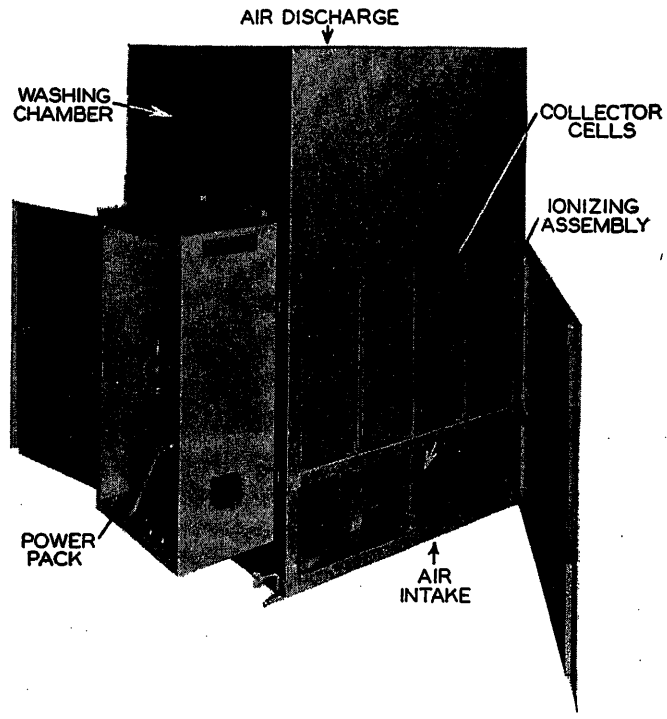



**Fig. 3. An electrostatic precipitator developed for use with a spray booth in a pottery plant**

indicate that this charge is approached in a small fraction of a second as compared to the 2 to 10 seconds ordinarily required for precipitation in conventional practice.

### Effect of Molecular Motion of Electrons or Ions

In addition to the driving force of the electrostatic field the heat or molecular motion of the electrons or ions tends to charge the dust particles. The effect of this heat motion becomes increasingly important as the particle size decreases. Ladenburg considers this effect to be the controlling factor for particles less than $^1/_4$ micron in diameter. When the dust particle is uncharged, the ion will not be repelled but as a charge accumulates on the particle, this charge tends to repel ions so that there will be relatively few ions having sufficient velocity to overcome the repulsive force. This gives a rapid rate of charging the particle as long as the ion velocity required is below the most probable velocity but when the charge on the particle reaches such a value that only a few ions have sufficient energy to reach the dust particle, the charging proceeds very slowly. The mathematical theory is rather long[5,6,7,8] to review here but a few values are given in table I which compares the values of $n$ obtained by this theory with that given by equation 2. The particle will, of course, tend to take the maximum number of charges.

### Separation of Particles From the Gas

In the conventional precipitator the charging of the particles and their separation from the gas was accomplished in one chamber with a discharge taking place throughout the length of travel of the gas. Both experiment and theory indicate that the charging of the particles

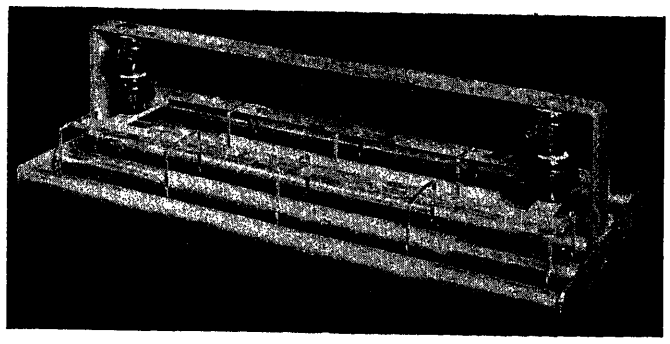


**Fig. 4. The ionizing unit of the precipitator**

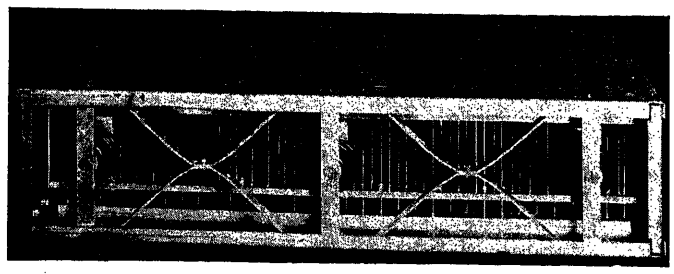


**Fig. 5. Parallel-plate dust-collecting assembly**

takes place very rapidly as compared to their separation from the gas. Furthermore, the charging process inherently requires a nonuniform field while for most efficient separation the field should be uniformly high. It has been found possible to make the process much more efficient by first ionizing the particles and then separating them from the gas in the electrostatic field between parallel charged plates.

Figure 2 is a schematic drawing showing a cross section of a precipitator using an ionizing unit and a separate dust collector consisting of parallel plates, alternate plates being grounded and the remaining plates being connected to a source of high d-c potential.

If we assume any given charge $ne$ on a dust particle, in an electrostatic field, there will be a force $neE_0$ acting to pull the particle toward the opposite electrode. The drift of the particle through the gas is opposed by the viscous resistance of the gas and can be calculated by Stokes' Law.

$$n \cdot e \cdot E = V_d \cdot 6\pi\mu r \tag{3}$$

$$V_d = \frac{ne\ E_0}{6\pi\mu r} \tag{4}$$

The velocity of a given charged particle will then be proportioned to the field strength. The time required to travel the distance $A$ perpendicular to the air is given by

$$t_d = \frac{A}{V_d} = A\,\frac{6\pi\mu r}{n \cdot e \cdot E_0} \tag{5}$$

If we assume such a negatively charged particle moving between 2 parallel electrodes (figure 2) and starting near the negative electrode, the maximum allowable air velocity is that at which the charged particle will just reach the positive electrode before passing out of the region between the plates. The time required to travel the distance $L$ is given by

$$t_g = \frac{L}{V_g} \tag{6}$$

Equating

$$t_d = t_g = \frac{A}{V_d} = \frac{A}{V_g} \tag{7}$$

$$V_g = \frac{LV_d}{A} \tag{8}$$

To secure the maximum capacity, $V_g$ should be as large as possible. It is evident that $V_g$ is inversely proportional to the plate spacing $A$ for a given electrostatic field strength. Over a considerable range of plate spacing the electrostatic field strength can be greater as the plate spacing is decreased, so that the capacity of a given precipitator increases faster than inversely proportional to the plate spacing. The lower limit of plate spacing is usually determined by manufacturing limitations and by space required for the collection of dust.

The arrangement of separate ionization and parallel dust collecting plates has been proposed years ago. But the use of this construction to obtain a more compact and efficient unit for removing low concentrations of dust with a very low generation of ozone and oxides of nitrogen does not appear to have been appreciated.

This discussion has been based on the assumption of streamline flow between parallel electrodes. Actually some turbulence frequently exists but tests have demonstrated that these relations approximate most of the actual conditions and constitute a very valuable guide in the general discussion of precipitation.

### Effect of Particle Size

From equation 2 it is evident that the charge collected by a particle due to the effect of the electrostatic field is proportional to the square of the diameter. While from equation 3 the resistance offered by the air is proportional to the first power of the diameter, the allowable velocity is according to this theory proportional to the diameter of the particle to be removed. As the particle size decreases, the heat motion of the ion gives an additional charge

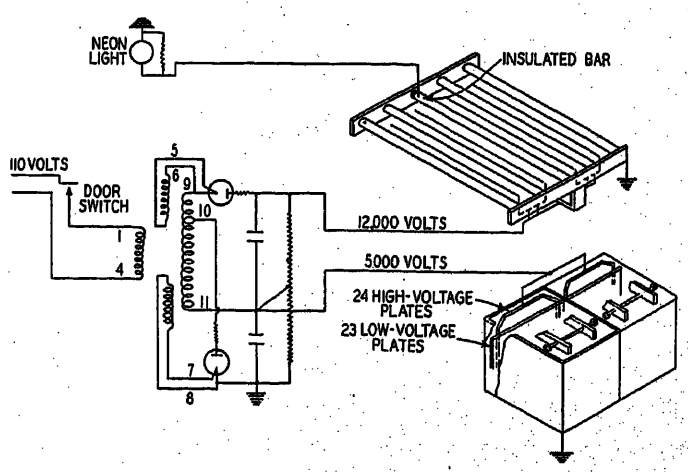



**Fig. 6. Wiring diagram of the precipitator**

above that due to the electrostatic field so that actually the allowable velocity does not decrease directly with the particle size, although the fine particles are more difficult to remove than large particles.

### Retention of Particles on Collecting Electrodes

The electrostatic force exerted by the field on the charged particle acts to carry the particle through the air toward the oppositely charged electrode.

But when the particle touches that electrode if the dust is conducting the charge leaves the particle and a surface charge of opposite sign appears representing the condenser charge of the electrodes. This tends to repel the particle from the electrode. On the other hand, if the particle could be a perfect insulator, at least on the second layer of particles, the charge would remain on the particle and the attraction be maintained. The actual case will be somewhere between these extremes. But in any case we cannot rely on the electrostatic force to hold the particle on the electrode. It must be held by adhesion. Most fine particles normally adhere. In special cases the plates may be coated with oil or other material which will cause particles to adhere, although in this case they adhere so well that cleaning of the plates is very difficult. With some types of dust, it may collect normally but a jar may loosen agglomerations of dust.

**Table I—Theoretical Maximum Charge on a Dust Particle**

| Radius of Particle, Centimeter | Diameter Microns | Dielectric Constant | Maximum Charge Due to Field Equation 2, $E_0 = 5$ | Maximum Charge Due to Heat Motion |
|---|---|---|---|---|
| $1 \times 10^{-3}$ | 20 | 1 | $1.05 \times 10^4$ | |
| $1 \times 10^{-3}$ | 20 | 4 | $2.1 \times 10^4$ | 2,100 |
| $1 \times 10^{-3}$ | 20 | $\infty$ | $3.15 \times 10^4$ | |
| $1 \times 10^{-4}$ | 2 | 1 | 105 | |
| $1 \times 10^{-4}$ | 2 | 4 | 210 | 207 |
| $1 \times 10^{-4}$ | 2 | $\infty$ | 315 | |
| $1 \times 10^{-5}$ | 0.2 | 1 | 1 | |
| $1 \times 10^{-5}$ | 0.2 | 4 | 2 | 19 |
| $1 \times 10^{-5}$ | 0.2 | $\infty$ | 3 | |

Many cases of this type can be solved by using a simple mechanical filter past the precipitator. Such a filter would not remove the dust in its original, finely divided state but when the dust breaks loose from the plates it tends to do so in large pieces or agglomerations which are sufficiently large to be caught by the filter.

## Description of the New Precipitator

Figure 3 shows a photograph of a complete precipitator which was built for removing the glaze from the air exhausted from a spray booth in a pottery plant. The high-voltage power supply unit consisting of transformer, rectifier tubes, and condensers, is mounted in the case at the left of the photograph. The ionizing units are mounted at the lower part of the case and the plate assemblies above. The ionizing unit consists of parallel grounded cylinders with wires carried on insulated supports spaced between the cylinders. The wires are connected to the high-potential power source giving 12 to 14 kilovolts d-c. Figure 4 shows a photograph of an ionizing unit removed from the case.

Some dust collects on the grounded cylinders of the ionizing unit. However, most of the dust is deposited in the dust collection plate assemblies. Figure 5 shows one of these units removed from the case. Alternate plates are grounded, being supported from the case. The remaining or intermediate plates are supported by insulated bars and are charged to a lower voltage than the ionizing units. Figure 6 shows a wiring diagram.

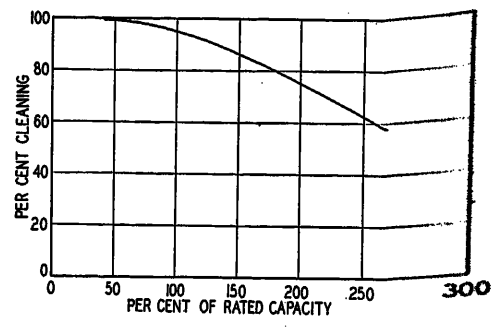



**Fig. 7. Efficiency-volume curve of the precipitator**

## Efficiency of Precipitation

The equations derived on the basis of maximum charge obtainable would indicate 100 per cent efficiency up to a given critical velocity (equation 8) and a rapid reduction in efficiency above this velocity. In practice, this abrupt transition is not obtained for several reasons. Particles vary greatly in size. All particles of a given size do not obtain the same charge because the dielectric constant varies, the field is not uniform over the ionizing region, the shape of the particles vary, and the equations governing the charging of small particles depend on the probable movement of ions and in the smaller particles the numbers involved are too small to give a uniform result. Figure 7 shows a typical curve obtained by test. This shows that we can increase the efficiency of a given unit to almost any desired value by merely reducing the volume of gas cleaned.

The initial development on this precipitator was for the purpose of removing the dust, mainly black smoke particles, from air particularly in cities where soft coal is burned. In this application we are interested primarily in the tendency of the air to blacken wall paper, draperies, merchandise, etc. This characteristic can be measured by drawing the air to be tested at a measured rate, through a piece of white cloth. Figure 8 is a photograph of 3 such samples taken simultaneously. One shows unfiltered air. The second sample shows air which had passed through a common commercial oil-coated filter. On coarse dusts, tests can be made which will give a weight efficiency of over 99 per cent for this same coated filter, but when tested using these fine smoke particles, the cleaning effect of the coated filter was almost negligible. The third sample shows air which had been passed through an electrostatic precipitator.

Another method of determining efficiency is to count the number of particles suspended in the air before and after passing through the cleaning device, using the Greenburg Impinger[2] recommended by the Bureau of Public Health. A test made using a dust of ground silica rock and counting the particles by this method gave the following results:

1. Unfiltered air—430 × $10^7$ particles per cubic foot.
2. Air filtered through the viscous coated filter—350 × $10^7$ particles per cubic foot or 19 per cent efficiency of cleaning.
3. Air passed through the electrostatic cleaner—2.3 × $10^7$ particles per cubic foot or 99.5 per cent efficiency.

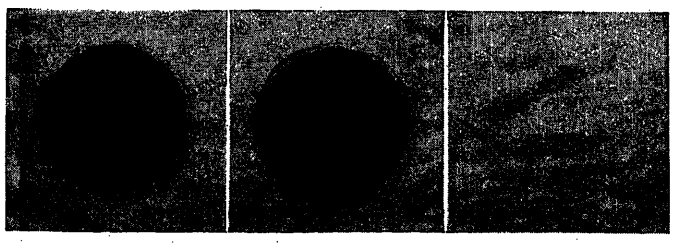
Another method of making such particle counts is the electrostatic dust sampler.[4]

The efficiency of a given unit will vary over wide limits based on the method of test. Usually a weight test gives a high efficiency, since the larger particles are efficiently removed and constitute a large portion of the weight. It is possible on filters for instance, to make tests where the weight efficiency will be above 95 per cent and yet the particle count using the impinger may show an efficiency below 20 per cent. The tests used to obtain the curve of figure 7 were made using a smoke and air mixture and measuring the time required to produce a given blackness of a piece of cloth. A condition giving 95 per cent based on this test would give well over 99 per cent using a weight test.

## Fields of Application

This type of precipitator is particularly adapted to removing light concentrations of fine dust. Some of the principle fields of application are:

1. Removal of industrial dusts which constitute a hazard to health of employees.
2. Air cleaning to protect delicate apparatus or processes.
3. Air cleaning in homes and offices in soft-coal burning cities to reduce cleaning of walls, draperies, etc.
4. Air cleaning for the relief of hay fever and asthma.
5. Air cleaning in stores to reduce damage to merchandise.



A B C

**Fig. 8. Results of passing through cloth filters a volume of 10,000 cubic feet of air cleaned by 3 different methods**

*A*—Uncleaned air
*B*—Mechanically cleaned air
C—Electrostatically cleaned air

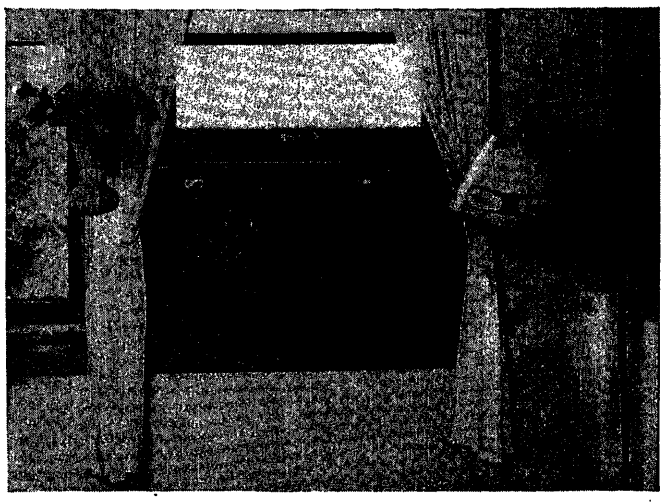


**Fig. 9. A type of electrostatic air cleaner used for the relief of hay fever and asthma**

In the operation of delicate relays such as automatic telephone switching equipment, considerable trouble may be caused by atmospheric dust which is so fine that it is not removed by ordinary means. Precipitators are giving satisfactory results in such service.

Experimental electrostatic air cleaners have been operated in connection with hot air furnaces and have shown a remarkable reduction in household cleaning required in locations where atmospheric pollution is serious.

Hay fever has been recognized as a disease caused by pollen carried by the air. Some types of asthma are also caused by air-borne dust, some of this dust being very fine. Early in the experimental work on the precipitator, 2 hospital rooms were equipped with electrostatic air cleaners. Very satisfactory results were obtained on hay fever and certain asthma cases. This work has been reported by Criep and Green.[3] Since the publication of this paper even more startling results have been obtained in relieving certain asthma cases. Figure 9 shows a picture of a precipitator designed for this service. This unit consists of a fan, ionizing unit, dust collection chamber, and high-voltage power supply consisting of transformer, 2 rectifier tubes and condensers. It is equipped with a small neon light which glows when the unit is operating. The dust collecting element is easily removed for cleaning and is constructed entirely of metal and porcelain so that it can be washed out using an ordinary hose and nozzle. The time required for precipitating the dust (including ionization) is a measure of the size of the unit. In the unit shown in figure 9 the precipitation time is $^1/_5$ second as compared to 2 to 10 in older conventional precipitators.

## Appendix I—Symbols

$\mu$ = viscosity of the gas
$e$ = charge on the electron
$n$ = number of electrons on a dust particle
$E$ = electrostatic field strength in volts per centimeter

(*Concluded on page 128*)

# Dielectric Strength of Transformer Insulation

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**This paper presents a summary of the results of over 2,000 tests on the dielectric strength of transformer oil and insulating material for impulse, switching, and 60-cycle voltages. From these tests the voltage-time characteristics of the 2 insulations tested may be established over the entire range from a fraction of a microsecond to more than one minute.**

THE voltage-time characteristic of insulation is of great importance in engineering and theoretical dielectric problems. A practical case is the early recognition that the time of application of voltage be reduced when testing transformers at industrial frequencies higher than the normal.[1,2] Later when the protection of electrical apparatus against lightning received close attention, naturally insulation was studied in considerable detail in the impulse region which extends from about 100 microseconds to a fraction of a microsecond.[3,4] Recently some data[5,6] have been reported to the AIEE to establish the voltage-time characteristic of insulation over its range up to the order of one minute, but these data are limited in scope. More data are therefore required to establish adequately the voltage-time characteristics of insulation.

The purpose of this paper is to fulfill this need more fully. It presents the data and results of a comprehensive investigation on solid and liquid insulations (0.056- and 0.125-inch fullerboard; 0.25-, 0.50-, and 1.00-inch transformer oil). Some 2,000 tests were made and approximately 750 cathode-ray and magnetic oscillograms recorded. These data permit establishing the voltage-time characteristics of the insulation tested over the entire range from a fraction of a microsecond to beyond one minute. Tests were also made on insulation structures similar to those in large high-voltage electrical apparatus, thus enhancing the usefulness of the investigation. In the paper the technique and test methods developed, always an important factor in fundamental work, are given in detail. These methods can be applied in similar investigations on other insulation materials. Besides the data reported in curve form, other pertinent observations and findings (such as corona, character of breakdown, etc.) are reported, which should be of guidance in the correct interpretation of the mechanism of insulation breakdown.

## Test Methods

The voltages which appear on electrical systems may conveniently be classified according to their duration as impulse, switching, and normal-frequency voltages. Means were therefore provided to produce corresponding testing voltages and to measure the voltage and its duration.

### Impulse Tests

These tests were made with the standard impulse generator set up to produce a nominal $1^1/_2 \times 40$ microsecond wave. Voltage and time were measured with a cathode-ray oscillograph connected across the test piece through a capacitance divider which was calibrated against a resistance divider. The equipment and general procedure conform to the established practice in impulse testing[7-10]. Typical oscillograms of impulse voltages applied to the test piece are shown in figure 8*A*, *B*, and *C*.

### Switching Surge Tests

The circuit in figure 1 was devised for these tests. The surge generator is arranged for a high capacitance ($C_s$ = 0.1 microfarad) and supplies a voltage of 350 kv or less. The generator discharges into a load capacitance of 0.08 microfarad through an inductance of 1.2 henries. The test piece is across the load capacitance. The duration and wave form of the surge across the test piece is fixed by the constants of the circuit and the magnitude can be controlled by the charging voltage applied to the surge generator. A typical oscillogram of the surge voltage employed in these tests is given in figure 8*D*.

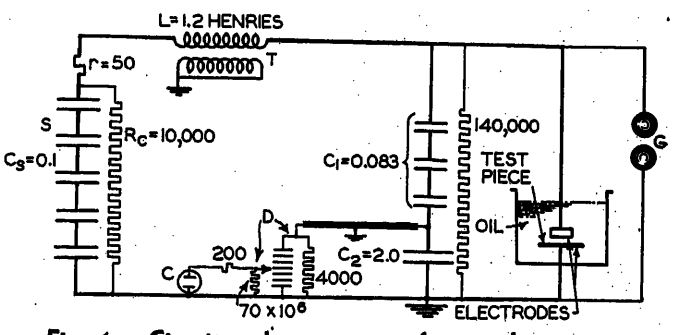



**Fig. 1. Circuit and arrangement for switching-surge tests**

Resistances in ohms; capacitances in microfarads

*C*—Cathode-ray oscillograph
*D*—Voltage divider
*G*—25-centimeter sphere gap
*S*—Surge-voltage generator
*T*—1,000-kva 132-kv transformer

The method of measuring the voltage was by means of the cathode-ray oscillograph connected through the

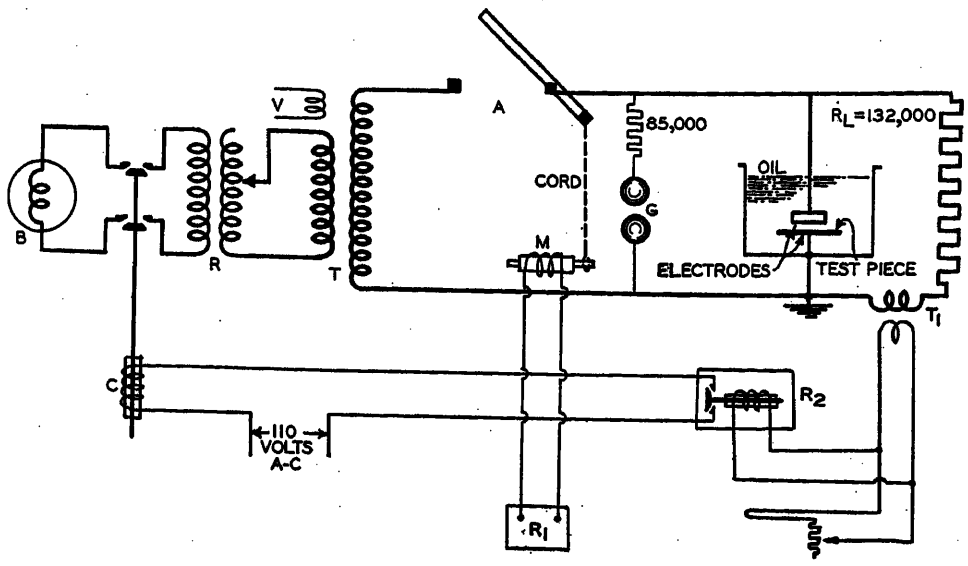
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1. For all numbered references see list at end of paper.

**Fig. 2. Circuit and arrangement for short-time 60-cycle tests**

Resistances in ohms
*A*—Switch
*B*—600-kva single-phase 60-cycle generator
*C*—Circuit-breaker tripout coil
*G*—25-centimeter sphere gap
*M*—Release magnet for switch *A*
*R*—500-kva step induction regulator
$R_1$—Initiating relay operated by magnetic oscillograph
$R_2$—Time relay
*T*—300-kv 150-kva testing transformer
$T_1$—Current transformer, 5 to 50 amperes
*V*—Voltmeter coil




capacitance divider as indicated in figure 1. The capacitance divider was calibrated against a resistance divider connected across the load. The resistance divider calibration established that the wave form of the surge applied to the test object was faithfully recorded at the cathode-ray oscillograph with the capacitance divider. The testing set was also calibrated against a 25-centimeter sphere gap and the relation between the output voltage at the load and the charging voltage of the surge generator was established. The 2 methods of voltage measurement checked within 3 per cent.

### Short-Time 60-Cycle Tests

The circuit diagram and test arrangement for the short-time 60-cycle tests are shown in figure 2. The arrangement is such that a voltage of a desired magnitude can be applied for only a short time in the range of 5 to 90 cycles. The voltage was supplied from a 300-kv 150-

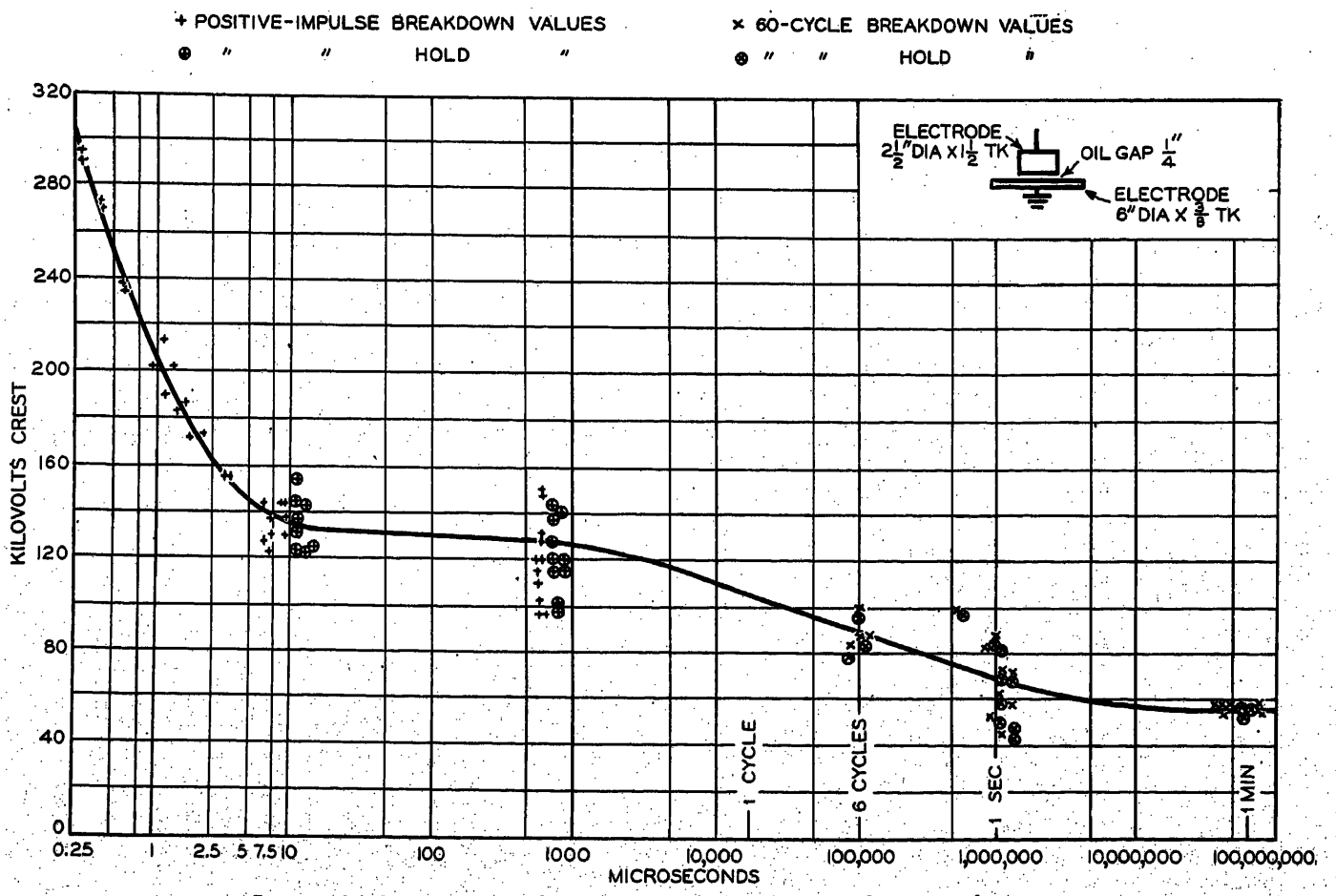



**Fig. 3. Voltage-time breakdown curve for transformer oil, 0.25-inch spacing**

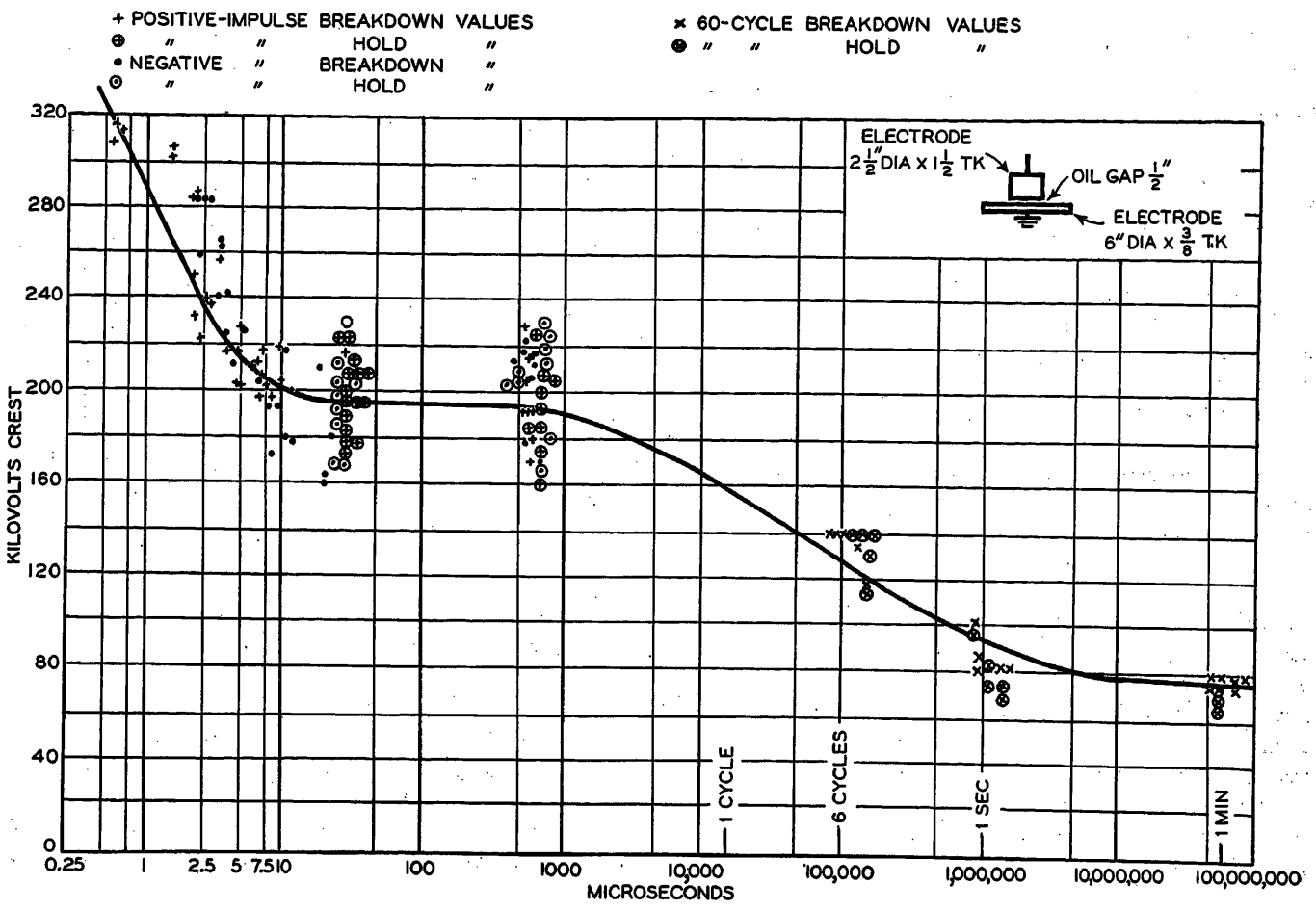



**Fig. 4. Voltage-time breakdown curve for transformer oil, 0.5-inch spacing**

kva testing transformer excited from a step-induction regulator by which the voltage could be adjusted. A load resistance of 132,000 ohms was connected across the testing transformer by means of a large air insulated switch *A*. The test piece was connected directly across this load resistance. The test set was calibrated, measuring the voltage at the test piece with a 25-centimeter sphere gap and the voltage on the voltmeter coil of the testing transformer with the set operating to trip off the voltage in the same way as when making the actual tests.

The method of controlling and measuring the time will be apparent from a brief description of the test procedure and reference to figure 2. The testing transformer is first excited to give the desired voltage. Then the initiating relay, operated by the magnetic oscillograph, energizes the "release magnet" and permits switch *A* to close by gravity, and apply the voltage to the load resistance and the test piece.

The current flowing through the load resistance is stepped up through a 5/50-ampere current transformer and energizes the "time relay". The time relay closes the circuit that energizes the trip-out coil of the circuit breaker in the primary of the regulator and thus the voltage across the test piece is removed. The number of cycles the voltage is applied can be varied by adjusting the timing relay. The time of voltage application is measured by the magnetic oscillograph connected across the secondary of the current transformer. It registers the number of cycles that the current flows through the load resistance and hence the time that the voltage is applied to the test piece. Typical oscillograms of the voltage-time application are shown in figure 8*F* and *G*.

### Long-Time 60-Cycle Tests

The voltage supply for these tests was a 150-kv 75-kva testing transformer excited through an induction regulator for voltage control. The voltage measured at the voltmeter coil of the testing transformer was calibrated against a 25-centimeter sphere gap connected across the test load. The time in these tests was of sufficient duration for direct measurement with an ordinary watch.

## Testing Technique and Data

The fullerboard samples used in the tests were 12 inches by 12 inches for the 0.056-inch thickness and either 12 inches by 12 inches or 24 inches by 24 inches for the 0.125-inch thickness. The fullerboard was thoroughly dried out in a heating oven and oil-impregnated under vacuum similar to the treatment for transformers. In all the tests standard transformer oil was used. The oil was at room temperature, 13 to 22 degrees centigrade, and its strength as tested in the standard AIEE cup was between the limits of 28 to 36 kv (root mean square)

which is well above the accepted value for good oil.

In all tests the line electrode was a 2 1/2 inch diameter, 1 1/2-inch thick polished brass disk with square edges and the grounded electrode was a 6-inch diameter, 3/8-inch thick smooth brass plate. The electrodes were arranged coaxially and supported by a rigid Micarta framework. In the oil tests the electrodes were set and rigidly clamped at the desired separation and in the fullerboard tests they were pressed firmly against the test sample.

All tests were started at 60 to 70 per cent of the expected breakdown value. The voltage was first increased in steps of about 10 per cent and as breakdown was approached the steps were reduced to 2 to 3 per cent. The total number of voltage applications on each sample was from a few up to as many as 25 with an average of about 10. In the impulse tests where the breakdown occurred on the front of the wave (figure 8*A*), the first test resulted in failure. A rest period of 2 minutes or more was allowed between repeated voltage applications on a sample.

The minimum corona voltage was determined starting at a low voltage and increasing it in small increments until corona could just be detected. In the impulse, switching, and short-time 60-cycle tests corona was first detected visually, whereas in the long-time 60-cycle tests it was first detected audibly.

From these tests the voltage-time characteristic curves for transformer oil and oil-impregnated fullerboard are plotted in figures 3, 4, 5, 6, and 7. Both the breakdown and the maximum hold values are given on the curves. The corona values are also shown.

## Discussion of Tests and Data

The breakdown of oil on impulse, switching, and short-time 60-cycle voltages was somewhat erratic. The variation was reduced to an apparent minimum when proper precautions were taken in cleaning the electrodes, in replacing burned oil from between the electrodes with fresh oil, in removing trapped air from the oil, and in beginning the tests at low voltage and increasing it in small steps to failure. Even with these precautions a spread of 20 to 30 per cent is found as shown in figures 3, 4, and 5.

One inherent characteristic of oil is the long time-to-breakdown on impulses, as illustrated in oscillogram figure 8*C*. In some cases the time-to-breakdown was as great as 25 microseconds, as can be seen in figure 4.

No corona could be observed previous to breakdown in any of the tests on oil except there appeared to be a slight amount just preceding breakdown of the 1-inch spacing in the short-time 60-cycle tests. Most of the failures occurred from the edge of the line electrode, though for the 1-inch spacing a considerable proportion was from the face of the line electrode.

Tests with positive and negative impulse and switching voltages were made on the 1/2-inch oil gap. There is no marked difference in breakdown voltage for the 2 polar-

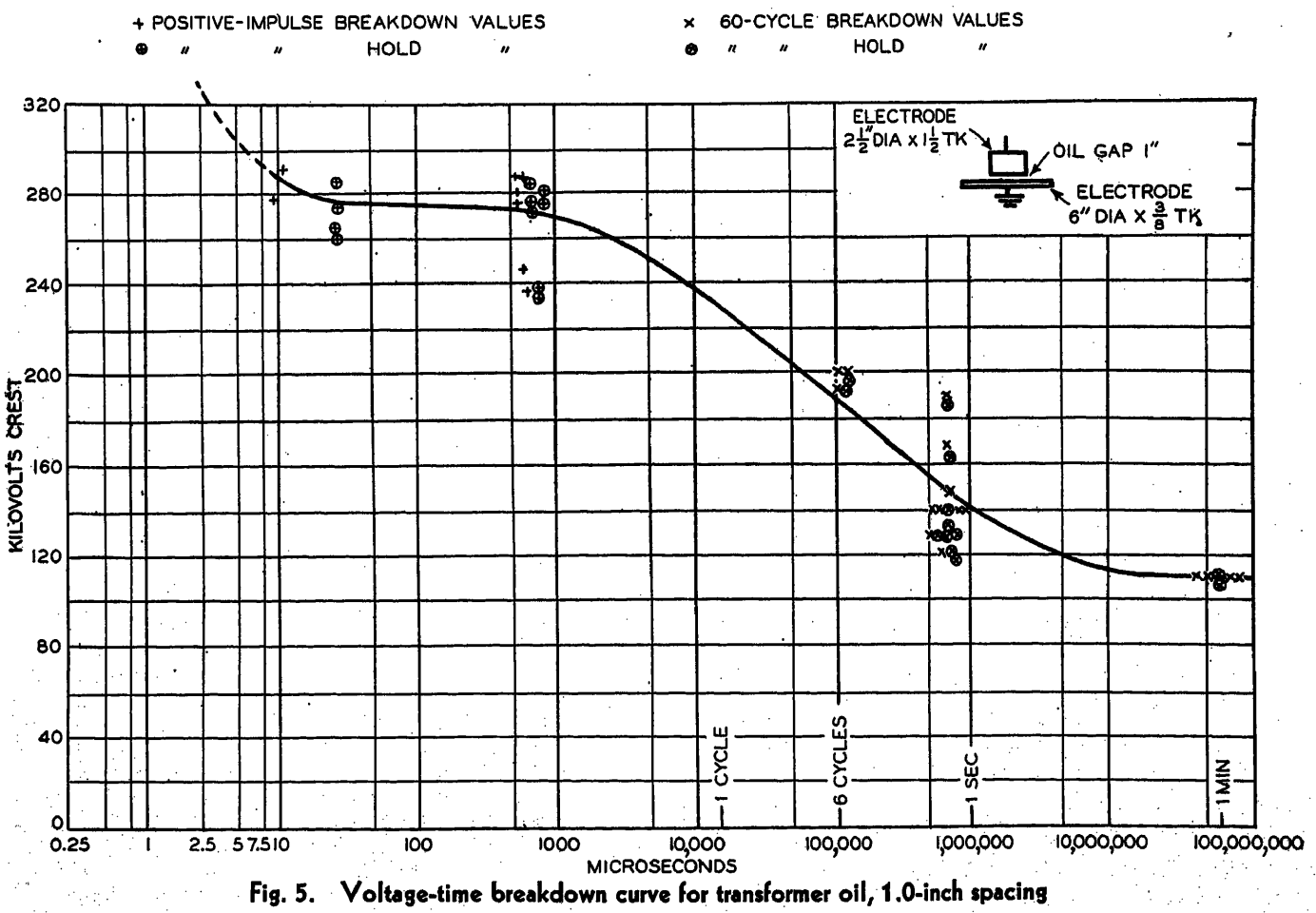



**Fig. 5. Voltage-time breakdown curve for transformer oil, 1.0-inch spacing**

ities, though the negative breakdown values are on the average somewhat greater than the positive. In the short-time 60-cycle tests the polarity of the 60-cycle voltage at failure could be determined from the magnetic oscillograms. Of 22 tests, 15 failed on positive polarity.

The voltage-time characteristic curves for the 1/4-inch, 1/2-inch, and 1-inch oil gaps (figures 3, 4, and 5) are essentially of the same form. They are flat in the region between 10 to 1,000 microseconds, rise rapidly for impulse voltages shorter than 10 microseconds and fall gradually from 1,000 microseconds to one minute. The close similarity of the 3 curves can be seen by comparing the ratios of voltage at any time value to the one-minute voltage (impulse ratio). For example, the impulse ratios for the 1/4-inch, 1/2-inch, and 1-inch oil gaps are respectively 2.4, 2.6, and 2.5 at 40 microseconds. The relation between voltage breakdown ($V$) and oil gap spacings ($d$) for these curves is closely expressed by $\log V = 0.5 \log d$.

The voltage-time characteristic curves of oil-impregnated fullerboard tested in transformer oil are given in figures 6 and 7 for 0.056-inch and 0.125-inch thicknesses respectively. In these tests breakdown was definitely preceded by corona. In the impulse tests the corona voltage for the 2 thicknesses appeared at approximately 45 per cent of breakdown voltage. On increasing the impulse voltage above the corona value visible streamers in increasing length extended from the edge of the line electrode along the surface of the fullerboard reaching a length at breakdown of about 2 1/2 inches for the 0.056-inch fullerboard and 3 1/2 inches for the 0.125-inch fullerboard. These observations of corona were confirmed by the inspection of the marking on the fullerboard after test. The maximum time-to-breakdown in the impulse tests on fullerboard occurred near the crest, figures 6 and 7 and oscillogram figure 8*B*, as compared to the long time breakdown in oil. It is of interest to note that the corona voltages of the 2 thicknesses of fullerboard (60 kv and 95 kv) correspond closely to the estimated breakdown voltage for the same spacing of oil gaps.

An important observation is the nature of breakdown. For the positive polarity impulse tests somewhat more than 80 per cent of failures for the 2 thicknesses of fullerboard were from the face of the line electrode and less than 20 per cent were from the edge. Whereas for the negative polarity tests, which were made on the 0.125-inch fullerboard alone, only 35 per cent of the failures were from the face of the electrode and 65 per cent occurred at the edge. The location of these failures indicates the grading effect of the positive streamers on the edge of the line electrode and also suggests a considerable voltage drop along the length of the streamer from the base to the tip. Apparently negative impulse streamers are of a different character than the positive and do not produce the same grading effect on the edge.

The length of the corona streamers for the switching surges (oscillograms, figures 8*D* and *E*) were considerably

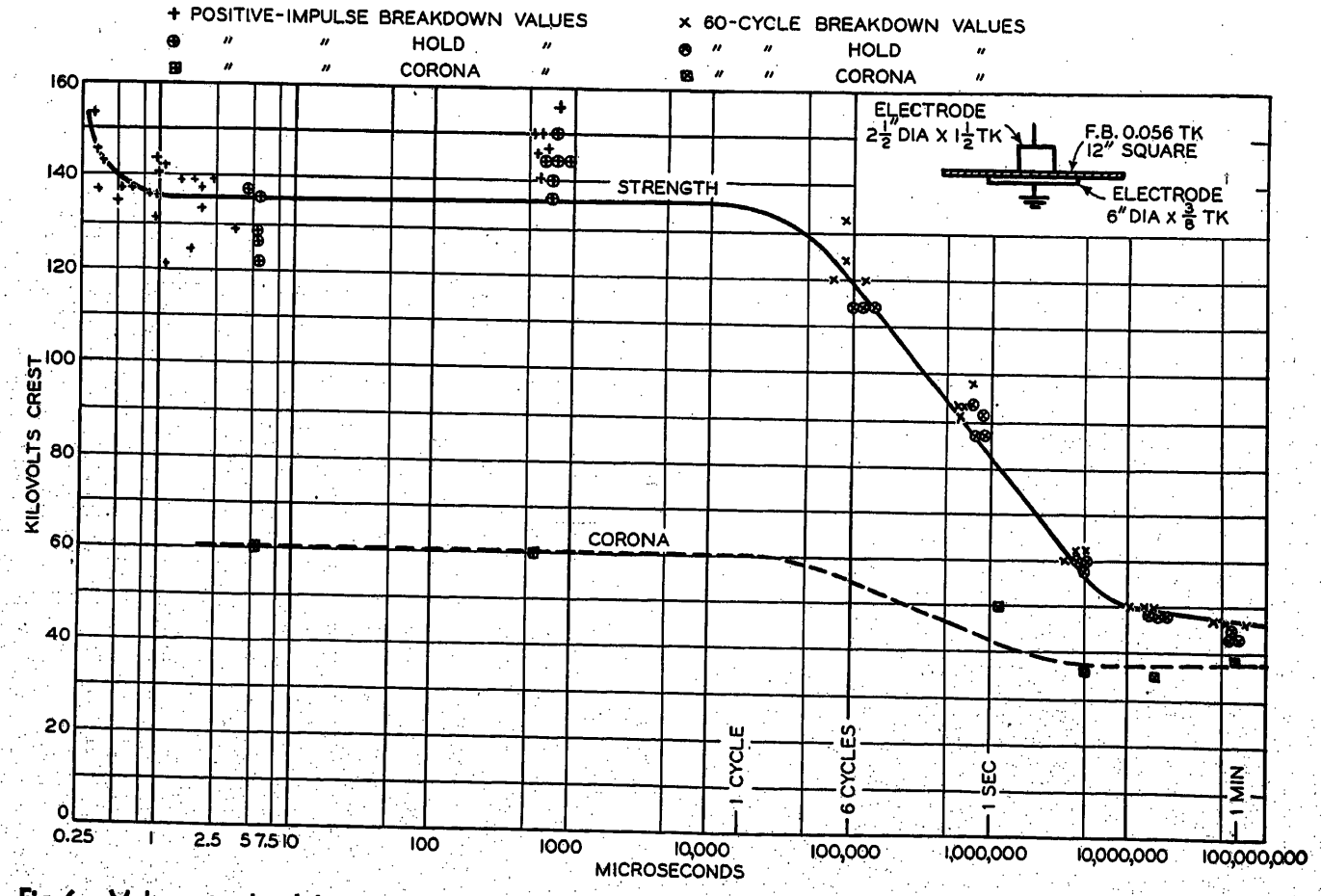



**Fig. 6. Voltage-time breakdown and corona-time curves for 0.056-inch oil-impregnated fullerboard tested in transformer oil**

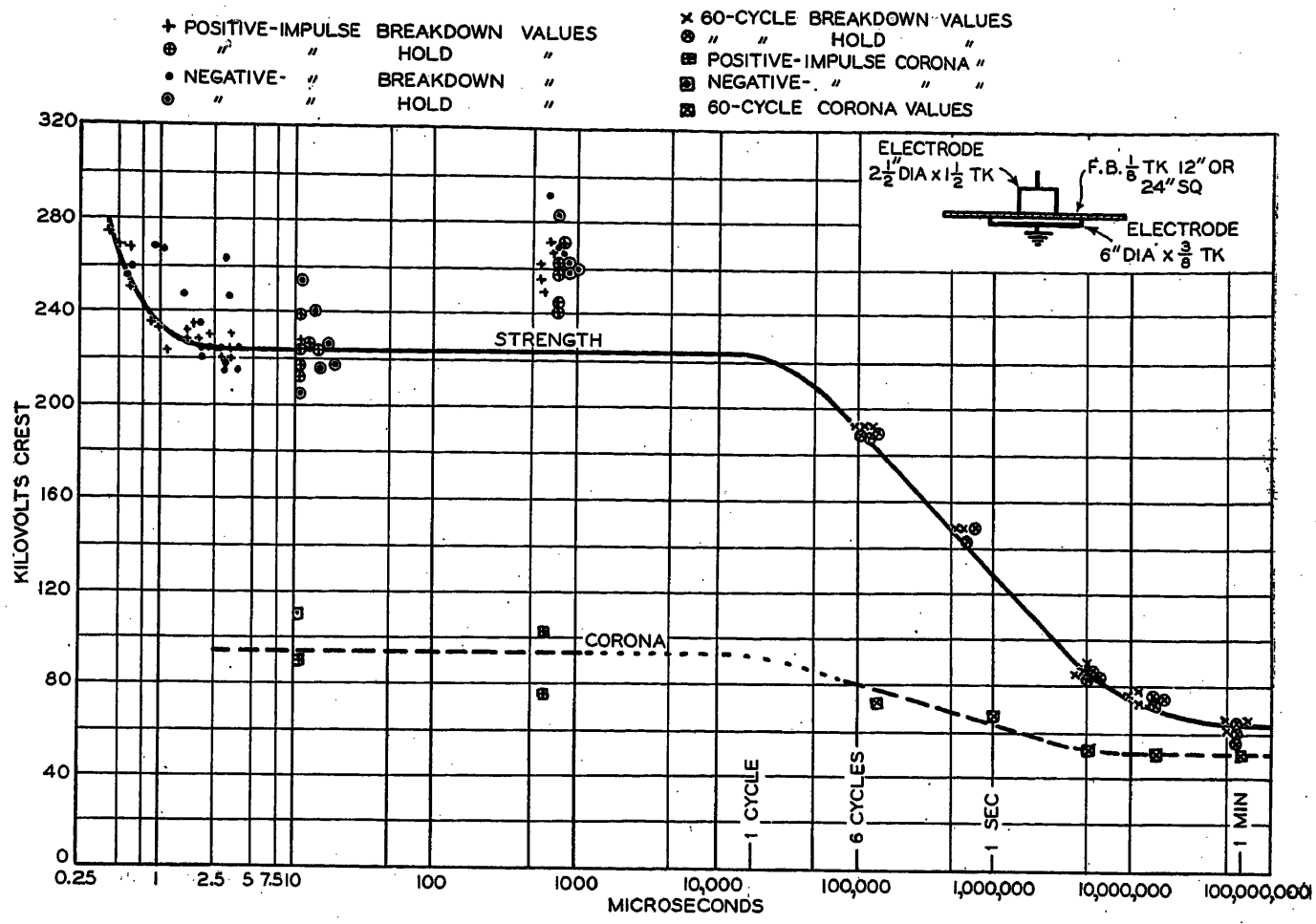



**Fig. 7. Voltage-time breakdown and corona-time curves for 0.125-inch oil-impregnated fullerboard tested in transformer oil**

greater than for the impulse. In fact creepage took place at 160 kv over the edge of the 12-inch by 12-inch samples, 0.125-inch thickness, this making it essential to use 24-inch by 24-inch samples. The location of the breakdown for the positive polarity switching surges was in 55 per cent of the tests from about $^1/_2$ to $1^1/_2$ inches outside the edge of the line electrode. These points of failure were from a streamer. The other 45 per cent of the failures were either from the edge of the electrode or from the face near the edge. These observations for the positive switching surges suggest that due to the relatively long time of application of the voltage the streamers develop into a more conducting path resulting frequently in failure from a streamer rather than from the electrode. The points of failure for the negative polarity were at or near the edge of the electrode, thus indicating again the difference in nature between positive and negative breakdown.

In the short-time 60-cycle tests (oscillograms figure 8*F* and *G*), 12 out of the 13 failures occurred on the positive polarity of the 60-cycle wave. The streamers were about the same length as for the switching surges. One-half of the failures occurred on streamers $^1/_4$ to 1 inch away from the electrode, the others were at the edge. Apparently the nature of breakdown for the short-time 60-cycle tests is of the same general character as that for the positive switching surges. Further evidence on the nature of breakdown is given from the 60-cycle tests applied for durations from 5 seconds to one minute. In 80 per cent of these tests, failure occurred on a streamer $^1/_4$ to 1 inch from the electrode and the other 20 per cent were at the edge. The extent of the visible corona from the electrode was much less pronounced than for short-time 60-cycle switching and impulse voltages, due undoubtedly to the lower breakdown voltage.

The appearance of the breakdown in the fullerboard is illustrated in figure 9. For the impulse voltages the failures are distinctly of a disruptive character with practically no indication of burning. The switching tests produced failures similar in appearance to those of the impulse, although the extent of the rupture was greater due to the larger current. The short-time 60-cycle tests were somewhat disruptive in character and also showed considerable burning. The 5 seconds to one minute 60-cycle failures showed a decided burned effect.

An important observation of the fullerboard tests was in connection with the surface marking on the test sample. Even though as many as 25 repeated impulse or switching surge voltages were applied to a sample up to breakdown, entailing profuse corona discharges, yet the amount of damage was extremely small and appeared to be confined to the surface layer.

The form of the voltage-time characteristic for the 2 thicknesses of fullerboard (figures 6 and 7) is of the same

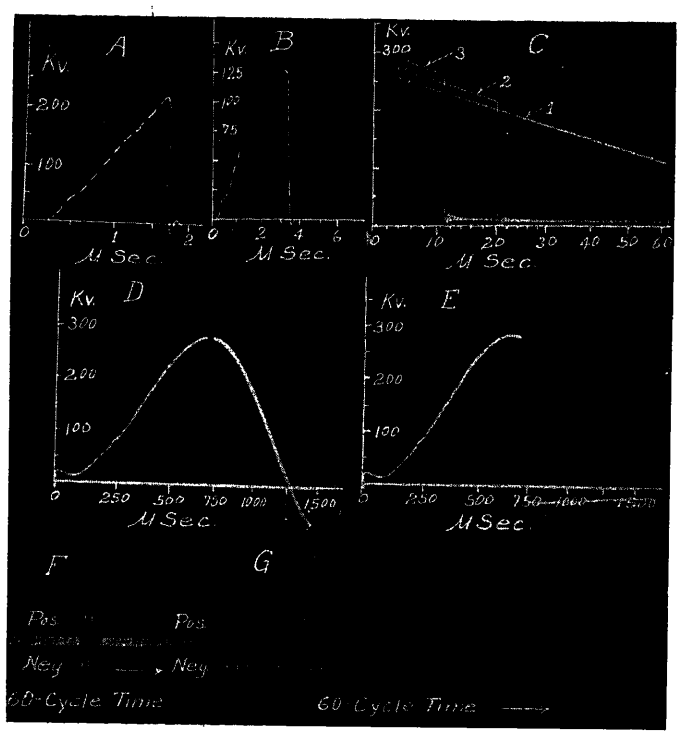



**Fig. 8. Typical oscillograms**

*A*—Impulse tests, 1/8-inch thick fullerboard
*B*—Impulse tests, 0.056-inch thick fullerboard
*C*—Impulse tests, 1.0-inch oil gap
*D*—Switching surge tests, 1.0-inch oil gap
*E*—Switching surge tests, 1.0-inch oil gap
*F*—Short-time 60-cycle tests, 0.25-inch oil gap
*G*—Short-time 60-cycle tests, 1.0-inch oil gap

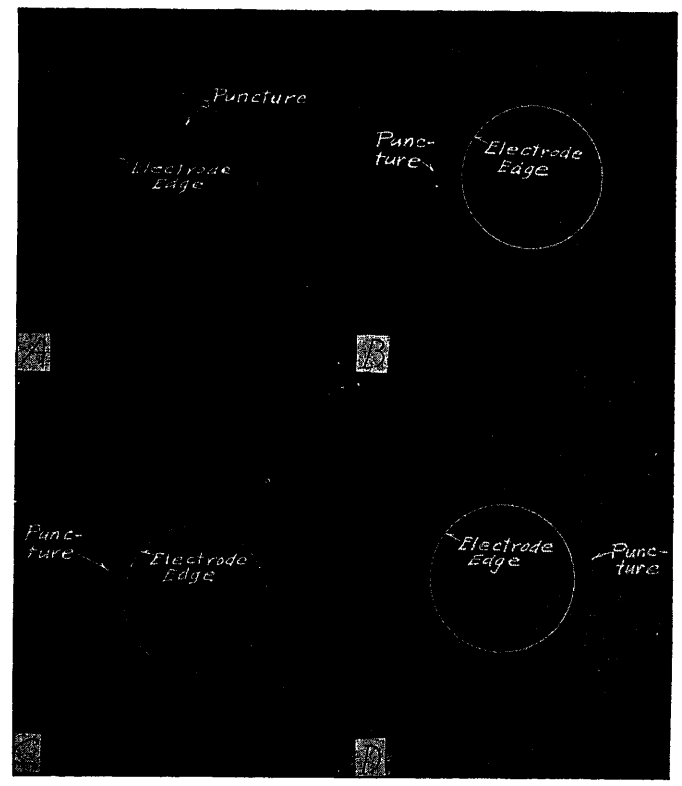



**Fig. 9. Typical fullerboard failures**

*A*—Impulse tests, 0.056-inch thick fullerboard
*B*—Switching surge tests, 0.056-inch thick fullerboard
*C*—Short-time 60-cycle tests, 0.056-inch thick fullerboard
*D*—One-minute 60-cycle tests, 0.056-inch thick fullerboard

type. As compared to the characteristic of oil however, the fullerboard characteristic is flat for a greater range of time in the impulse and switching surge regions. The fullerboard curves are flat from 2 to 10,000 microseconds, rise for shorter times than 2 microseconds, and fall quite rapidly from 10,000 microseconds to one minute. The corona curves are of similar shape. The data points are quite consistent from 6 cycles to one minute. In the switching surge region the spread in the points is about 20 per cent, which is the same as in the impulse region, but the values are higher than for the long impulses, apparently due to a better grading effect.

The impulse ratio for the 2 thicknesses of fullerboard is of the same order for the entire range of time and at 2 microseconds the average is 3.1.

The relation between voltage strength ($V$) and thickness over the greater range of the 2 curves for fullerboard is expressed by $\log V = 0.6$ to $0.7 \log d$.

## Combined Solid and Liquid Insulation

To further extend the investigation, tests were made on a barrier structure of 2 0.056-inch thick, 36-inch by 36-inch fullerboard sheets and 3 1/8-inch oil ducts arranged alternately. A 4-inch disk and a plate were used for the line and the ground electrodes, respectively. Impulse tests were made by applying 100 repeated applications at each voltage setting up to failure. The one-minute 60-cycle breakdown strength was also established. The average test values were 300, 300, 280, and 130 kv for 0.35 microsecond, 2.5 microseconds, full 40 microseconds, and one-minute 60-cycle test (crest), respectively. These results show an average impulse ratio of 2.2. These tests for a large number of repeated impulses confirm the constant strength over the impulse region even down to the very short times, as previously established.[4] For the longer times these values indicate the same form of voltage-time characteristic as shown for the fullerboard and oil alone.

Though this barrier and the fullerboard and oil alone are elements of electrical apparatus insulation, they do not conform to the best design structure used in practice. Therefore 2 power transformers, a 132 kv core-type and a 132 kv shell-type were tested, as shown in figure 10. The impulse tests from 1 microsecond and less were made with a 24-inch rod gap chopping the wave on the front.[11] From about 2.5-microsecond duration to the 40-microsecond full wave the tests were made in the same manner as in the recommended practice[12,13] using a test rod gap. Switching surges limited by a 38 1/4-inch co-ordinating rod gap were made on the core-type transformer and in a few of the tests the gap actually flashed over. Furthermore this transformer had previously been used in the switching surge tests in the set-up of figure 1 and had been subjected to more than 500 of these tests from 350 kv and less.

The standard one-minute 60-cycle test had also been made.

The dotted line at 860 kv (391 × 2.2) shows the maximum permissible impulse test level corresponding to the standard AIEE 60-cycle test.[3,4] It will be seen that the tests above this line in region *E* encroach on the margin of the insulation impulse strength. The tests in region *D* verify the adequate impulse strength levels of the transformers. The tests in region *C* represent AIEE recommended impulse tests.[12,13] The highest switching tests are indicated at *B*. These tests on the transformer are amply indicative that the voltage-time characteristic of this and other apparatus of the kind is similar in shape to that for the oil and fullerboard. These large numbers of tests over the entire time range, from a fraction of a microsecond to a minute, indicate that impulse and 60-cycle tests are sufficient to establish the adequacy of a transformer design for practically all conditions of service.

## Conclusions

1. In the oil tests corona and breakdown apparently occurred simultaneously.

2. The impulse ratio at the full impulse wave for the oil tested is approximately 2.5. The average strength of the oil is practically constant from 15 to 1,000 microseconds.

3. In the fullerboard tests even though profuse corona preceded breakdown, no appreciable damage could be observed on the insulation.

4. The strength of fullerboard is practically constant from 2 to 16,000 microseconds. Over this range the impulse ratio is close to 3.1.

5. In the fullerboard tests a distinct difference was found in the nature of breakdown between the positive and the negative polarity as indicated by the corona streamers, the failures and the 60-cycle tests.

6. The character of the breakdown for the impulse, switching, short-time 60-cycle, and long-time 60-cycle voltages was progressively from a distinct disruptive character to a burning effect.

7. The strength of fullerboard and oil is essentially the same for switching surges as for impulse voltages at the full 40-microsecond wave. This characteristic and the tests on the transformers indicate that 60-cycle and impulse tests are proof of the adequacy of design for practical service conditions.

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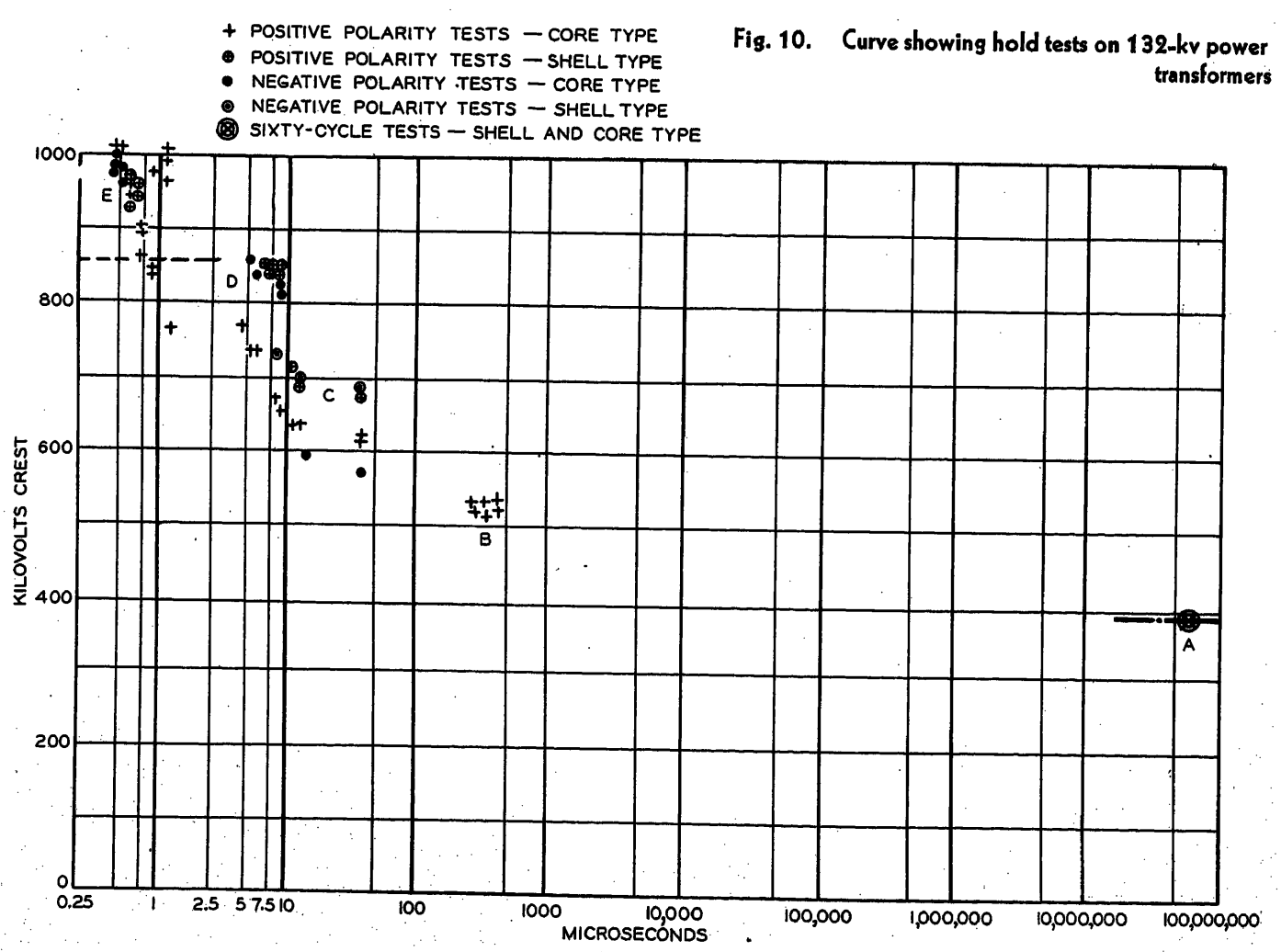



**Fig. 10. Curve showing hold tests on 132-kv power transformers**

# Development of a Modern Watt-Hour Meter

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**A comprehensive discussion of the factors affecting the performance of a watt-hour meter is presented in this paper, and the general discussion is applied to a description of the development of a new type of domestic watt-hour meter. Design and performance data on the new meter also are presented.**

THE a-c watt-hour meter has undergone many stages of development and improvement since the first ac-dc meter designed by Thomson in 1889 and the first induction watt-hour meter by Shallenberger in 1894. Meters have grown smaller, they have become much more accurate under varying load conditions, and their cost has been reduced. There has been a definite tendency to increase the current range over which a meter will operate successfully. Another important improvement has been the minimizing of errors due to variations in ambient temperature. Both of these features are of particular significance when considered from the standpoint of modern metering conditions.

Watt-hour meters as they exist today have built up a deserved reputation for accuracy and reliability and at first thought it might appear that further attempts to improve performance might be unwarranted, if not impossible. When carefully analyzed, however, it is evident that the "long range accuracy" that has been built into recent meters has really been an attempt to reach closer to the ideal, which would be a single meter capable of measuring all currents encountered in a given class of installations. Such a meter would simplify the problem of providing for future growth of load on an installation and at the same time adequately take care of the very small loads that are frequently of importance. It would eliminate the uncertainty of choosing the correct current rating for a given job, because there would be only one meter to use—one meter for all domestic loads. Such an arrangement would obviously be advantageous, particularly from the standpoint of reduction in inventory expense of complete meters and parts.

More general mounting of meters out-of-doors in locations where extreme high and low temperatures were encountered presented new problems. One of these was to provide higher accuracy over wider temperature ranges than heretofore.

There appeared, therefore, sufficient justification to warrant a complete analysis of the fundamentals of watt-hour meter design with the objective of discovering means of providing these and other desirable improvements.

## Factors Affecting Meter Performance

At the outset, the basic design problems with an induction watt-hour meter are: first, to provide sufficient torque with a minimum of friction so that the effects of friction are minimized; second, to minimize the damping effects of the a-c fluxes in order that the performance will be good at abnormal voltages and at heavy loads; third, to decrease the inherent lagging angle and the potential circuit watts loss in order that wave form, frequency, low power factor, and class II temperature errors will be minimized. The induction meter is inherently accurate but it is these details that are the main causes of any inaccuracy. A good design must incorporate a consideration of all these factors.

### Analysis of Element Driving and Damping Torques

To analyze the inherent effects of the a-c fluxes in the driving element of a watt-hour meter, it is well to consider how these fluxes determine the element driving and damping torques. At normal conditions of load—that is, rated frequency and voltage, unity power factor, and nominal-load current, there will be established definite values of flux, and the driving torque at this point is commonly known as the nominal or full-load torque. For this condition, it may be assumed that the effective potential flux crossing the disk lags the applied voltage by 90 electrical degrees and that the useful current flux is in phase with the load current. For this condition, Jimbo[1] has shown that the load torque is equal to

$$T = 4\pi \frac{stf}{g} G_d \phi_e' \phi_i' \cos\theta \, 10^{-8} \qquad (1)$$

where

$T$ = load torque in gram-millimeters
$s$ = conductivity of disk in mhos per centimeter cube
$t$ = thickness of disk in centimeters
$f$ = frequency in cycles per second
$g$ = gravitational constant
$G_d$ = driving constant
$\phi_e'$ = useful potential flux in maxwells, effective values
$\phi_i'$ = useful current flux in maxwells, effective values
$\theta$ = phase angle between voltage and current

$G_d$ is a dimensionless constant which is determined by pole shapes and displacements, their position relative to the disk, and the size of the disk. For any design, $G_d$ may be readily estimated by methods of Jimbo or by methods proposed by Morton.[2] This driving constant is a direct measure of the effectiveness of any design in producing torque from given amounts of flux.

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1. For all numbered references, see list at end of paper.

The current and potential fluxes not only produce a driving torque but each also provides a damping torque which in the case of the current flux is the major cause of heavy-load droop, and in the case of the potential flux is the major cause of meter voltage errors. These damping torques are expressed as follows:

$$T_i = \frac{st\omega}{g} G_i (\phi_i')^2 10^{-8} \quad (2)$$

$$T_e = \frac{st\omega}{g} G_e (\phi_e')^2 10^{-8} \quad (3)$$

where

$T_i$ = current flux damping torque in gram-millimeters
$T_e$ = potential flux damping torque in gram-millimeters
$\omega$ = speed of disk in radians per second
$G_i$ = current damping constant
$G_e$ = potential damping constant

These damping constants are also dimensionless and depend upon the inherent meter design. The designer's problem is to provide the useful potential and current fluxes from appropriate windings, so designing the magnetic structure that the driving constant $G_d$ is as large as possible and the damping constants $G_i$ and $G_e$ are as small as possible. By knowing these constants, the inherent qualities of any element are largely established although there are other features that must be considered. For instance, the structure which gives desirable driving and damping constants may not be at all practical in that it may be difficult to efficiently provide the required magnitude of a-c fluxes.

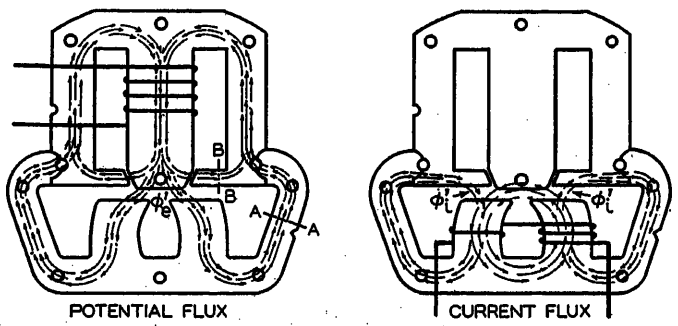



**Fig. 1. Distribution of potential and current fluxes in a watt-hour meter**

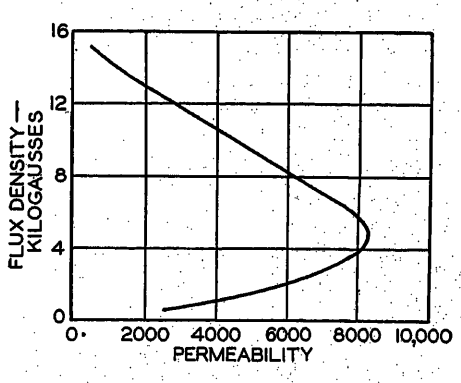



**Fig. 2. Permeability curve for silicon steel**

Equations 1, 2, and 3 have further value for they show that:

1. The a-c damping torques in a meter are proportional to the meter speed so it is desirable to make the nominal speed as small as possible. This is accomplished by the use of a high-strength control magnet.

2. For small current damping, the ratio $\phi_i'/\phi_e'$ should be small and for small potential damping the inverse is true. The final choice depends upon the errors and the relative ease of correcting for them in the design.

3. For given amounts of flux, the driving torque is proportional to frequency so that for the higher frequency ratings the damping effects of the a-c fluxes are relatively smaller. The damping torques do not depend upon the rated frequency.

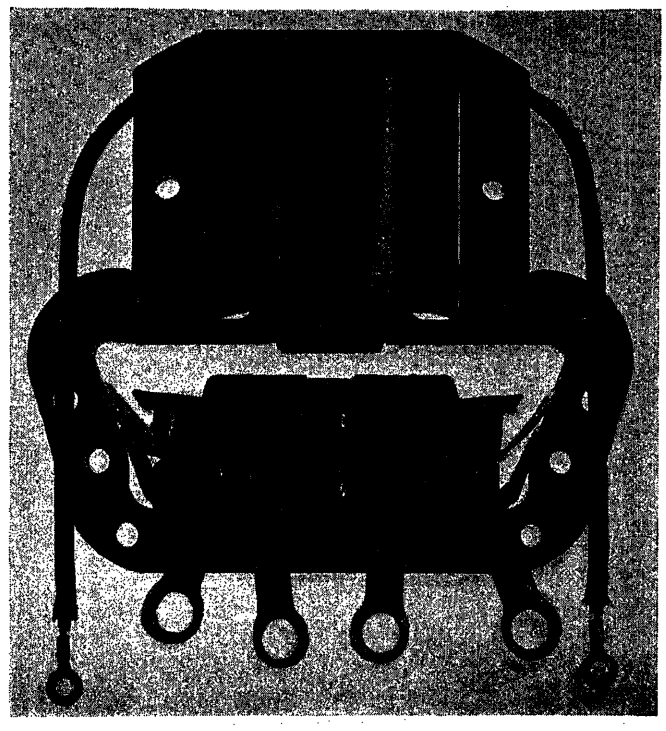


**Fig. 3. Element assembly of a new 3-wire domestic watt-hour meter**

High-conductivity aluminum is used for the disk because of the superior torque to weight ratio that results.

## The Voltage Curve

Since commercial power systems usually hold voltage within 10 per cent, it is necessary that a meter be correct for only a rather limited voltage range. Because of this and since the error is easily corrected in the design, the useful potential flux in modern watt-hour meters is usually 4 or 5 times as large as the useful current flux at nominal load. This practice gives less current damping torque, improving the heavy load registration curve. A common method in use today to correct for the voltage damping torque or voltage error is to proportion the magnetic structure so that the useful potential flux increases more rapidly than the applied voltage. This has been accomplished[8] without resorting to saturation. In this

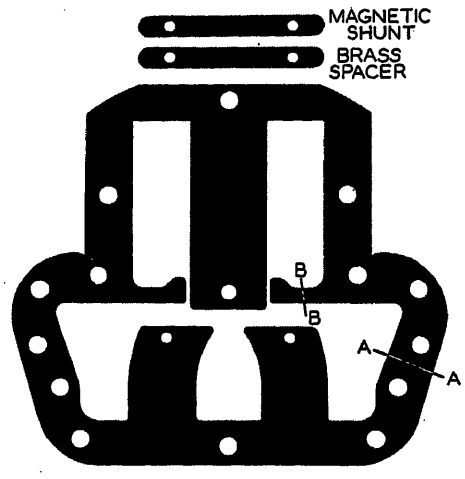



**Fig. 4. The type of lamination used for all sizes of watt - hour meters**

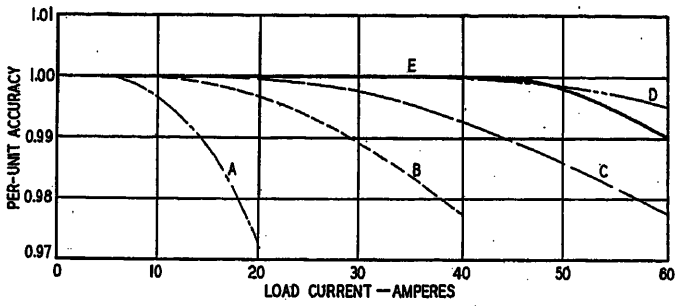



**Fig. 5. Heavy-load curves of the new domestic watt-hour meter and the superseded type of meters at unity power factor**

*A*, *B*, *C*, and *D*—Superseded type, rated at 5, 10, 15, and 25 amperes, respectively
*E*—New domestic meter

scheme, the useful potential flux through sections *A*—*A*, figure 1, works below the point of maximum permeability in the iron and is operated in parallel with the shunt path at section *B*—*B* which works above the point of maximum permeability.

## The Load Curve

The factors which determine the shape of the speed-load or meter-accuracy curve, some of which have been previously published,[4] may be divided into 2 classes: (1) those that are significant in affecting the light load performance and (2) those that have the most influence on heavy load performance. These factors include:

1. Ratio of friction to load torque.
2. Variation of iron permeability.
3. Variation of torque due to anticreep holes.

These factors affect light-load performance.

4. Damping effect of current flux.
5. Torque due to load current alone.

These factors affect heavy-load performance.

These 5 factors are the inherent factors in any meter that determine the load curve. A sixth factor which is a powerful tool to correct for error is load compensation which will be considered later in this paper.

*Friction.* Friction largely determines the reliability of sustained performance and its presence is the principal reason for a high driving torque which minimizes the effect of the friction torque. Friction is essentially constant in value at light loads where it is significant and provides a constant retarding torque which, unless compensated, will cause a drooping characteristic in the registration curve as light load is approached from nominal load. In a meter, this retarding torque is balanced by the light-load adjustment torque. At normal voltage, the 2 torques cancel and the shape of the load curve is not affected. It is very desirable to keep the total friction

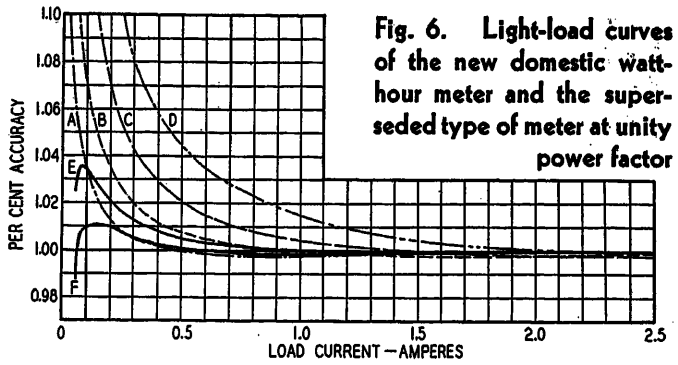



**Fig. 6. Light-load curves of the new domestic watt-hour meter and the superseded type of meter at unity power factor**

*A*, *B*, *C*, and *D*—Superseded type, rated at 5, 10, 15, and 25 amperes, respectively
*E*—New domestic meter calibrated at 10 per cent of nominal load
*F*—New domestic meter calibrated at 5 per cent of nominal load

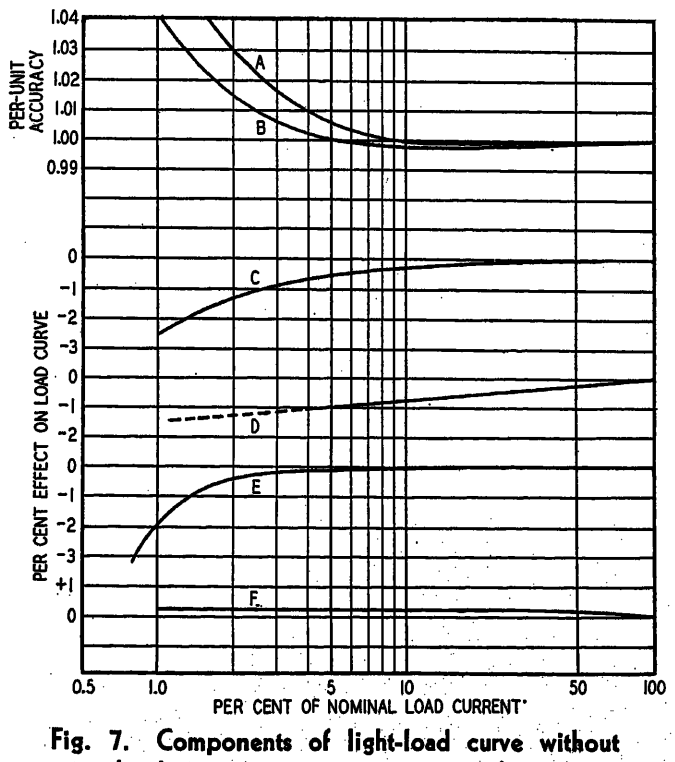



**Fig. 7. Components of light-load curve without load compensation at unity power factor**

*A*—Load curve, calibrated at 10 per cent of nominal load
*B*—Load curve, calibrated at 5 per cent of nominal load
*C*—Friction
*D*—Iron
*E*—Anticreep holes
*F*—Current damping

torque low in order to decrease variations and to reduce the compensation required. With latest improvements in bearing design which have been described recently,[5] the total bearing and register friction as measured[6] is approximately 0.013 gram-millimeter. With a nominal load torque of 52 gram-millimeters, the friction represents only 0.25 per cent of the torque at 10 per cent nominal load. In the earlier days of the metering art, friction was a greater limitation, and the introduction of high-torque meters was a significant advance. Further refinements in bearings which give long life and low friction have reduced the effect of friction until other factors at light load are equally or more important.

*Iron Permeability.* With iron in the element magnetic circuit, the current flux is usually more than proportional to the load current. This is due to the fact that in most designs the current flux magnetic circuit operates below the point of maximum permeability. The effect on the load curve is often confused with friction since the effect of the permeability change is also a drooping characteristic as light load is approached, unless it is corrected by means

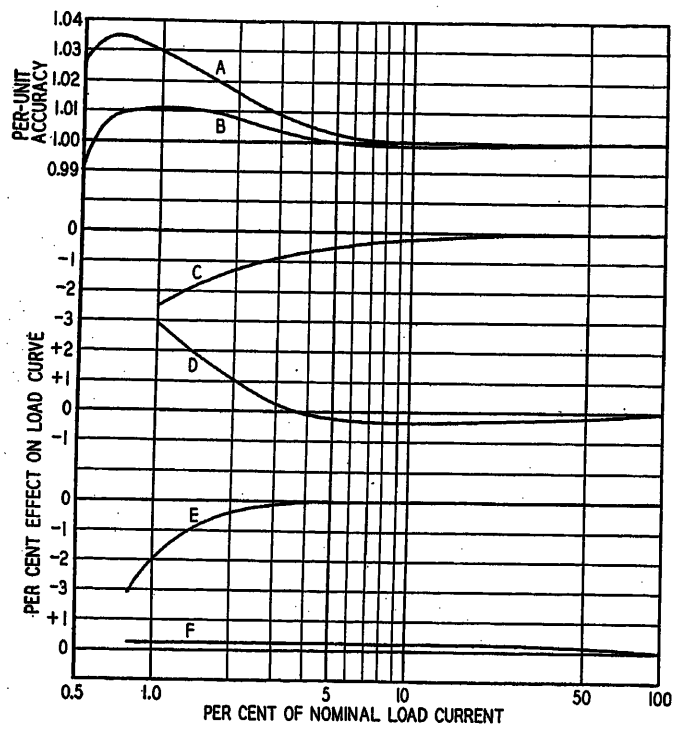


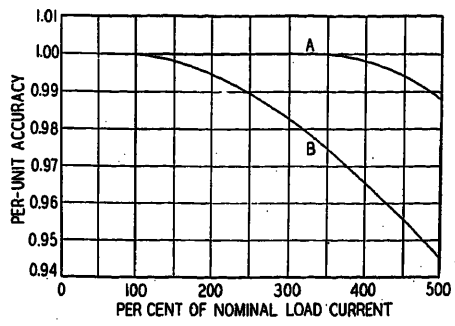

**Fig. 8. Components of light-load curve with load compensation at unity power factor**

*A*—Load curve, calibrated at 10 per cent of nominal load
*B*—Load curve, calibrated at 5 per cent of nominal load
*C*—Friction
*D*—Iron
*E*—Anticreep holes
*F*—Current damping

of the light-load compensation. Usually the compensation required at 10 per cent nominal load, the usual calibration point, is more than that required at smaller loads so the net result is a rising load curve below 10 per cent nominal load. The effect of the iron can be minimized by the proper choice of magnetic sections, the use of high-

**Fig. 9. Heavy-load curves, with and without load compensation, at unity power factor**

*A*—Compensated
*B*—Uncompensated




permeability iron, and by using a large main air gap with a large number of ampere-turns in the current coils.

*Anticreep Holes.* The anticreep holes in the disk reacting with the potential flux cause a small locking torque which must be overcome by load torque due to both current and potential flux before the meter will start. It is in this manner that the anticreep holes keep the disk from rotating when there is no load current flowing even though the light-load compensation torque has an average positive value. At loads just above starting, the meter speed varies due to the anticreep holes and the variation causes the average meter speed to be lower than it would be without the holes. This influence is present to a significant extent only at loads below 5 per cent of nominal rating. It may be considered beneficial because it he ps to correct for the effect of iron permeability variation.

*Current Flux Damping Torque.* The presence of the current flux damping torque has been explained with the analysis of the element driving and damping torques. The current flux damping torque is the largest cause of heavy load errors. For any design, this error is approximately proportional to the square of the load current since the current damping torque increases as $(\phi_i'^2)$ and $\omega$ whereas the load torque is proportional to $\phi_i'$. Meter speed $\omega$ is proportional to $\phi_i'$ neglecting the meter error. There has been much progress in design to decrease this inherent error. In early meters, the error at 400 per cent nominal load amounted to as much as 12 per cent, thus limiting the load range for acceptable accuracy within 150 per cent of nominal rating. This error at 400 per cent nominal load had been reduced to less than 2.7 per cent by the year 1927.[6] This was accomplished by designing a meter element to make the best known possible use of the a-c fluxes as regards driving and damping torques, by using a high useful potential flux and a low useful current flux, and by using a strong permanent magnet and a low meter speed. This design gave very good performance without the use of heavy load compensation, giving satisfactory operation up to 300 per cent nominal load and still retaining good operation at light loads.

*Current Torque.* It is well known by designers and has been experimentally determined that when there is an unbalance in the current flux magnetic circuit caused by having more turns on one current pole than on the other, there will be a driving torque generated in the disk due to the current flux alone. By making the proper pole have the greater number of turns, this torque will be

forward and will tend to correct for heavy load droop. This effect may amount to as much as 1 per cent at 400 per cent nominal load with a 2 to 1 unbalance. This torque is present at all power factors so that it is proportionately more effective at the lower power factors. This feature is usually not desirable, particularly when heavy load compensation is used. In this case, the compensation is designed to be satisfactory at unity power factor so that with the current circuit unbalance the compensation will be too great at lower power factors and the meter will run fast.

### Potential and Current Flux Circuits

The design of the current flux circuit is determined largely by the ampere-turns desired, the ratings in which a line of meters must be manufactured, and the space limitations. Provision must be made to include sufficient section so that temperature rise will be small, and the coils must be insulated for abnormal voltages. These features, with a consideration of the driving and damping constants, establish the current pole shapes and the current coil designs.

The potential coil and core must provide useful flux at a phase angle not far from quadrature with the applied voltage. The design problem is to provide sufficient sections so that the watts loss is low. Furthermore, the ratio of resistance to reactance must be as small as possible. This is helped by using a coil of small mean length of turn and a good space factor. The number of potential coil turns should be low, calling for potential air gaps of small reluctance. This takes loss from the copper and places it in the iron where it is not so effective in determining the inherent lagging angle.

### Temperature Errors

The causes of temperature errors have been considered by Kinnard and Faus.[7] These errors are divided into 2 classes, depending upon their influence on the meter. These 2 classes are:

*Class* I. Those errors which affect all loads alike and which are equivalent to a change in magnet strength.

*Class* II. Those errors caused by a change in phase angle between the useful potential and current fluxes. These errors appear only at lower power factors.

The common method of class I temperature compensation is that described in the paper referred to, in which a material having a negative permeability-temperature characteristic is used to shunt some of the permanent magnet flux. With increases in temperature, the shunt is less effective and the magnet damping strength is held within desired limits. Much research has been undertaken since 1925 to extend the range of compensation to wider temperature differences.

Class II errors should first be minimized by designing with a small inherent lagging angle. The error can be reduced by using lag plates and lag coils of low resistivity-temperature coefficient materials. A common method of compensation, described by Brooks,[8] is to overlag the useful potential flux with a low-coefficient material and then correspondingly lag the useful current flux with a high-coefficient material. With the proper balance, the phase angle will remain unchanged with change in temperature. This method has its disadvantages because it introduces additional watts loss and in some cases makes the low power factor operation poor. A more successful method of class II compensation is described later in this paper.

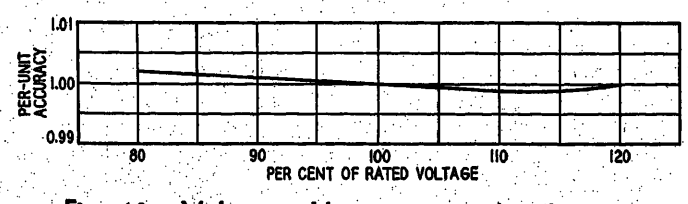



**Fig. 10. Voltage calibration curve for the new domestic watt-hour meter**

## Consideration of a Specific Design

### Inherent Accuracy

The real criterion of any meter is its performance, but the reasons for all characteristic curves are related with the above factors affecting meter performance. A fundamental method of comparison and analysis is to prepare a table listing the major design constants for any design. The choice of any design is then very straightforward, for the various factors can be weighed in their true sense. In developing the meter described below, many samples were tested and analyzed. All designs were compared by listing the characteristic constants as

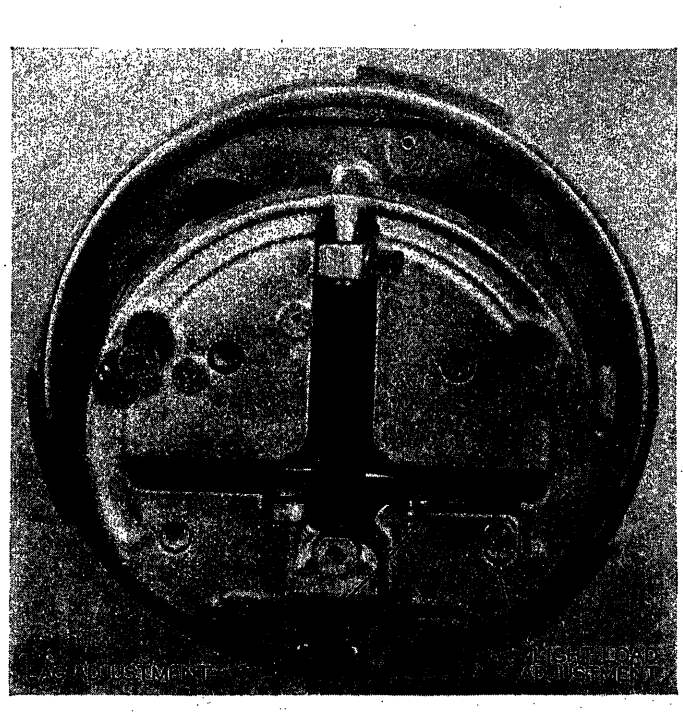


**Fig. 11. Interior view of the new domestic watt-hour meter, showing the light-load and lag adjustments mounted on the frame**

shown in table I, which in this instance includes only the data for the design finally chosen.

Table I shows the inherent errors of the latest design to be small without compensation. It was found that better and more consistent operation was obtained by thus reducing inherent errors and applying a minimum amount of compensation.

Sufficient amounts of flux and a large driving constant result in a high torque-to-weight ratio. It was necessary to keep the watts loss down to a reasonable value in deciding on flux values.

The slow meter speed and the small damping constants $G_i$ and $G_e$ result in small inherent errors for abnormal

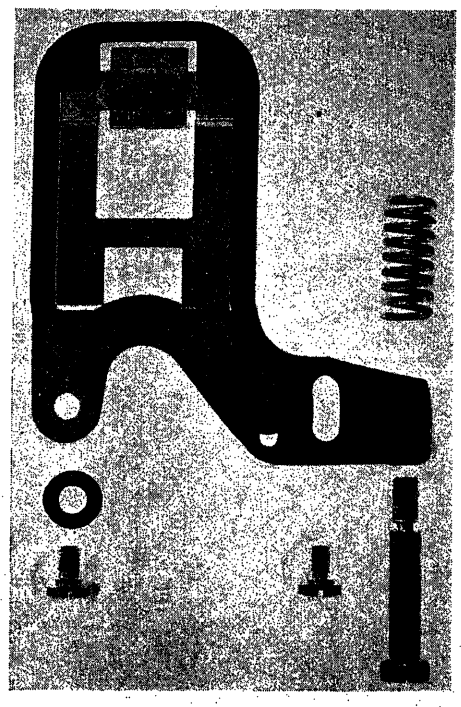


**Fig. 12. Lag plate and support, showing class II temperature-compensating device**

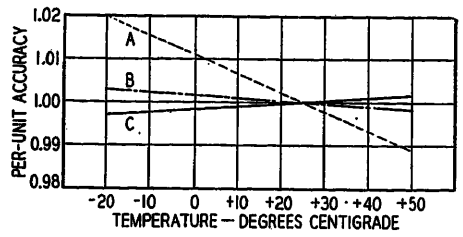
voltages and heavy loads. Improved compensations then result in negligible resultant errors due to voltage and temperature variations and permit a much longer load range than before possible.

The choice of current circuit ampere-turns is limited on the low side by the required flux and necessary air gap; it is limited on the high side by the same factors, also heating and volt-ampere burden. The number within this range found to be most suitable for all ratings was 100. This number makes it possible to use an equal number of turns on each current pole on one iron structure for all ratings, 2-wire and 3-wire. This insures most consistent performance and simplifies manufacture and stocking due to having only one iron structure, magnet strength, and adjustment mechanism with which to deal.

## Ratings

Figure 3 shows the complete assembled element. Form-wound current coils are used and are readily placed on the current poles. Figure 4 shows the laminations and the load shunt and spacer which are securely attached to the

**Fig. 13. Temperature calibration curve for the new domestic watt-hour meter**




*A*—Without temperature compensation at 0.5 lagging power factor

*B*—With temperature compensation at 0.5 lagging power factor

*C*—With temperature compensation at unity power factor

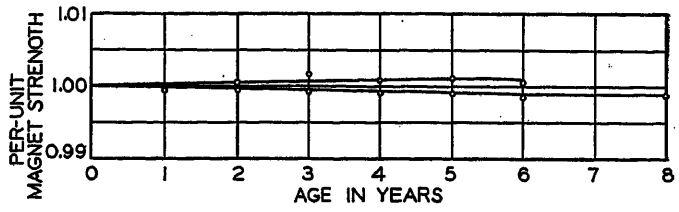



**Fig. 14. Typical aging curves for the magnet used in the new watt-hour meter**

current laminations and also serve to hold the current coils in place. Using this iron structure, 3 self-contained sizes are suggested: a long-range domestic meter, a long-range commercial meter, and a low-capacity meter.

The domestic meter is proposed for modern home loads, including the latest advances in lighting, appliances, cooking, refrigeration, and air conditioning. At the same time, this meter should measure small loads such as clocks and night lights. A 2-wire 115-volt meter of this type will start at 4 watts and will measure accurately loads up to 6,000 watts.

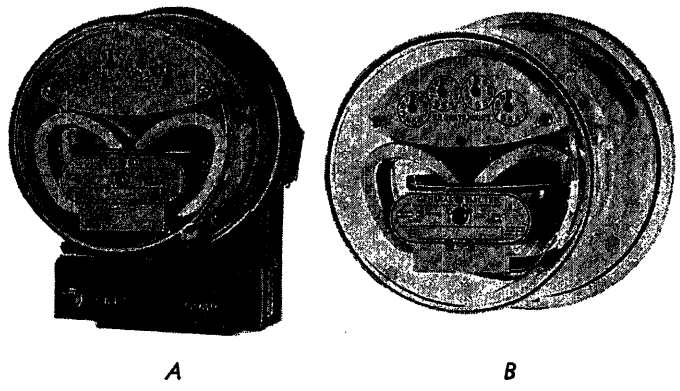
The commercial meter is intended to handle heavier loads. This meter will start at 16 watts and will measure loads accurately up to 150 amperes.

The low-capacity meter is proposed for use where small loads are of primary importance and provision for higher loads is not required.

It will be interesting to compare the performance of the domestic meter just described with existing meters rated 5, 10, 15, and 25 amperes, respectively. This is shown in figures 5 and 6 where meter accuracy is plotted as a function of load current. At heavy currents up to 60 amperes, the accuracy of the domestic meter is superior to that of any of the 3 lower ratings of the existing meter and about equal to that of the 25-ampere rating. At light loads, its accuracy is definitely superior to the 10-, 15-, and 25-ampere ratings. When the domestic meter is calibrated at 5 per cent nominal load, its performance is superior to the existing 5-ampere meter except from the standpoint of starting watts. Even when calibrated at 10 per cent nominal load, the performance is comparable.

Because of this long load range, the number of essential self-contained ratings required is reduced from 5 to 2. These 2 ratings, together with the proposed low-capacity meter, are shown in table II with the nominal and maximum

current ratings, the watt-hour constant, and the balanced current coil turns. The nominal rating corresponds to what has been known in the past as the full-load or name-plate rating. With improved heavy-load performance, the nominal rating represents only a calibration and reference point. The maximum rating is determined by accuracy and heating limitations so that it does have real significance. All 3 ratings have the same speed and



A B

**Fig. 15. Types of the new watt-hour meter**

*A*—Type *A* bottom-connected meter
*B*—Type *S* socket meter

torque obtained by the use of 100 ampere-turns in the current circuit at nominal load.

The domestic meter has a watt-hour constant of 1.5. This provides a good compromise between the 2 basic meter speed systems in general use today. Assuming all meters concerned to be 100 per cent accurate, a given even number of revolutions of this domestic meter corresponds to integral numbers of revolutions of all watt-hour meter standards now in production. Other possible constants do not have this desirable feature.

### The Load Curve

The load shunt not only compensates for heavy load droop but also improves the performance at light loads. Figure 7 shows the light-load curve and the relative values of all the factors comprising it when no compensation is used. These curves are plotted on a semilogarithmic scale in order to expand the extremely light load portions. As described previously the curve rises at light loads due to the effect of the iron.

When the load shunt is applied, figure 8, the droop due to the iron is reduced because the shunt was designed so that its permeability decreases with decrease in load from the nominal rating. This reduces the light-load compensation necessary for correct calibration and the resulting load curve is accurate to lower values.

At heavy loads, compensation for the droop is accomplished as a result of the load shunt approaching saturation so that the current flux is more than proportional to load current. Figure 9 shows the compensated and uncompensated heavy-load curves at unity power factor. The use of balanced ampere-turns on the current poles and the particular design of load shunt result in equivalent performance at low power factors.

**Table I—Analysis Chart of a Watt-Hour Meter**

| Quantity* | Symbol | Unit | Value |
|---|---|---|---|
| Rated voltage | $V$ | volts | 115 |
| Nominal current | $I$ | amperes | 12.5 |
| Frequency | $f$ | cycles per second | 60 |
| Watt-hour per revolution | $K$ | | 1.5 |
| Speed at nominal load | $\omega$ | radians per second | 1.672 |
| Disk diameter | $D$ | inches | 3.5 |
| Disk thickness | $t$ | inches | 0.027 |
| Disk thickness | $t$ | centimeters | 0.0686 |
| Disk weight | $W$ | grams | 13.3 |
| Torque at nominal load | $T$ | gram-millimeters | 52.5 |
| Torque-to-weight ratio | $T/W$ | | 3.95 |
| Friction constant† | $\frac{T}{W^{4/3}}$ | | 1.67 |
| Potential coil turns | $N_e$ | turns | 2,400 |
| Exciting current | $I_e$ | amperes | 0.095 |
| Potential coil resistance | $R_e$ | ohms | 58 |
| Out-of-phase voltage | $I_eR_e$ | volts | 5.5 |
| Potential watts loss | $W_eL$ | watts | 1.25 |
| Potential ampere-turns | $N_eI_e$ | | 228 |
| Total potential flux | $\phi_e$ | maxwells | 12,700 |
| Useful potential flux | $\phi_e'$ | maxwells | 2,490 |
| Current ampere-turns | $A.T.$ | | 100 |
| Useful current flux | $\varphi_i'$ | maxwells | 495 |
| Current damping torque at nominal load | $T_i$ | gram-millimeters | 0.130 |
| Potential damping torque at nominal load | $T_e$ | gram-millimeters | 1.17 |
| Driving constant | $G_d$ | | 0.227 |
| Current damping constant | $G_i$ | | 1.28 |
| Potential damping constant | $G_e$ | | 0.455 |
| Inherent droop at 400 per cent nominal load** | $R$ | per cent | 3.55 |
| Inherent voltage error at 120 per cent rated voltage‡ | $S$ | per cent | 0.98 |
| | $G_i/G_d$ | | 5.63 |
| | $G_e/G_d$ | | 2.00 |

* Unless otherwise indicated values are given for nominal load.
† Goss[9] has shown friction to vary as $(W)^{4/3}$.

** $R = 100\,\frac{15\,T_i/T}{1 + 15\,T_i/T}$

‡ $S = 100\left(\frac{(1.2)^2 T_e}{1.2T} - \frac{T_e}{T}\right) = 44.4\frac{T_e}{T}$

**Table II—Self-Contained Ratings**

| Meter | Nominal Rating, Amperes | Maximum Rating, K (115 Amperes Volts) | Turns on Current Poles: Right | Left | Total | Nominal Ampere-Turns |
|---|---|---|---|---|---|---|
| Commercial | 50 | 150 | 6.0 | 1 | 1 | 2 | 100 |
| Domestic | 12.5 | 60 | 1.5 | 4 | 4 | 8 | 100 |
| Low capacity | 5 | 20 | 0.6 | 10 | 10 | 20 | 100 |

### The Voltage Curve

The inherent voltage error at 120 per cent of rated voltage is shown in table I to be 0.98 per cent. As previously described, this error can be compensated for effectively by the use of the proper sections at *B*—*B* and *A*—*A* in the magnetic circuit (figure 4). The resulting voltage curve obtained is shown in figure 10. It was found possible to reduce the actual error to less than 0.2 per cent for 40 per cent voltage range.

### Light-Load and Lag Adjustment

The most straightforward and effective method of providing light-load and lag adjustment in this design was found to be modification of a mechanism already in general use, as shown in figures 11 and 12. The lag

plate is supported in the proper position by a bracket made of high-resistivity alloy. For light-load adjustment, this support is rotated by the light-load adjusting screw. A spring mounted on this screw between the lag plate support and the frame prevents backlash. The lag adjustment is accomplished by moving the lag plate radially with respect to the disk.

### Temperature Compensation

Class II temperature compensation is accomplished by a novel method proposed by Faus.[10] The lag plate is made with a small core linking it, composed of a material having a negative permeability-temperature characteristic similar to that used for magnet compensation. This core imposes an impedance in the lag circuit which becomes less effective with increases in temperature so that the lag plate becomes more effective. In this manner, the necessary increase in lagging is obtained to compensate for the shift in flux angles. Figure 13 shows the resulting temperature curves with both class I and class II compensation. Improvements in characteristics of the temperature-sensitive material has made possible more effective compensation of class I errors.

### Control Magnet

The control or damping magnet is of standard construction that has been used for many years. It is designed to give a high braking torque, making possible the slow meter speed which is so desirable for improved accuracy and a long load range. Magnets of this form are unusually stable. Figure 14 shows typical aging curves on 2 groups of magnets over periods of 6 and 8 years, respectively. At no time does the strength vary more than 0.2 per cent from the initial value.

## Summary


1. It is shown that fundamental analysis of meter theory can be used effectively in meter design and provides a basis of accurate comparison of inherent characteristics.
2. Emphasis is laid on the importance of minimizing the inherent errors, thereby reducing the magnitude of the required compensations. This results in improved accuracy and more consistent performance.
3. Slow meter speeds are desirable from the standpoint of higher accuracies and greater suitability for operation over a long load range.
4. The meter described with long range performance reduces the number of ratings required. It also provides for growth of load without sacrificing light load accuracy.
5. An improved temperature compensation is described which insures accurate registration under conditions of extreme temperature variations.
6. With improved performance, "full load" has lost its significance and should be replaced by a "nominal" and "maximum" rating. Nominal rating aids in comparisons and in calibration, but a maximum rating, corresponding to both accuracy and thermal limits, is the real criterion of a meter's capacity.


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# Synchronous Machines With Solid Cylindrical Rotor

(*Continued from page 58*)

By equation 22, assuming that $e_r$ also varies as $e^{pt}$, we obtain the rotor-coil equation:

$$RI_r = e_r + Zk\int_0^e A_1 \cos ax\, E_r(x)dx = e_r - \frac{Kp\left[I_r A_1^2 \cosh ag + \frac{3}{2}A_1B_1(De^{-j\gamma} + D'e^{j\gamma})\right]}{a(q\cosh ag + \sinh ag)} \quad (52)$$

where

$$q = \frac{\beta}{\mu a}\left[p + \left(\frac{a}{\beta}\right)^2\right]^{\frac{1}{2}},\ K = 2\pi 10^{-9} Z l k$$

Similarly by equation 24, the voltage equation of stator coil $a$ is

$$r_s I_a = e_a + Zk\int_0^l B_1 \cos ax_1 E_s(x_1)dx_1 = Ce^{j\omega t} + C'e^{-j\omega t} + e_0 - \frac{K}{a(q\cosh ag + \sinh ag)}\left\{\frac{1}{2}I_r A_1 B_1[(p + j\omega)e^{j(\omega t+\gamma)} + (p - j\omega)e^{-j(\omega t+\gamma)}] + \frac{3}{2}B_1^2[D(p + j\omega)e^{j\omega t} + D'(p - j\omega)e^{-j\omega t}][\cosh ag + q\sinh ag]\right\} = r_s(De^{j\omega t} + D'e^{-j\omega t} + i_0) \quad (53)$$

Equation 53 is seen to be composed of 3 components, constant terms, terms containing $e^{j\omega t}$ as a factor, and terms containing $e^{-j\omega t}$ as a factor. By combining this equation with 2 similar equations for coils $b$ and $c$ it may be separated into its 3 component equations. Thus from equations 49 and 53 are formed the 4 final equations 30 given in the body of the paper.

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# A New Service Restorer

By E. F. SIXTUS ASSOCIATE  W. R. NODDER NONMEMBER

**Equipment capable of restoring service automatically after temporary interruptions on transmission and distribution systems has been developed to a high degree of effectiveness; however, most of such equipment is suitable only for systems of high capacity, and comparatively little attention has been given to systems of low and intermediate capacities. An automatic service restorer, designed primarily for use on systems of low capacity, is described in this paper, and some data on its operating characteristics are presented.**

IN RECENT years there has been an increasing demand on the part of operating companies for equipment capable of automatically restoring service after interruptions due to momentary or self-clearing faults on transmission and distribution systems. Where protective equipment of high interrupting capacity is involved, this demand has been met by the use of the conventional oil circuit breaker in conjunction with protective relays and an adjustable timing relay to control the reclosing cycle. This equipment has been developed to such an extent that immediate reclosing breakers, capable of reclosing so quickly that in most cases service will be restored before synchronous motors can fall out of step, are now available for use on systems as high as 115,000 volts.

Up to the present time little has been done to extend the line of automatic reclosing breakers to the lower capacities, due mainly to the fact that the cost of such equipment could not be justified in the low-revenue field where it would be applied. The 7,500-volt breaker with an interrupting capacity of 50,000 kva has so far set the lower limit at which the conventional reclosing equipment has been economically feasible for outdoor service.

A study of outages on rural distribution systems has shown that from 75 to 90 per cent of the faults are momentary and self-clearing, but will blow a fuse and thereby cause a long power outage. It is evident, therefore, that a low-capacity automatic-reclosing breaker, if used in place of fuses, would result in a great improvement in service. Reclosing fuses have, of course, been available but they cannot be expected to give service equivalent to an enclosed high-speed reclosing breaker.

To be completely successful a breaker to fill this low-capacity requirement must have certain very definite characteristics:

1. It must be low in cost—considerably lower than the conventional reclosing breakers now on the market. It must be simple to install, to keep the labor and cost of installation at a minimum.
2. It must be simple to operate, so that it can be opened, closed or reset by an inexperienced person and thus save trained power company employees from making long trips to isolated installations.
3. It must be suitable for outdoor service and for pole mounting.
4. It must provide dependable overload and short circuit protection under all weather conditions with very little maintenance.
5. It should provide at least 3 automatic reclosures with the first reclosure immediate if so desired.
6. It should be multipole with all poles opening simultaneously to prevent single phase operation of three phase equipment.
7. It should trip on extremely low currents, about 10 amperes minimum, to provide dependable overload protection for lightly loaded lines.

After giving careful consideration to the above requirements it was decided that conventional designs must be discarded and it was on this basis that the type *AP*-1 automatic service restorer illustrated in figure 1 was developed.

One of the first problems to be solved in the design of the device was that of securing power to provide 3 automatic reclosures. Two types of control were considered; one where the operating power is derived from a relatively inexhaustible source such as an auxiliary battery and charger unit, or the line voltage or current itself; and the other where the actuating power is derived from an exhaustible source such as a spring.

If an inexhaustible power supply were used it would be necessary for an attendant to visit the switch every time it locked open for the purpose of resetting the lockout mechanism. Assuming that 75 per cent of the shorts are self clearing, the device would lock out and require the service of an attendant after every 4 short circuits.

With an exhaustible power supply, such as a spring that could be wound to provide sufficient energy for 4 openings and 3 reclosures, the attendant would be required to reset the lockout mechanism after every lockout as above and in addition would be required to restore the energy in the spring after every 4 shorts which were cleared, because the spring would be completely unwound. This would result, let us assume, in the attendant making twice as many trips to a device with a spring type of power supply as to one with an inexhaustible power supply. It is possible, of course, that a carrier current control could be used in lieu of an attendant to reset the lockout mechanism, although such an arrangement does not seem economically advisable at present.

The inexhaustible power supply could be provided by:

1. The use of a potential transformer placed in the tank of the device and connected to a small motor arranged to rewind an operating spring and keep it wound at all times.
2. The use of some sort of capacitance device in place of the potential transformer to supply energy to the rewinding motor. The out-

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put of such a device would necessarily be small but rewinding could be accomplished over a relatively long period of time, as the spring could be designed to provide enough energy for 4 openings without rewinding.

3. The use of a falling weight heavy enough to provide energy for a large number of operations, possibly 20 or 30.

4. Using the short-circuit current, which causes the device to trip, to store sufficient energy for the next closing and opening operation.

In the design of the type *AP*-1 the first 2 methods listed above were discarded because they added materially to the cost of the device, and it was felt that the increased expense would not be justified in the majority of installations. The third alternative, that of using the falling weight was considered impractical and was not used because of the probable unfavorable reception such construction would receive from prospective users of the device. The fourth idea, that of using the short-circuit current to provide energy for closing and reopening the circuit, was not considered favorable because of the high current required to trip a device of this kind; a low tripping current being one of the requisites of the design.

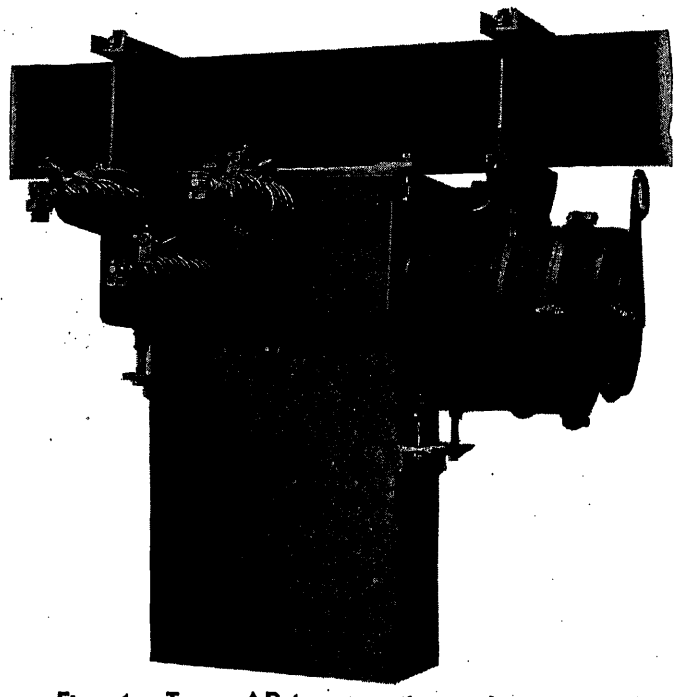


**Fig. 1. Type AP-1 automatic service restorer, 7,500/12,500 Y volts**

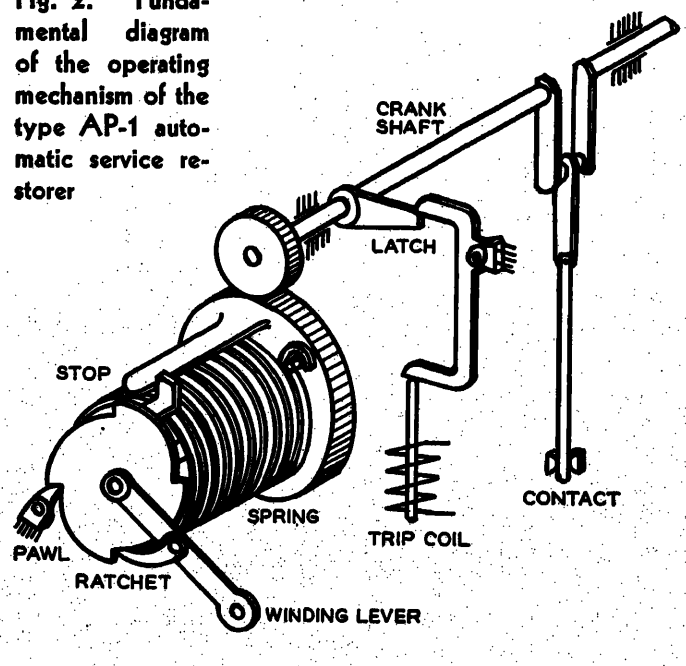



**Fig. 2. Fundamental diagram of the operating mechanism of the type AP-1 automatic service restorer**

In view of the disadvantages of the inexhaustible power supply as applied to this particular device, the *AP*-1 was designed to use, as an operating mechanism, a manually wound spring which when fully wound, would store enough energy to give 3 closing and 4 opening operations. A helical twist spring was selected because its unidirectional motion was most easily adapted to the reciprocating motion of the switch blades. In actual construction one end of the spring is connected to a rewinding lever and the other, through a 4-to-1 reduction gear, to a crankshaft to which the blades are connected. See figure 2. The 4-to-1 reduction gear is used so that a $^1/_4$ turn on the rewinding lever will rewind the spring sufficiently for one reclosing cycle and a dial has been added to indicate to what extent the spring is wound. A stop is provided to hold the contacts in the open position upon completion of the last opening stroke.

The crankshaft is fitted with a latch plate engaging a latch to hold the breaker closed with the spring wound. This latch, which is actuated by a series trip coil in each pole, is released on overload permitting the contacts to open at high speed under the action of the helical spring. There being no latch to hold the switch open, it recloses and remains closed until the latch is again released by one of the trip coils, except in the case of the last opening when it locks in the open position.

In order to provide a timing mechanism to control the reclosing interval a special dashpot was developed. Upon attempting to determine the reclosing interval to use it was found that prospective users required different reclosing cycles. Some required an immediate first reclosure and others 3 reclosures at equal time intervals. In order to give the device as wide an application as possible the dashpot was designed so that it could be set to provide either 3 reclosures at an adjustable time interval, or one immediate reclosure with 2 additional reclosures at an adjustable time interval. In each case the reclosing interval is adjustable from 1 to 10 seconds.

The design of the arc-rupturing chamber for such a low interrupting capacity

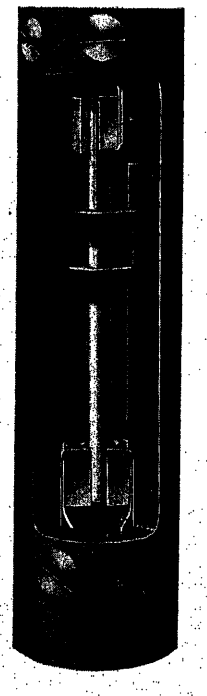


**Fig. 3. Cross-sectional view of expulsion contact chamber of the automatic service restorer**

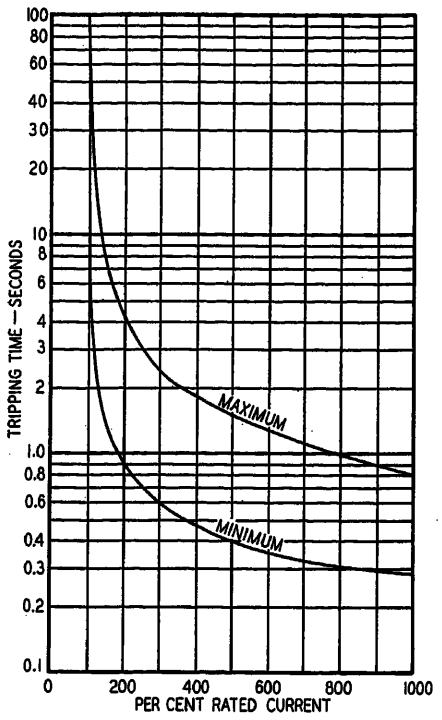



**Fig. 4. Time-current curves of delayed trip attachment**

device presented no problem, as previous papers have demonstrated the ability of the expulsion chamber contact to easily interrupt currents both greater and smaller than those required in this instance. The contact design used is shown in cross section in figure 3. It consists essentially of a moving blade engaging with high-pressure full-floating stationary contacts and separating at high speed in an enclosed chamber provided with baffles and vents to secure the most efficient arc extinguishing action.

The continuous current rating of the service restorer was set at 100 amperes in order to include the full current range normally covered by fuses. It was felt inadvisable to provide for larger currents because of the desire to keep the dimensions as small as possible and because investigation indicated that a 100-ampere capacity would be ample for most applications.

Consideration was, of course, given in the design to the need for co-ordinating the series trip coils with the blowing characteristics of fuses and the time current characteristics of oil circuit breaker relays. Trip coils for instantaneous and inverse time delay action have been developed. Instantaneous coils are provided with current adjustments so that they can be adjusted to operate at either 100, 150, or 200 per cent of the coil rating. Time-delay coils are provided with current and time adjustments, the characteristics of which are shown in figure 4.

Extensive tests were performed on the service restorer to verify its assigned interrupting rating of 1,200 amperes at 12,500 volts. Typical results are shown in figure 5.

Film *A* shows the performance during 2 interruptions of 1,780 amperes with 2,600 volts across the terminals. The total fault time in the first case is 7.0 cycles and in the second 7.4 cycles.

(*Concluded on page 152*)

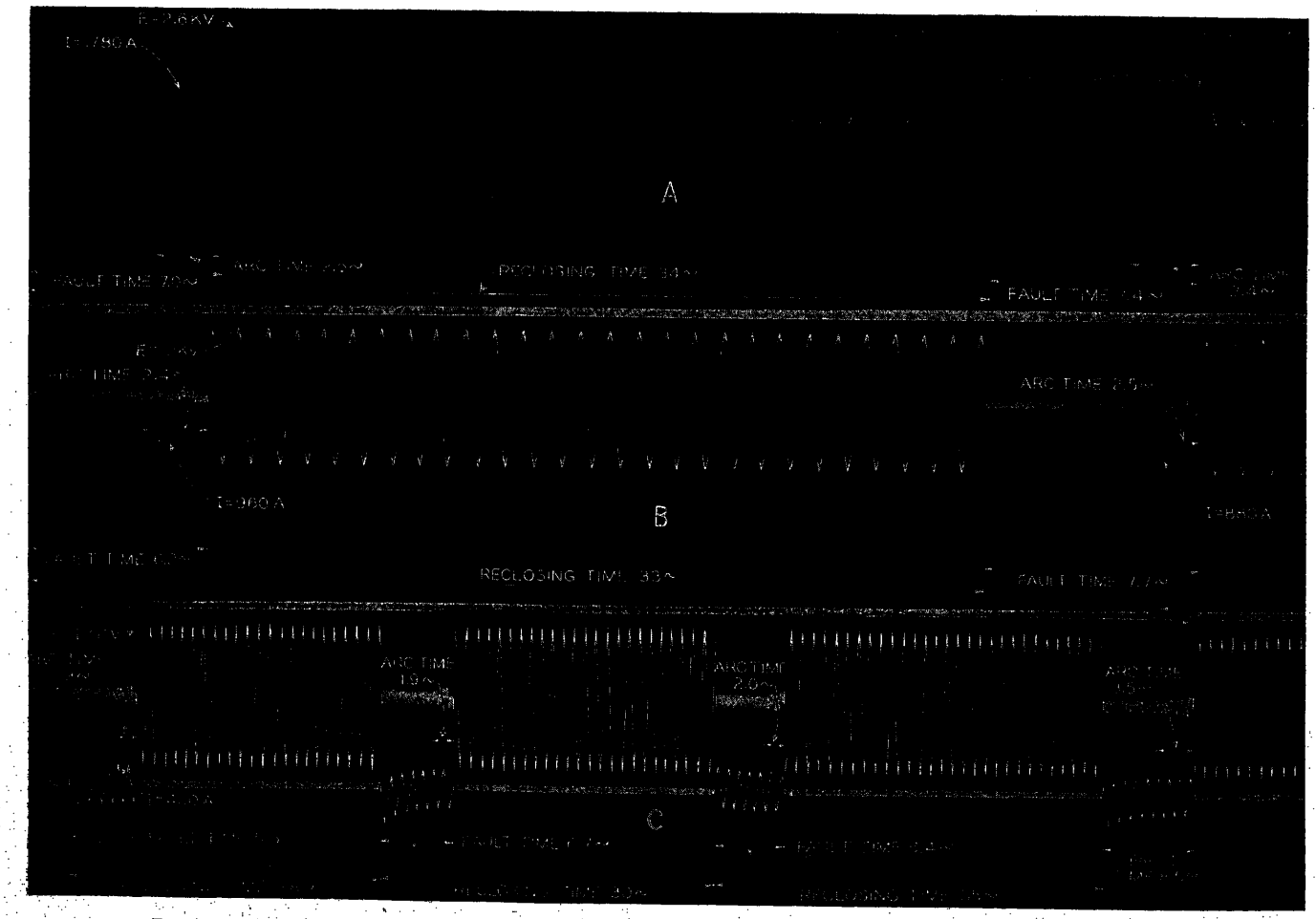



**Fig. 5. Typical oscillographic records of the operation of the type AP-1 automatic service restorer**

# Impulse-Generator Voltage Charts for Selecting Circuit Constants

By J. L. THOMASON
ASSOCIATE AIEE

**It is suggested in this paper that impulse generator voltage waves for commercial testing may be compared not only on the basis of wave shape but also on the basis of relations between circuit constants. The charts and graphs included are intended to show how desirable this is, and they may be used to facilitate both front-of-wave and full-wave testing.**

PREVIOUSLY published articles[1-6] have indicated the need of an accurate method of comparing impulse voltage waves, and although it has already been recommended[1] that impulse voltage waves be designated by the "2 point" method, that is, 1.5x40, a considerable range for wave shape variation is possible even if it is specified that the wave is smooth. It seems desirable therefore in those cases where more accurate determination of wave shape is required to specify the generator circuit constants and to compare the wave shapes on some definite basis such as on a basis of ratios between the different circuit constants as presented here.

There are numerous impulse-generator circuits, each having its merits, which will produce desirable voltage test waves. However, to escape the use of a multiplicity of circuits it seems desirable to use one or 2 circuits. Then the small differences and oddities in waves produced by the different circuits can be eliminated, theoretically at least, in comparing test results.

## Circuits Analyzed

In this paper only 2 impulse-generator circuits are considered, figures 1 and 2. Such circuits of the impulse generator are well enough known and are in such common use that they need only a brief explanation. Referring[7] to figure 2, $C_1$ is the generator capacitance, $L_1$ is the total series inductance, $R_1$ is the total series resistance, $R_2$ is the shunt resistance, and $C_2$ is the total load capacitance. These constants are basic in the impulse generator circuit, and although in an actual generator they may be distributed and have mutual effects on each other, for the purpose of this paper they alone are considered. This circuit of figure 2 is recommended as basic by the International Electrochemical Commission.[6]

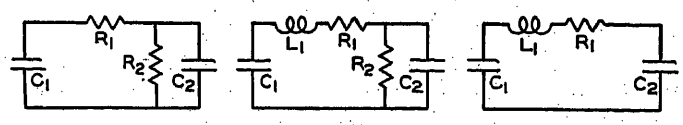
In the first circuit, figure 1, the inductance is considered negligible.

In the second circuit, figure 2, the inductance is considered and in the calculations is made of such value that neglecting $R_2$ as in figure 3 the series resistance $R_1$ will just damp out oscillations. That is, the critical resistance is $R_1^2 = 4L_1/C$, or transposing, $L_1 = R_1^2C/4$, where $C = (C_1C_2)/(C_1 + C_2)$. By using this relation the oscillations are negligible (less than one per cent) at the crest. Thus using this relation between various circuit constants, the impulse generator applies to the test piece a voltage wave which has 3 desirable characteristics, considering that each is dependent upon the others:

1. A practically smooth wave
2. A minimum wave front
3. A maximum crest voltage

## Relationship Between Circuit Constants

In analyzing the circuits, the relationship of the constants is considered also from the point of practical importance. The available capacitance of the generator is frequently a limiting factor both theoretically and economically, and when oscillograms are taken the shunt resistance may frequently be the divider resistance only, so both $C_1$ and $R_2$ are limiting factors. In making the tests the relation of the load to the generator capacitance, $C_2/C_1$, as well as the relation of the series resistance to the shunt resistance, $R_1/R_2$, must be considered if the proper voltage and wave shape are to be applied to the test piece.




**Figs. 1–3. Schematic diagrams of impulse generator circuits**

## Calculated Charts

With these relationships in mind the characteristics of the voltage test waves applied to a capacitance load were calculated for a wide range of circuit constants in the 2 circuits and the characteristics were so expressed in the calculated charts, charts I and II. In chart I the impulse generator circuit of figure 1 is considered in which the inductance is made equal to zero. At the top of the chart $K_2$ shows the ratio between the load and generator ca-

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1. For all numbered references see list at end of paper.

## Chart I

| $K_1 = \frac{R_1}{R_2}$ | | $K_2 = C_2/C_1$ | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 0.00 | 0.01 | 0.02 | 0.04 | 0.10 | 0.20 | 0.40 | 1.00 | 2.00 | 4.00 | 10.00 |
| 0.00 | *F* | 0.00000... | 0.000000... | 0.00000... | 0.00000... | 0.00000... | 0.0000... | 0.0000... | 0.0000... | 0.0000... | 0.0000... | 0.0000 |
| | *D* | 0.693 ... | 0.700 ... | 0.707 ... | 0.721 ... | 0.762 ... | 0.832 ... | 0.970 ... | 1.39 ... | 2.08 ... | 3.46 ... | 7.62 |
| | *C* | 1.000 ... | 0.990 ... | 0.980 ... | 0.961 ... | 0.909 ... | 0.833 ... | 0.714 ... | 0.500 ... | 0.333 ... | 0.200 ... | 0.0909 |
| | *R* | 0.00000... | 0.00000 ... | 0.00000... | 0.00000... | 0.00000... | 0.0000... | 0.0000... | 0.0000... | 0.0000... | 0.0000... | 0.0000 |
| | *a* | 1.0000 ... | 0.9901 ... | 0.9804 ... | 0.9615 ... | 0.9091 ... | 0.8333... | 0.7143... | 0.5000... | 0.3333... | 0.2000... | 0.0909 |
| | *b* | OC ... | OC ... | OC ... | OC ... | OC ... | OC ... | OC ... | OC ... | OC ... | OC ... | OC |
| 0.01 | *F* | 0.00000... | 0.000908... | 0.00167... | 0.00302... | 0.00641... | 0.0109... | 0.0177... | 0.0299... | 0.0408... | 0.0516... | 0.0646 |
| | *D* | 0.700 ... | 0.708 ... | 0.715 ... | 0.731 ... | 0.776 ... | 0.850 ... | 0.995 ... | 1.40 ... | 2.13 ... | 3.53 ... | 7.70 |
| | *C* | 0.990 ... | 0.979 ... | 0.969 ... | 0.951 ... | 0.896 ... | 0.820 ... | 0.702 ... | 0.496 ... | 0.328 ... | 0.198 ... | 0.0903 |
| | *R* | 0.00000... | 0.00128 ... | 0.00233... | 0.00413... | 0.00826... | 0.0128... | 0.0178... | 0.0213... | 0.0192... | 0.0146... | 0.00840 |
| | *a* | 0.9901 ... | 0.9805 ... | 0.9711 ... | 0.9528 ... | 0.9017 ... | 0.8275... | 0.7106... | 0.4987... | 0.3330... | 0.1999... | 0.0909 |
| | *b* | OC ... | 10199.02 ... | 5149.03 ... | 2624.05 ... | 1109.10 ... | 604.17 ... | 351.79 ... | 200.50 ... | 150.17 ... | 125.05 ... | 110.01 |
| 0.02 | *F* | 0.00000... | 0.00167 ... | 0.00304... | 0.00547... | 0.0115 ... | 0.0195... | 0.0313... | 0.0531... | 0.0724... | 0.0921... | 0.117 |
| | *D* | 0.707 ... | 0.715 ... | 0.724 ... | 0.741 ... | 0.790 ... | 0.866 ... | 1.02 ... | 1.46 ... | 2.17 ... | 3.58 ... | 7.77 |
| | *C* | 0.980 ... | 0.969 ... | 0.960 ... | 0.939 ... | 0.885 ... | 0.809 ... | 0.692 ... | 0.484 ... | 0.325 ... | 0.196 ... | 0.0899 |
| | *R* | 0.00000... | 0.00233 ... | 0.00420... | 0.00738... | 0.0146 ... | 0.0225... | 0.0308... | 0.0364... | 0.0334... | 0.0258... | 0.0150 |
| | *a* | 0.9804 ... | 0.9711 ... | 0.9619 ... | 0.9441 ... | 0.8943 ... | 0.8219... | 0.7070... | 0.4975... | 0.3326... | 0.1998... | 0.0909 |
| | *b* | OC ... | 5149.03 ... | 2599.04 ... | 1324.05 ... | 559.106 ... | 304.18 ... | 176.08 ... | 100.50 ... | 75.167 ... | 62.550 ... | 55.009 |
| 0.04 | *F* | 0.00000... | 0.00302 ... | 0.00547... | 0.00979... | 0.0204 ... | 0.0342... | 0.0547... | 0.0925... | 0.126 ... | 0.162 ... | 0.208 |
| | *D* | 0.721 ... | 0.731 ... | 0.741 ... | 0.759 ... | 0.814 ... | 0.896 ... | 1.06 ... | 1.51 ... | 2.24 ... | 3.66 ... | 7.88 |
| | *C* | 0.961 ... | 0.951 ... | 0.939 ... | 0.919 ... | 0.864 ... | 0.789 ... | 0.672 ... | 0.473 ... | 0.318 ... | 0.193 ... | 0.0891 |
| | *R* | 0.00000... | 0.00413 ... | 0.00738... | 0.0129 ... | 0.0251 ... | 0.0381... | 0.0518... | 0.0612... | 0.0564... | 0.0445... | 0.0264 |
| | *a* | 0.9615 ... | 0.9528 ... | 0.9441 ... | 0.9272 ... | 0.8799 ... | 0.8107... | 0.6999... | 0.4950... | 0.3318... | 0.1998... | 0.0909 |
| | *b* | OC ... | 2624.05 ... | 1324.05 ... | 674.073 ... | 284.120 ... | 154.19 ... | 89.300 ... | 50.505 ... | 37.668 ... | 31.300 ... | 27.509 |
| 0.10 | *F* | 0.00000... | 0.00641 ... | 0.0115 ... | 0.0204 ... | 0.0419 ... | 0.0695... | 0.113 ... | 0.187 ... | 0.258 ... | 0.335 ... | 0.439 |
| | *D* | 0.762 ... | 0.776 ... | 0.790 ... | 0.814 ... | 0.878 ... | 0.974 ... | 1.16 ... | 1.65 ... | 2.43 ... | 3.89 ... | 8.18 |
| | *C* | 0.909 ... | 0.896 ... | 0.885 ... | 0.864 ... | 0.810 ... | 0.739 ... | 0.630 ... | 0.445 ... | 0.303 ... | 0.187 ... | 0.0872 |
| | *R* | 0.00000... | 0.00826 ... | 0.01461... | 0.0251 ... | 0.0477 ... | 0.0714... | 0.0974... | 0.113 ... | 0.106 ... | 0.0861... | 0.0537 |
| | *a* | 0.9091 ... | 0.9017 ... | 0.8943 ... | 0.8799 ... | 0.8390 ... | 0.7786... | 0.6790... | 0.4875... | 0.3296... | 0.1992... | 0.0908 |
| | *b* | OC ... | 1109.10 ... | 559.106 ... | 284.120 ... | 119.161 ... | 64.221 ... | 36.821 ... | 20.512 ... | 15.170 ... | 12.551 ... | 11.009 |
| 0.20 | *F* | 0.00000... | 0.0109 ... | 0.0195 ... | 0.0342 ... | 0.0695 ... | 0.115 ... | 0.182 ... | 0.308 ... | 0.430 ... | 0.566 ... | 0.758 |
| | *D* | 0.832 ... | 0.850 ... | 0.866 ... | 0.896 ... | 0.974 ... | 1.09 ... | 1.30 ... | 1.87 ... | 2.69 ... | 4.21 ... | 8.59 |
| | *C* | 0.833 ... | 0.820 ... | 0.809 ... | 0.789 ... | 0.739 ... | 0.671 .. | 0.574 ... | 0.410 ... | 0.284 ... | 0.178 ... | 0.0846 |
| | *R* | 0.00000... | 0.0128 ... | 0.0225 ... | 0.0381 ... | 0.0714 ... | 0.105 ... | 0.140 ... | 0.165 ... | 0.160 ... | 0.134 ... | 0.0882 |
| | *a* | 0.8333 ... | 0.8275 ... | 0.8219 ... | 0.8107 ... | 0.7786 ... | 0.7296... | 0.6459... | 0.4750... | 0.3258... | 0.1984... | 0.0908 |
| | *b* | OC ... | 604.1725 ... | 304.178 ... | 154.189 ... | 64.2214 ... | 34.270 ... | 19.354 ... | 10.525 ... | 7.6742... | 6.3016... | 5.5092 |
| 0.40 | *F* | 0.00000... | 0.0177 ... | 0.0313 ... | 0.0547 ... | 0.113 ... | 0.182 ... | 0.295 ... | 0.492 ... | 0.695 ... | 0.933 ... | 1.28 |
| | *D* | 0.970 ... | 0.995 ... | 1.02 ... | 1.06 ... | 1.16 ... | 1.30 ... | 1.71 ... | 2.22 ... | 3.15 ... | 4.79 ... | 9.29 |
| | *C* | 0.714 ... | 0.702 ... | 0.692 ... | 0.672 ... | 0.630 ... | 0.574 ... | 0.499 ... | 0.361 ... | 0.254 ... | 0.163 ... | 0.0807 |
| | *R* | 0.00000... | 0.0178 ... | 0.0308 ... | 0.0518 ... | 0.0974 ... | 0.140 ... | 0.172 ... | 0.222 ... | 0.221 ... | 0.195 ... | 0.138 |
| | *a* | 0.7143 ... | 0.7106 ... | 0.7070 ... | 0.6999 ... | 0.6790 ... | 0.6459... | 0.5244... | 0.4505... | 0.3179... | 0.1966... | 0.0906 |
| | *b* | OC ... | 351.7894 ... | 176.079 ... | 89.3001 ... | 36.8210 ... | 19.354 ... | 10.725 ... | 5.5495... | 3.9321... | 3.1783... | 2.7594 |
| 1.00 | *F* | 0.00000... | 0.0299 ... | 0.0531 ... | 0.0925 ... | 0.187 ... | 0.308 ... | 0.492 ... | 0.860 ... | 1.25 ... | 1.72 ... | 2.46 |
| | *D* | 1.39 ... | 1.40 ... | 1.46 ... | 1.51 ... | 1.65 ... | 1.87 ... | 2.22 ... | 3.06 ... | 4.25 ... | 6.16 ... | 11.1 |
| | *C* | 0.500 ... | 0.496 ... | 0.484 ... | 0.473 ... | 0.445 ... | 0.410 ... | 0.361 ... | 0.275 ... | 0.204 ... | 0.137 ... | 0.0721 |
| | *R* | 0.00000... | 0.0213 ... | 0.0364 ... | 0.0612 ... | 0.113 ... | 0.165 ... | 0.222 ... | 0.281 ... | 0.294 ... | 0.279 ... | 0.222 |
| | *a* | 0.5000 ... | 0.4987 ... | 0.4975 ... | 0.4950 ... | 0.4875 ... | 0.4750... | 0.4505... | 0.3820... | 0.2929... | 0.1910... | 0.0901 |
| | *b* | OC ... | 200.5012 ... | 100.502 ... | 50.5050 ... | 20.5125 ... | 10.525 ... | 5.5495... | 2.6180... | 1.7071... | 1.3090... | 1.1099 |
| 2.00 | *F* | 0.00000... | 0.0408 ... | 0.0724 ... | 0.126 ... | 0.258 ... | 0.430 ... | 0.695... | 1.25 ... | 1.85 ... | 2.62 ... | 3.89 |
| | *D* | 2.08 ... | 2.13 ... | 2.17 ... | 2.24 ... | 2.43 ... | 2.69 ... | 3.15 ... | 4.25 ... | 5.71 ... | 8.06 ... | 13.6 |
| | *C* | 0.333 ... | 0.328 ... | 0.325 ... | 0.318 ... | 0.303 ... | 0.284 ... | 0.254 ... | 0.204 ... | 0.158 ... | 0.112 ... | 0.0629 |
| | *R* | 0.00000.... | 0.0192 ... | 0.0334 ... | 0.0564 ... | 0.106 ... | 0.160 ... | 0.221 ... | 0.294 ... | 0.323 ... | 0.325 ... | 0.286 |
| | *a* | 0.3333 ... | 0.3330 ... | 0.3326 ... | 0.3318 ... | 0.3296 ... | 0.3258... | 0.3179... | 0.2929... | 0.2500... | 0.1798... | 0.0891 |
| | *b* | OC ... | 150.1670 ... | 75.1674 ... | 37.6682 ... | 15.1704 ... | 7.6742... | 3.9321... | 1.7071... | 1.0000... | 0.6952... | 0.5608 |
| 4.00 | *F* | 0.00000... | 0.0516 ... | 0.0921 ... | 0.162 ... | 0.335 ... | 0.5666... | 0.933 ... | 1.72 ... | 2.62 ... | 3.84 ... | 5.95 |
| | *D* | 3.46 ... | 3.53 ... | 3.58 ... | 3.66 ... | 3.89 ... | 4.21 ... | 4.79 ... | 6.16 ... | 8.06 ... | 11.0 ... | 17.7 |
| | *C* | 0.200 ... | 0.198 ... | 0.196 ... | 0.193 ... | 0.187 ... | 0.178 ... | 0.163 ... | 0.137 ... | 0.112 ... | 0.0849... | 0.0517 |
| | *R* | 0.00000... | 0.0146 ... | 0.0258 ... | 0.445 ... | 0.0861 ... | 0.134 ... | 0.195 ... | 0.279 ... | 0.325 ... | 0.349 ... | 0.336 |
| | *a* | 0.2000 ... | 0.1999 ... | 0.1998 ... | 0.1998 ... | 0.1992 ... | 0.1984... | 0.1966... | 0.1910 . | 0.1798... | 0.1524... | 0.0867 |
| | *b* | OC ... | 125.0501 ... | 62.5502 ... | 31.3002 ... | 12.5508 ... | 6.3016... | 3.1783... | 1.3090... | 0.6952... | 0.4101... | 0.2883 |
| 10.00 | *F* | 0.00000... | 0.0646 ... | 0.117 ... | 0.208 ... | 0.439 ... | 0.758 ... | 1.28 ... | 2.46 ... | 3.89 ... | 5.95 ... | 9.83 |
| | *D* | 7.62 ... | 7.70 ... | 7.77 ... | 7.88 ... | 8.18 ... | 8.59 ... | 9.29 ... | 11.1 ... | 13.6 ... | 17.7 ... | 27.0 |
| | *C* | 0.0909 ... | 0.0903 ... | 0.0899 ... | 0.0891 ... | 0.0872 ... | 0.0846... | 0.0807... | 0.0721... | 0.0629... | 0.0517... | 0.0357 |
| | *R* | 0.00000... | 0.00840 ... | 0.0150 ... | 0.0264 ... | 0.0537 ... | 0.0882... | 0.138 ... | 0.222 ... | 0.286 ... | 0.336 ... | 0.364 |
| | *a* | 0.09091... | 0.09090 ... | 0.09089... | 0.09087... | 0.09085... | 0.0908... | 0.0906... | 0.0901... | 0.0891... | 0.0867... | 0.0730 |
| | *b* | OC ... | 110.0091 ... | 55.0091 ... | 27.5091 ... | 11.0091 ... | 5.5092... | 2.7594... | 1.1099... | 0.5608... | 0.2883... | 0.1370 |

OC indicates an infinite value.

pacitances. At the left of the chart $K_1$ shows the ratio between the series and shunt resistances.

For any particular values, for instance, $K_1 = 0.04$ and $K_2 = 0.20$, line *F* gives the wave front divided by $C_1R_2$. Thus *F*, or here 0.0342, times $C_1R_2$ equals the wave front. Likewise *D*, or here 0.896, times $C_1R_2$ gives the duration of the wave. As before explained[1] the wave front is the time from zero to crest and the wave duration is the time from zero to half crest on the tail of the wave.

Line *C* expresses as a ratio the crest magnitude of the test wave in terms of the initial voltage charge on the generator. For the example given, $C = 0.789$ which means that the voltage on the test piece will be 78.9 per cent of the initial voltage on the impulse generator.

Line *R* is the ratio between the wave front and duration. For the example, $R = 0.0381$. For a 1.5x40 wave $R = 0.0375$.

Lines *a* and *b* give the values of the 2 exponents of the

equation expressing the test wave. See appendix I. The values are expressed in terms of $C_1R_2$, that is, $a = m \times C_1R_2$ and $b = n \times C_1R_2$.

In chart II the inductance is considered and has the value previously determined, $L_1 = R_1^2C/4$. The symbols have meanings similar to those in chart I and there is added the term $w$ which equals $\omega \times C_1R_2$, as shown in appendix II. In chart II there are 3 values of $w$, indicated by asterisks, which denote that the roots are real numbers and that these waves are perfectly smooth.

## Curves and Illustrative Example

From these 2 charts a set of curves is plotted in figure 4. In figures 4*a*, 4*b*, and 4*c*, $L_1 = 0$ and in figures 4*A*, 4*B*, and 4*C*, $L_1 = R_1^2C/4$ where $C = (C_1C_2)/(C_1 + C_2)$.

These curves show (1) that with widely different values of circuit constants the same wave front, wave shape, and crest can be obtained, and (2) that wave shape is to a considerable extent a function of ratios between circuit constants.

Figure 5 shows the relation between $L_1$, $R_1$, and $C$ and is an aid in making tests and calculations.

For purposes of mathematical interest numerous curves could be drawn to show the relation between $a$, $b$, and $w$ and the wave characteristics but these curves will be omitted here for the sake of brevity. However, the data are presented in the charts for such use.

As an example of how to use these charts and curves suppose a 1.5x40 wave is desired where $C_1 = 0.005$ microfarad and $C_2 = 0.001$ microfarad. In circuit I neglect the inductance and in circuit II consider that the inductance has a value determined from figure 5. Then constant by constant,

| Constant | Circuit I | Circuit II | Remarks |
|---|---|---|---|
| $K_2$ | 0.2 | 0.2 | $K_2 = C_2/C_1$ |
| $K_1$ | 0.04 | 0.06 | Figures 4*b* and 4*B* |
| $F$ | 0.035 | 0.034 | Figures 4*a* and 4*A* |
| $R_2$ | 8,600 | 8,800 | Front = $FC_1R_2$ |
| $R_1$ | 340 | 530 | $K_1 = R_1/R_2$ |
| $L_1$ | 0 | 58 | Figure 5 |

The procedure is to first determine from figures 4*b* and 4*B* the values of $K_1$. Then determine from figures 4*a* and 4*A* the values of $F$. The values of $R_2$ and $R_1$ can then be quickly calculated and the value of $L_1$ can be obtained from figure 5. In case the stipulated values of inductance cannot be obtained, the values of the circuit constants will have to be estimated on a straight line basis.[7] Thus in circuit II hereinbefore if $L_1 = 40$ microhenries, make $R_2 = 8{,}700$ and $R_1 = 460$.

## Front-of-Wave Testing and Example

Charts I and II and figure 4 show how easy it is even with widely varying circuit constants to make front-of-wave tests approximating the same rate of voltage rise. The main stipulation is to have the waves for the different circuits reach the same crest voltage at the same time.

For the smooth wave characteristics shown in figure 4, the first thing to do is to choose circuit constants giving the same wave fronts (same $C_1R_2$ values in figures 4*a* and 4*A*) and the second thing to do is to choose the proper charging voltages on the generators to give the same crest voltages on the test pieces. The refining stipulation would be to have in all circuits, if possible, equal values of $L_1$, $K_1$, and $K_2$.

As an example, suppose figure 2 with series inductance was used to get a long wave for test purposes and that $C_1 = 0.02$ microfarad, $C_2 = 0.001$ microfarad, $R_1 = 4{,}000$, $R_2 = 10{,}000$, and the crest voltage = 1,500 kv. Therefore $K_1 = 0.4$, $K_2 = 0.05$, and from figure 4*A*, $F = 0.053$. Suppose that only series resistance as in figure 1 was available for securing the same rate of voltage rise, given $C_1 = 0.008$ microfarad, and as before $C_2 = 0.001$ microfarad. Since the wave fronts must be equal $(FC_1R_2)_1 = (FC_1R_2)_2 = 10.6$ microseconds, and $R_{22} = (0.053 \times 0.02 \times 10{,}000)/(0.053 \times 0.008) = 25{,}000$. As $K_2 = 0.001/0.008 = 0.125$ and $F = 0.053$, $K_1$ must equal 0.12 from

### Chart II

| $K_1 = R_1/R_2$ | | $K_2 = C_2/C_1$ 0.00 | 0.01 | 0.10 | 1.00 | 10.00 |
|---|---|---|---|---|---|---|
| 0.00 | *F* | 0.000000 | 0.000000 | 0.00000 | 0.00000 | 0.00000 |
| | *D* | 0.693 | 0.700 | 0.762 | 1.39 | 7.62 |
| | *C* | 1.000 | 0.990 | 0.909 | 0.500 | 0.0909 |
| | *R* | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 |
| | *a* | 1.000 | 0.990 | 0.909 | 0.500 | 0.0909 |
| | *b* | OC | OC | OC | OC | OC |
| | *w* | | | | | |
| 0.01 | *F* | 0.000258 | 0.000589 | 0.00444 | 0.0213 | 0.0462 |
| | *D* | 0.700 | 0.707 | 0.774 | 1.42 | 7.67 |
| | *C* | 0.990 | 0.981 | 0.898 | 0.493 | 0.0905 |
| | *R* | 0.000369 | 0.000832 | 0.00574 | 0.0150 | 0.00602 |
| | *a* | 0.990 | 0.989 | 0.902 | 0.499 | 0.0909 |
| | *b* | 40,399 | 20,249 | 2,204 | 400.2 | 220.0 |
| | *w* | | 1,407 | 141 | 14.16 | *1.414 |
| 0.10 | *F* | 0.0130 | 0.00441 | 0.0318 | 0.157 | 0.324 |
| | *D* | 0.777 | 0.774 | 0.861 | 1.62 | 8.01 |
| | *C* | 0.899 | 0.898 | 0.820 | 0.456 | 0.0886 |
| | *R* | 0.0167 | 0.00571 | 0.0369 | 0.0969 | 0.0404 |
| | *a* | 0.911 | 0.902 | 0.840 | 0.487 | 0.0908 |
| | *b* | 439 | 2070 | 225 | 40.2 | 21.5 |
| | *w* | | 445 | 44.6 | 4.50 | 4.70 |
| 1.00 | *F* | 0.385 | 0.0213 | 0.170 | 0.882 | 2.21 |
| | *D* | 1.81 | 1.41 | 1.60 | 2.91 | 10.5 |
| | *C* | 0.437 | 0.495 | 0.461 | 0.296 | 0.0763 |
| | *R* | 0.213 | 0.0151 | 0.106 | 0.303 | 0.211 |
| | *a* | 0.536 | 0.499 | 0.490 | 0.387 | 0.0903 |
| | *b* | 7.46 | 252 | 26.7 | 4.31 | 2.20 |
| | *w* | | 133 | 13.5 | 1.46 | 0.0988 |
| 10.00 | *F* | 4.80 | 0.143 | 0.965 | 4.26 | 11.9 |
| | *D* | 26.2 | 7.75 | 8.60 | 12.4 | 26.6 |
| | *C* | 0.0691 | 0.0900 | 0.0856 | 0.0728 | 0.0394 |
| | *R* | 0.183 | 0.0184 | 0.112 | 0.344 | 0.447 |
| | *a* | 0.128 | 0.0911 | 0.0926 | 0.1016 | 0.0781 |
| | *b* | 0.312 | 70.1 | 7.15 | 0.849 | 0.231 |
| | *w* | | *22.5 | *1.91 | 0.257 | 0.0547 |

* The asterisks indicate that the roots are real.
OC indicates an infinite value.

figure 4*a* and $R_1 = 3{,}000$. The charged voltage on the second generator must be from figure 4*c*, 1,500/0.77 = 1,950 kv.

In constructing an impulse generator for wave-front testing, adjunct load capacitances as well as series resistances and inductances could be used for increasing the wave front.

By using the data presented here the slope of the wave-

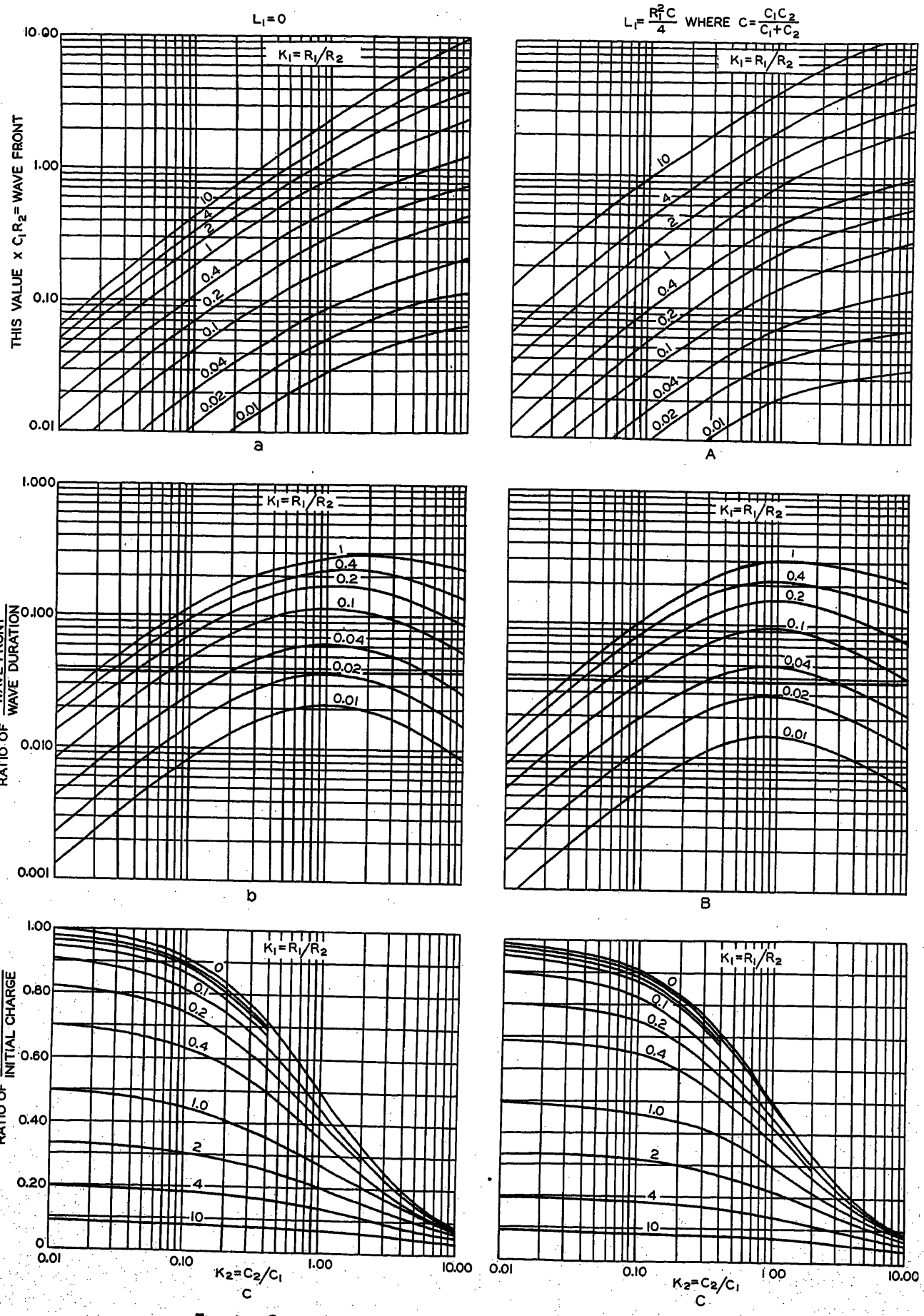



**Fig. 4. Curves for wave shape as related to circuit constants**

front could be calculated between points other than the zero and the crest points of the wave. Some laboratories may wish to use the slope equal to the tangent at the mid-point (50 per cent crest) of the front, others may wish to use the slope determined by 2 points on the front such as the points at 10 and at 90 per cent of crest, and so on. After the method of determining the slope had been agreed upon, the slopes could be determined from a set of calculated fronts, then tabulated similarly to charts I and II and plotted similarly to figure 4 so that any desired time rate of voltage rise could be easily applied to a test piece.

## Accuracy of Charts and Curves

The charts were calculated on the calculating machine and on the slide rule with the intent that the third significant figure of the $F$, $D$, and $C$ values would be approximately correct. On the curves of figure 4 the second significant figure should be approximately correct.

## Oscillograms Verifying Tables and Curves

Up to this point the paper has been devoted to presenting the desirability of comparing and securing impulse voltage test waves on the basis of ratios between circuit constants. In practice, isolated, lumped circuit constants cannot be dealt with and the distribution of the generator capacitors, the effect of stray capacitance, and the idiosyncrasies of the divider and oscillograph must be considered. In general most of these factors are pretty well under control as proved by the fact that cathode-ray oscillograms closely duplicate calculations.

To show this verification, 2 oscillograms are shown in figures 6 and 7 and compared with the calculated charts and curves. In figure 6 a 1.9x40 wave is shown. $C_1$ = 0.00926 microfarad, $C_2$ = 525 micromicrofarads, $L_1$ = 110 microhenrys, $R_1$ = 1,250 ohms, $R_2$ = 4,250 ohms, the charged voltage on the generator = 1,300 kv, and the test-piece voltage = 932 kv. Therefore the similarity between the test results and the charts results can be compared as follows:

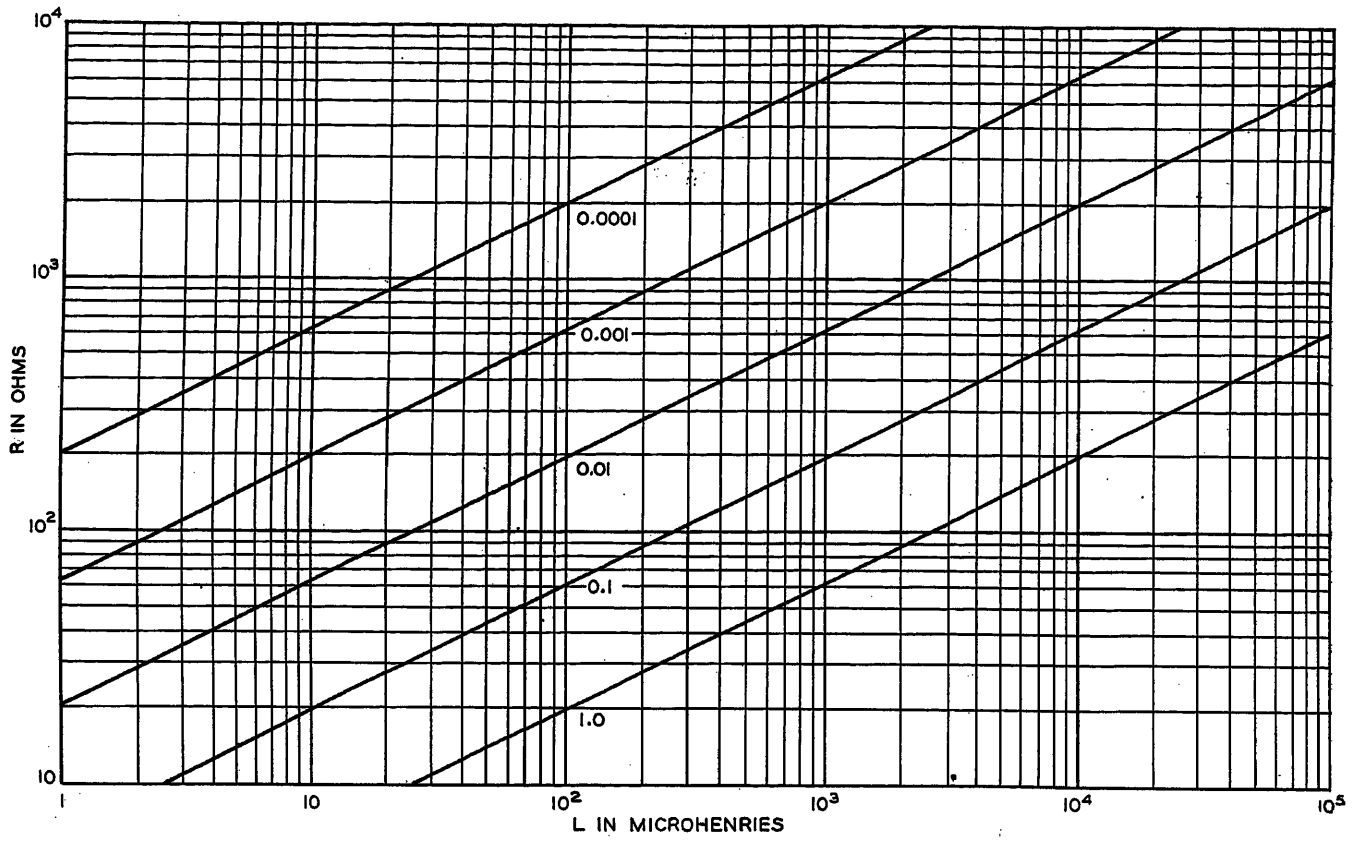



**Fig. 5. Relations between inductance, resistance, and capacitance**

Numbers on curves are capacitances in microfarads $L = R^2C/4$

| Constant | By Test | By Chart |
|---|---|---|
| $K_1$ | 0.30 | 0.30 |
| $K_2$ | 0.057 | 0.057 |
| Front | 1.9 microseconds | 1.9 microseconds |
| Duration | 40 microseconds | 39 microseconds |
| Crest | 72 per cent | 71 per cent |
| $R$ | 0.047 | 0.048 |
| $L$ | 110 microhenrys | 110 microhenrys |

In figure 7 a 1.4x44 wave is shown. $C_1$ = 0.00476 microfarad, $C_2$ = 0.00035 microfarad, $L_1$ = 160 microhenry, $R_1$ = 1,375 ohms, $R_2$ = 10,700 ohms, the charged voltage

on the generator = 550 kv, and the test-piece voltage = 446 kv. Then

| Constant | By Test | By Chart |
|---|---|---|
| $K_1$ | 0.128 | 0.128 |
| $K_2$ | 0.073 | 0.073 |
| Front | 1.4 microseconds | 1.5 microseconds |
| Duration | 44 microseconds | 44 microseconds |
| Crest | 81 per cent | 80 per cent |
| $R$ | 0.032 | 0.034 |
| $L$ | 160 microhenrys | 154 microhenrys |

The values from these 2 oscillograms check closely the values from the charts and curves even though the charts were calculated for wide ranges of values.

Thus these charts can be used with a capacitance meter to determine the constant of the impulse generator circuit for any desired wave shape. These are also conveniently used to supplement the electric transient analyzer[8] in the solution of problems involving impulse generator transients.

## Conclusions

In conclusion the following observations can be pointed out:

1. With widely different values of circuit constants the same wave front, wave shape, and crest can be obtained.

2. Wave shapes depend upon the ratios between circuit constants and may frequently be compared to advantage on this basis.

3. A comparison with oscillograms shows that the charts in this paper are accurate enough for practical work and the examples show how easily the charts can be used for selecting circuit constants.

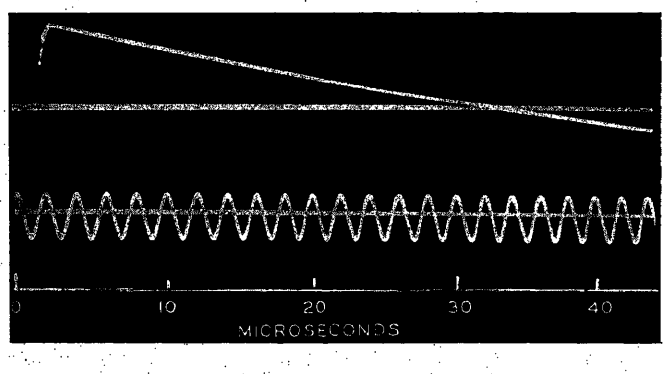



Fig. 6. Oscillogram for 1.9x40 microsecond wave

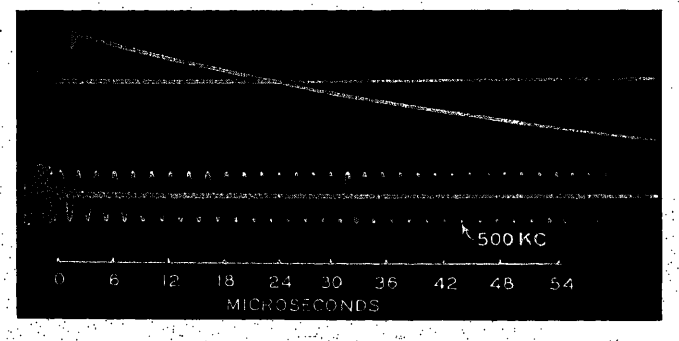



Fig. 7. Oscillogram for 1.4x44 microsecond wave

## Appendix I

Referring to figure 1, the equation[7] for voltage across the capacitance load is

$$\frac{E_{c2}}{E_{c1}} = \frac{1}{n-m}\left[\frac{\epsilon^{-mt} - \epsilon^{-nt}}{C_2R_1}\right]$$

This may be rewritten

$$\frac{E_{c2}}{E_{c1}} = \frac{1}{b-a}\left[\frac{\epsilon^{-T} - \epsilon^{-bT}}{K_1K_2}\right]$$

where

$K_1 = R_1/R_2$
$K_2 = C_2/C_1$
$a = mC_1K_2$
$b = nC_1R_2$
$t = TC_1R_2$

## Appendix II

Referring to figure 2, the equation[7] for voltage across the capacitance load is

$$\frac{E_{c2}}{E_{c1}} = \frac{1}{C_2L_1}\left[\frac{\epsilon^{-\alpha t} - \epsilon^{-\beta t}\left\{\cos \omega t + \frac{\beta - \alpha}{\omega}\sin \omega t\right\}}{(\alpha-\beta)^2 + \omega^2}\right]$$

This may be rewritten

$$\frac{E_{c2}}{E_{c1}} = \frac{4(K_2+1)}{(K_1K_2)^2}\left[\frac{\epsilon^{-aT} - \epsilon^{-bT}\left\{\cos wT + \frac{b-a}{w}\sin wT\right\}}{(a-b)^2 + w^2}\right]$$

where

$L_1 = R_1^2C/4$
$C = (C_1C_2)/(C_1 + C_2)$
$K_1 = R_1/R_2$
$K_2 = C_2/C_1$
$a = \alpha C_1R_2$
$b = \beta C_1R_2$
$w = \omega C_1R_2$
$t = TC_1R_2$

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## Inductive Co-ordination

(*Continued from page 26*)

phone pairs, and the importance, therefore, of suitable telephone-circuit transpositions.

Figure 5 shows exposure conditions such as may be encountered in a small community serving a nearby rural area and table IX shows the noise conditions at several locations during heavy power loads.

The extent to which various measures of co-ordination could be applied to reduce the noise induction or to restrict the extent of special arrangements is shown in table X.

It is evident from table X that, for the conditions assumed, the use of reasonably co-ordinated telephone-circuit transpositions will be necessary to care for the stations served by open wire. Ordinarily the use of such transpositions in combination with such other measures as are reasonably effective would serve to take care of the stations served by telephone cable and would limit the extent to which special telephone-station apparatus might be needed for the stations served by the longer open-wire extensions.

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## Lightning Investigation on Transmission Lines

(*Continued from page 106*)

in the tower legs and counterpoise wires on the Glenlyn-Roanoke line for 11 cases in which a comparison could be obtained. It was assumed that the total counterpoise current was twice the current measured in one long and one short wire. This comparison shows the summation of the tower currents to be 0.95 of the summation of the counterpoise currents.

It is quite important in considering the comparison between leg currents and counterpoise currents to bear in mind that some leg current may pass directly to earth through the tower footings without passing through the counterpoise wires. Also the counterpoise wires may occasionally carry some current which passes through cross members of the tower structure and is not included in the leg measurements. In all cases polarity indicated the current to be traveling from the free end of the counterpoise to the tower and from the bottom of the tower to the top.

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## A Review of Overhead Secondary Distribution

(*Continued from page 122*)

panies *A* and *C*. Replacements are favored by companies *B*, *D*, and *E* but frequently involve re-using transformers in new locations. Only one of the companies anticipates a general replacement of secondary conductors. This company has assumed a 15-year life for triple-braided weatherproof conductors, which apparently has influenced their choice of the replacement method.

Experience records indicate that conductors remaining in service in the same location have been used to a large extent for more than 15 years. While it is true that in case of replacement, it would generally become necessary to scrap such conductors, this should be avoided, if possible, as wires would continue to be serviceable for a good many more years if left in place in the same location. Some real savings are possible therefore by selecting the most economical wire size for the first installation and adding or respacing transformers.

Replacement costs of transformers should also be studied carefully whenever additional capacity is required. Since overloaded operation is considered permissible this should be given first consideration where voltage regulation permits. Additional transformers and subdividing secondaries with possibly some relocations should come next, and finally replacements. A table of annual costs for various per cent loadings of transformers and the net cost of replacements will prove very helpful in selecting the most economical method. Table III contains such typical information. While this information will vary somewhat for various companies, due possibly to a difference in operating or accounting practices, the table is shown here as a typical means of finding the best solutions.

Table IV shows a comparison of accumulated annual costs and indicates the economy of using transformers as long as possible in the same location. In order to benefit fully through long use of transformers, it is necessary to provide new poles, or poles in good condition, for new transformer installations.

# News

## Of Institute and Related Activities

# AIEE Winter Convention Program Provides Attractive Features

TECHNICAL developments in many specialties and attractive social functions comprise the program for the Institute's 1937 winter convention, which will be held in New York, N. Y., January 25–29. Headquarters will be in the Engineering Societies Building, 33 West 39th Street, and registration will begin at 10:00 a.m. on Monday. Thereafter technical sessions, conferences, and committee meetings, together with the social functions, the smoker, Edison medal presentation, dinner-dance, and inspection trips in the city and vicinity provide ample opportunity for a busy and profitable week. In addition, for those who would enjoy a few days vacation in a mild climate during midwinter a Bermuda cruise has been arranged as a post-convention trip. The women's entertainment committee, under the chairmanship of Mrs. George Sutherland, also is arranging a most attractive program for the visiting women. A summarized schedule of events is given in an accompanying tabulation.

### Edison Medal Presentation

The AIEE 1936 Edison Medal will be presented to Doctor Alex Dow at a special session of the convention to be held in the engineering auditorium Wednesday evening, January 27, at 8:15 p.m. Doctor Dow was awarded the medal "for outstanding leadership in the development of the central station industry and its service to the public." A biographical sketch of Doctor Dow is given on page 197 of this issue.

### Technical Program

The technical program is comprised of 13 technical sessions at which a wide variety of timely technical papers will be presented and discussed. The tentative technical program announced in ELECTRICAL ENGINEERING for December 1936, pages 1388–9, is complete with the changes which have been made in the following sessions. These sessions, as revised, are repeated for convenience.

### Selected Subjects

ELECTRONIC TRANSIENT VISUALIZERS, H. J. Reich, University of Illinois.
December issue, pages 1314–18

STUDIES OF STABILITY OF CABLE INSULATION, Herman Halperin and C. E. Betzer, Commonwealth Edison Company. October issue, pages 1074–82

PROPOSED TRANSFORMER STANDARDS, J. E. Clem, General Electric Company.
January issue, pages 32–6

A NEW ELECTROSTATIC PRECIPITATOR, G. W. Penney, Westinghouse Electric & Manufacturing Company. January issue, pages 159–63

### Induction Machinery

INDUCTION MOTOR RESISTANCE RING WIDTH, P. H. Trickey, Diehl Manufacturing Company.
February 1936 issue, pages 144–50

INDUCTION MOTORS UNDER UNBALANCED CONDITIONS, E. O. Lunn, Peterson and Cowan Elevator Company, Ltd. April 1936 issue, pages 387–93

INDUCTION MOTORS ON UNBALANCED VOLTAGES, H. R. Reed and R. J. W. Koopman, Michigan College of Mining and Technology.
November issue, pages 1206–13

CAPACITOR MOTORS WITH WINDINGS NOT IN QUADRATURE, A. F. Puchstein and T. C. Lloyd, Robbins & Myers, Inc.
November issue, pages 1235–9

AN ANALYSIS OF THE SHADED POLE MOTOR, P. H. Trickey, Diehl Manufacturing Company.
September issue, pages 1007–14

### Synchronous Machinery

NEGATIVE-SEQUENCE REACTANCE OF SYNCHRONOUS MACHINES, W. A. Thomas, Antioch College.
December issue, pages 1378–84

CONTRIBUTIONS TO SYNCHRONOUS-MACHINE THEORY, A. S. Langsdorf, Washington University.
January issue, pages 41–8

OPERATIONAL SOLUTION OF A-C MACHINES, A. R. Miller and W. S. Weil, Lehigh University.
November issue, pages 1191–1200

TWO-REACTION THEORY OF SYNCHRONOUS MACHINES, S. B. Crary, General Electric Company.
January issue, pages 27–31

SYNCHRONOUS MACHINE WITH SOLID CYLINDRICAL ROTOR, C. Concordia and H. Poritsky, General Electric Company. January issue, pages 49–58

### Electrical Machinery

SELF-REGULATED COMPOUND RECTIFIERS, W. M. Goodhue and R. B. Power, Harvard University.
November issue, pages 1200–06

ABRASION—A FACTOR IN ELECTRICAL BRUSH WEAR, V. P. Hessler, Iowa State College.
January issue, pages 8–12

ARC CHARACTERISTICS APPLYING TO FLASHING ON COMMUTATORS, R. E. Hellmund, Westinghouse Electric & Manufacturing Company.
January issue, pages 107–13

**Table I—Issues of "Electrical Engineering" Containing 1937 Winter Convention Papers**

| | | |
|---|---|---|
| February | 1936 | 1 paper |
| April | 1936 | 1 paper |
| August | 1936 | 4 papers |
| September | 1936 | 5 papers |
| October | 1936 | 3 papers |
| November | 1936 | 6 papers |
| December | 1936 | 10 papers |
| January | 1937 | 25 papers |
| February | 1837 | 1 paper |

CONTACT DROP AND WEAR OF SLIDING CONTACTS, R. M. Baker and G. W. Hewitt, Westinghouse Electric & Manufacturing Company.
January issue, pages 123–8

In addition to the technical conferences which were announced, an informal technical conference on the subject of noise will be held on Wednesday afternoon.

### Smoker

Winter convention smokers for the last few years have been increasing so in popularity that it has become a difficult problem for the committee to meet satisfactorily the ticket demand. This year they believe

### Summarized Schedule of Principal Events

**Monday, January 25**

10:00 a.m. Registration
2:00 p.m. Opening of convention
2:30 p.m. Parallel technical sessions:
—Communication
—Selected subjects

**Tuesday, January 26**

10:00 a.m. Parallel technical sessions:
—Power transmission
—Tensor analysis
2:00 p.m. Address
2:45 p.m. Parallel technical sessions:
—Power distribution
—Tensor analysis (continued)
6:30 p.m. Smoker at the Commodore Hotel

**Wednesday, January 27**

10:00 a.m. Parallel technical sessions:
—Induction machinery
—Protective devices
2:00 p.m. Parallel technical sessions:
—Synchronous machinery
—Electronics
8:15 p.m. Edison Medal presentation

**Thursday, January 28**

10:00 a.m. Parallel technical sessions:
—Electrical machinery
—Electrophysics
2:00 p.m. Parallel technical sessions:
—Instruments and measurements
—Electric welding demonstrations
7:00 p.m. Annual dinner-dance

**Friday, January 29**

All day Inspection trips

**Saturday, January 30**

3:00 p.m. "Monarch of Bermuda" sails on post-convention cruise to Bermuda

that problem is solved, as the Grand Ballroom and West Ballroom at the Hotel Commodore have been engaged. The seating will be at tables of 10 with ample space to move around; an excellent supper served by the experienced Commodore staff and a satisfactory view for all of a full-sized stage will insure everyone's having a pleasant evening. The entire West Ballroom will be available as a lounge with service bar. Those planning to attend are urged to send in their reservations to the AIEE Smoker Committee, 33 West 39th Street, New York, N. Y., at an early date. All tables will be reserved. Tickets will be $3.50 per person.

### Dinner-Dance

Continuing a social activity that has proved very popular in the past, a dinner-dance has been scheduled for Thursday evening, January 28, at the Hotel Astor, Broadway between 44th and 45th Streets. A combination dinner, dance, and buffet supper again will be featured. The flexibility of this arrangement will provide a very pleasant evening, which may be enjoyed by all according to their tastes, in one of New York's most popular hotels.

The Astor has been entirely redecorated and refurnished, making the surroundings more luxurious than ever. The Grand Ballroom and adjacent facilities will be reserved for the Institute's members and guests. Music will be furnished by George Ellner's Orchestra.

The program of the evening will be:

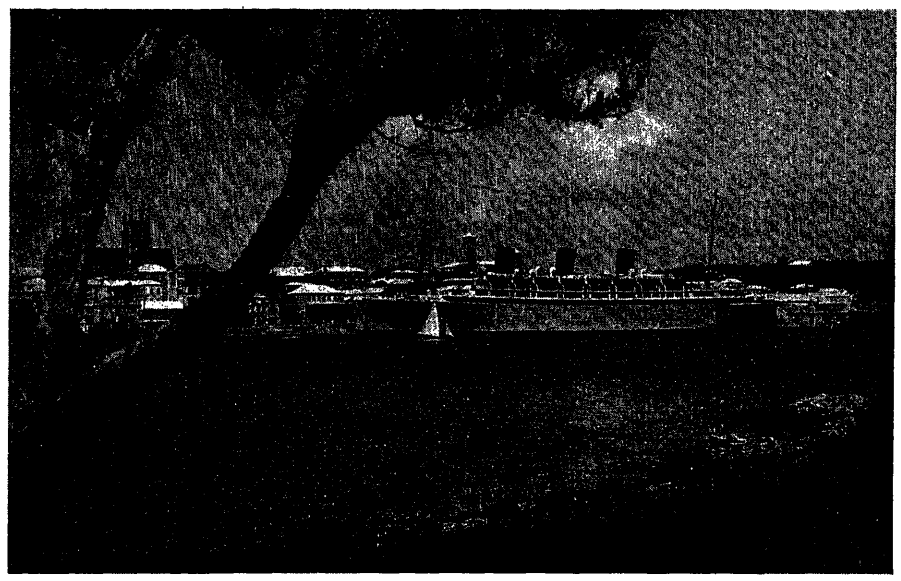
7:00 p.m. ..... Dinner
9:00 p.m. to 2:00 a.m. ..... Dancing
Midnight to 2:00 a.m. ..... Buffet supper

The rates for tickets will be the same as last year:

Dinner and dance ..... $5.00 per person
Dance and buffet supper ..... 3.00 per person
Dinner, dance, and buffet supper .. 6.50 per person

The dinner-dance committee requests early purchase of tickets. Dinner reservation requests should indicate names of guests and the desired seating arrangement. Tables will be set up for 8 or 10 places, and every effort will be made to comply with the requests of members. Reservation requests should be sent to the AIEE Dinner-Dance Committee, 33 West 39th Street, New York City, N. Y., and checks should be made payable to H. H. Henline, national secretary.

# Post-Convention Cruise to Bermuda Offered



A post-convention cruise to Bermuda will be offered to Institute members and their friends attending the AIEE 1937 winter convention. The party will sail on the "Monarch of Bermuda," which is shown above in the Hamilton Harbor, Bermuda, a thoroughly modern vessel in every respect. Those taking this cruise will have an opportunity to visit the engine room and the bridge of this quadruple-electric-turbine vessel, and to see the electrical equipment in action at sea.

### Inspection Trips

A variety of interesting places has been included in the inspection trips arranged for the convention this year. An attempt has been made to arrange some trips during the week as complementary to the technical sessions. As in previous years, Friday has been set aside exclusively for inspection trips. The tentative schedule of inspection trips, which is subject to change, follows:

**Monday, January 25**

Sponsored broadcast, RCA Studios
Edison Wonder House

**Tuesday, January 26**

Public Service Electric and Gas Company—mercury turbine
S. H. Kress and Company—lighting and air conditioning
RCA Radiotron Company
The M. W. Kellogg Company—welding

**Wednesday, January 27**

Weston Electrical Instrument Corporation—cable testing equipment
Columbia Presbyterian Medical Center—Sloan X-ray generator

**Thursday, January 28**

Associated Press
Third Avenue Railway Company—grid-controlled rectifier
Board of Transportation, New York City—power-control board

**Friday, January 29**

Brooklyn Navy Yard
New York Stock Exchange
"Monarch of Bermuda"
Hastings-on-Hudson Mill, Anaconda Wire and Cable Company
Warner Brothers moving picture studio
National Broadcasting Company studios

Arrangements have been made to secure a very limited number of tickets to the General Electric Company "Hour of Charm" radio broadcast featuring Phil Spitalny and his all-girl orchestra. This program is given in the National Broadcasting Company studios on Monday afternoon. It is hoped that interested out-of-town members will indicate their desire for tickets when they register.

The Columbia Presbyterian Medical Center will exhibit the 1,000,000 volt high-frequency X-ray generator placed in operation this year. This generator was seen under construction by many members during the convention last year.

Interesting trips to plants of manufacturers of thermionic tubes, electrical instruments, welding equipment, and wire and cable have been arranged. A sightseeing tour of New York will be arranged for interested members if weather conditions are favorable.

**Table II—A Few of the Hotels Available**

| Hotel | Location | Rooms With Private Bath | |
|---|---|---|---|
| | | Single | Double |
| Astor | Broadway and 44th St | $3.00– 6.00 | $4.50– 7.50 |
| Biltmore* | Madison Ave. and 43d St | 5.00–10.00 | 7.00–12.00 |
| Bristol* | 129 W. 48th St | 2.50– 4.00 | 3.00– 6.00 |
| Commodore | Lexington Ave. and 42d St | 3.00– 5.00 | 4.50– 8.00 |
| Edison | 228–248 W. 47th St | 2.50– 5.00 | 4.00– 8.00 |
| Governor Clinton | 31st St. and 7th Ave | 3.00– 5.00 | 4.00– 7.00 |
| McAlpin | Broadway and 34th St | 2.50– 7.00 | 4.00– 9.00 |
| Montclair* | Lexington Ave. and 49th St | 3.00 | 4.00– 4.50 |
| Murray Hill | Park Ave. and 40th St | 2.50– 5.00 | 3.50– 6.00 |
| New Yorker | 8th Ave. and 34th St | 3.50– 8.00 | 5.00–10.00 |
| Pennsylvania | 7th Ave. and 32d St | 3.50– 6.00 | 5.00– 9.00 |
| Plaza | Fifth Ave. and 59th St | 6.00 | 8.00 |
| Roosevelt | Madison Ave. and 45th St | 4.00– 8.00 | 6.00–12.00 |
| Vanderbilt | Park Ave. and 34th St | 3.50– 5.00 | 6.00– 8.00 |
| Waldorf-Astoria | Park Ave. and 50th St | 6.00– 8.00 | 9.00–11.00 |

* See advertising section for further details.

In addition to scheduled inspection trips, the committee will be pleased to arrange special trips for individuals and small groups. A list of possible items of interest will be available at the committee desk during the convention.

### Bermuda Cruise Offered

For the first time, a post-convention cruise, to Bermuda, will be offered to Institute members and their friends. The party will leave New York on January 30, by the "Monarch of Bermuda"—a magnificent hotel on water with the appointments of an exclusive club. The cruise will include 3 days at the Hotel Bermudiana, Hamilton, which will give an opportunity to visit the near-by caves and submarine coral gardens, and to drive, rest, or golf on some of Bermuda's fine courses. Returning, the party will reach New York on the morning of February 5. The inclusive prices for the entire trip begin at $86.25. This includes all necessary expenses of the trip except the Bermuda tax of 12 shillings, 6 pence (about $3.25) which is payable in Bermuda. Reduced rates for rooms on shipboard are offered, as well as special rates at the Hotel Bermudiana, and stopover privileges for as long as desired. Members wishing to take this cruise are urged to make their reservations at once to avoid possible disappointment. Reservations may be cancelled later, if necessary. Detailed information may be obtained from Leon V. Arnold, 36 Washington Square, West, New York, N. Y.

### Women's Entertainment

The women attending the convention this year are assured of plenty to occupy their time. The women's entertainment committee, under the chairmanship of Mrs. George Sutherland, is rapidly completing the details of a most attractive program. Monday, January 25, 1937, the first day of the Convention, will be devoted to registration at the women's headquarters on the 10th floor. On Tuesday several novel and interesting tours are scheduled with attendance at a radiobroadcast for the evening. On Wednesday there will be luncheon and bridge at the Engineering Woman's Club, and the Edison Medal presentation and lecture in the evening. Thursday will be devoted to a visit to the Edison Wonder House with the Dinner-Dance at the Hotel Astor for the evening. On Friday a visit is arranged to the Morgan Library. This necessarily will be for a limited group. If demand warrants, a visit to the Hayden Planetarium also will be provided.

### Hotel Rates

Reservations for hotel accommodations should be made by writing directly to the hotel of your preference. In table II is included a brief list of some of the leading hotels in the vicinity.

### Register in Advance

Members in near-by Districts should fill in and post promptly the mail registration card which was included with the mailed announcement of the winter convention sent them. This will permit the committee to have badges ready and prevent congestion at the registration desk upon arrival. There will be a registration fee of $2 for non-members with the exception of Enrolled Students of the Institute, and the immediate families of members.

The personnel of the 1937 winter convention committee is as follows: C. R. Beardsley, *chairman;* H. E. Farrer, *secretary;* T. F. Barton, O. B. Blackwell, E. E. Dorting, A. G. Oehler, C. S. Purnell, S. A. Smith, Jr., George Sutherland, and F. P. West. The chairmen of the subcommittees completing the arrangements are: C. M. Gilt, *dinner-dance;* E. S. Banghart, *smoker;* E. R. Thomas, *inspection trips;* and Mrs. George Sutherland, *women's entertainment.*

## Student Conference Held by Middle Eastern District

The annual conference of Branch counselors and chairmen of the Institute's Middle Eastern District (2) was held at Ohio State University, Columbus, Friday and Saturday, November 13–14, 1936. The official attendance at the conference consisted of the 34 delegates listed in table I. The meeting was attended also by National Secretary H. H. Henline and W. H. Harrison, vice-president of the Institute representing the Middle Eastern District. The student attendance at the evening meeting Friday night was 75, and at the final joint meeting on Saturday, 64.

Following registration, which was held from 5 to 7 p.m. Friday, the evening meeting opened with a dinner. After dinner, Professor F. C. Caldwell gave the address of welcome, following which there were several talks. Professors H. W. Bibber and W. L. Everett, of Ohio State, outlined in detail the course in electrical engineering as it is taught at that institution. Professor E. O. Lange spoke on Branch activities, and recommended that all Branches consider seriously the installation of new officers at a much earlier date in the spring. National Secretary Henline presented a historical outline of student Branches and the national AIEE organization. Vice-President Harrison, who spoke on District activities, convinced all present that engineering societies offer some exceptional opportunities to engineers at the present time and that all student engineers should associate themselves actively with the engineering society of their choice. Professor E. E. Kimberly, chairman of the Institute's Columbus Section, and V. Frederiksen, secretary of that Section, outlined the constructive work being done between the Section and the Ohio State University Branch.

On Saturday morning, November 14, the group was taken on an inspection trip of the laboratories at Ohio State. This was followed by separate meetings of the Branch chairmen and counselors. The student group with R. P. Stokely, chairman of the Ohio State Branch presiding, carried out informal discussion of: (1) participation by students in meetings; (2) credit for attendance; (3) competition for prizes; (4) encouragement of attendance of upperclassmen, sophomores, and freshmen; (5) inspection trips; and (6) social activities.

At the counselors session, there was some discussion concerning the student convention of the Branches in the east section of the District to be held at Johns Hopkins University, Baltimore, Md., next spring. It was decided that the Branches at George Washington University, the University of Maryland, and the Catholic University of America be invited to participate in this convention, since they are situated near Baltimore. It was the consensus of opinion that Branches situated in a central area should work as a unit in holding student Branch conventions.

It was decided that the next District

## Membership—

Mr. Institute Member:

Your response to our request for names of prospective members has been very helpful so far this year. We need your continued aid to reach the goal of 2,000 applications by May. Whether you have already suggested some one or not, send in the name of a good prospect now.

The busy season of the Institute year is now well under way. Take your fellow engineer who is not a member to your Section meetings, to the convention technical sessions, to the dinner-dance and the smoker, and show him what we do. When he is interested, send his name to your Section membership committee chairman. If you start the job he will finish it.



Vice-Chairman, District No. 3
National Membership Committee

**Table I**

| Branch | Counselor | Delegate |
|---|---|---|
| Univ. of Akron | J. T. Walther | |
| Bucknell Univ | | Ripple Schumaker |
| Carnegie Inst. of Tech | M. S. Schonvizner | J. C. Lynch |
| Case School of Applied Science | A. C. Seletzky | J. A. Harshaw |
| Catholic Univ. of America | | |
| Univ. of Cincinnati | L. R. Culver | B. Baumzweiger |
| Drexell Inst. of Tech | E. O. Lange | H. W. Graybill |
| George Washington Univ | A. G. Ennis | E. W. Thomas |
| Johns Hopkins Univ | J. H. Lampe | H. B. Peck |
| Lafayette College | F. W. Smith | R. S. Baum |
| Lehigh Univ | J. L. Beaver | T. R. Brown |
| Univ. of Maryland | L. J. Hodgins | W. G. Calder |
| Ohio Northern Univ | B. F. Wyandt | Glen Griffith |
| Ohio State Univ | F. C. Caldwell | R. P. Stokely |
| Ohio Univ | A. A. Atkinson | G. M. Kanable |
| Pennsylvania State College | L. A. Doggett | H. B. Stockham |
| Univ. of Pennsylvania | | R. S. Graham |
| Univ. of Pittsburgh | H. E. Dyche | E. B. McKinney |
| Princeton Univ | | |
| Swarthmore College | | |
| Villanova College | H. S. Bueche | |
| West Virginia Univ | A. H. Forman | M. W. Henderson |

conference of Branch counselors and chairmen should be held at Akron in October 1937, in conjunction with the District meeting to be held there at that time. Professor A. G. Ennis of George Washington University, was elected chairman of the conference for the year beginning August 1, 1937. Professor E. O. Lange was elected as a delegate to the Institute's 1937 summer convention to be held June 21–25, 1937, at Milwaukee, Wis.

At the conclusion of these sessions, the counselors and students reconvened for a final joint session during which the proceedings at the separate sessions were summarized.

## Eta Kappa Nu Announces Awards

Frank M. Starr (A'30), central station engineering staff, General Electric Company Schenectady, N. Y., has been named by Eta Kappa Nu, honorary electrical engineering society, as America's outstanding young electrical engineer for 1936. Mr. Starr was selected from 47 nominees, and he becomes the first to be so recognized by this society in its plan to recognize outstanding young electrical engineers. (See announcement in March 1936 issue of ELECTRICAL ENGINEERING, pages 306–07.) Four other candidates were selected as recipients of honorable mention certificates; these men are: P. L. Bellaschi (A'28, M'34) development and research engineer, Westinghouse Electric & Manufacturing Company, Sharon, Pa.; E. W. Boehne (A'29) engineer, large oil circuit breaker engineering department, General Electric Company, Philadelphia, Pa.; A. C. Seletzky (A'29, M'35) assistant professor of electrical engineering, Case School of Applied Science, Cleveland, Ohio; and C. G. Veinott (A'28, M'34) electrical engineer, Westinghouse Electric & Manufacturing Company, Springfield, Mass. Biographical sketches of the recipients may be found in the "personal" columns of this issue.

The awards were made by a committee composed of: E. B. Meyer (A'05, F'27, past-president) chief engineer, electric engineering department, Public Service Electric and Gas Company, Newark, N. J.; L. W. Morrow (A'13, F'25) general manager, fiber products division, Corning Glass Works, Corning, N. Y.; the late General R. I. Rees; C. A. Butcher (M'22) eastern engineering manager, Westinghouse Electric & Manufacturing Company, New York, N. Y.; Everett S. Lee (A'20, F'30) engineer, general engineering laboratory, General Electric Company, Schenectady, N. Y.; and R. I. Wilkinson (A'35) engineer, Bell Telephone Laboratories, New York, N. Y.; the last 2 men are past-presidents of Eta Kappa Nu.

The recognition plan sponsored by Eta Kappa Nu is designed: (1) to assure due and appropriate honors to young electrical engineers for "meritorious service in the interest of their fellowmen"; (2) to give the engineering profession concrete examples of what young men under 35 years of age and not more than 10 years out of college can be expected to achieve; and (3) to inspire by these young men's careers, and furnish guides for, undergraduates and new engineering graduates to take up their own professional development as soon as possible. A very broad range of accomplishments from scientific research to civic and political activity and artistic creation is recognized, the aim being to encourage engineers to obtain a truly liberal and humanistic perspective at an early point in their careers.

Nominations of candidates for the 1936 recognition were received from heads of electrical engineering departments of colleges and universities throughout the country, from Sections of the AIEE, and from individual members of the Eta Kappa Nu Association. Mr. Starr will have the honor of being the first to have his name placed on a large bronze bowl created by Eta Kappa Nu, which will be kept on display at the headquarters of the AIEE in the Engineering Societies Building in New York. Mr. Starr will also be presented with a smaller reproduction of the bowl, engraved with a brief résumé of his accomplishments, at the citation ceremonies to be held in New York on the evening of January 25, 1937, during the AIEE winter convention.

## Future AIEE Meetings

**Winter Convention**
New York, N. Y., Jan. 25–29, 1937

**North Eastern District Meeting**
Buffalo, N. Y., May 5–7, 1937

**Summer Convention**
Milwaukee, Wis., June 21–25, 1937

**Pacific Coast Convention**
Spokane, Wash., Date to be determined

**Middle Eastern District Meeting**
Akron, Ohio, Fall 1937

## District and National Prizes for 1936 Technical Papers

All who have presented technical papers before the Institute during the calendar year 1936 are eligible under the AIEE paper prize regulations for competitive consideration for one or more of the established prizes. Papers are eligible for submission to the prize committees regardless of whether presented before a Branch meeting, a Section meeting, a District meeting, or a national convention, the several classes providing for equitable competition. Both District and national prizes are awarded each spring for papers presented during the preceding calendar year. Rules governing the awards were outlined in the December 1935 issue of ELECTRICAL ENGINEERING, pages 1414–15.

Although all 1936 papers are *eligible* for consideration, every paper for which prize consideration is desired must be *submitted* specifically for that purpose (except as noted below) not later than February 15, 1937, through the District secretary for consideration for the District prizes, or through the national secretary's office for consideration for the national prizes. There is no provision for automatic consideration of papers, with the exception that those approved by the technical program committee and presented at national conventions or District meetings, will be considered by the national prize committee for the national "best paper" and "initial paper" prizes without being formally offered for competition.

## Executive Committee Meets at Institute Headquarters

A meeting of the executive committee of the American Institute of Electrical Engineers was held at Institute headquarters, New York, N. Y., December 10, 1936, in place of the regular meeting of the board of directors.

Present: A. M. MacCutcheon (chairman), O. B. Blackwell, Everett S. Lee, E. B. Meyer, L. W. W. Morrow, W. I. Slichter; National Secretary H. H. Henline.

Reports were presented and approved of meetings of the board of examiners held October 28 and December 2, 1936. Upon

the recommendation of the board of examiners, the following actions were taken: 3 applicants were transferred to the grade of Fellow; 17 applicants were transferred and 14 were elected to the grade of Member; 76 applicants were elected to the grade of Associate; 560 Students were enrolled.

Disbursements in November amounting to $20,511.61 were reported by the finance committee and approved.

Report was made and approved of the appointment, upon the nomination of the standards committee, of H. W. Samson as AIEE representative on the sectional committee on standardization of graphical symbols and abbreviations (Z32) of the American Standards Association.

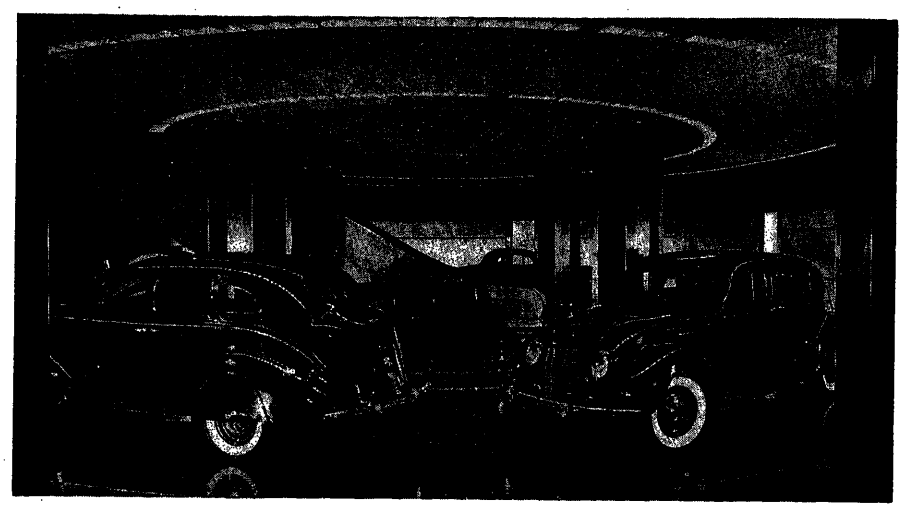
Further consideration was given to the subject of broadening Institute activities to cover discussions of social and economic subjects. At its October 1936 meeting, the board of directors passed a motion concurring in the suggestion that such topics are of general interest to electrical engineers, calling attention to the fact that the Institute offers opportunity for discussion of such questions, and suggesting that papers on these subjects be submitted to the proper committees of the Institute for consideration for national presentation and publication. After a discussion of the procedure to be followed in this matter, it was voted that a special committee on broadening of Institute activities be appointed, consisting of the chairman of the technical program committee as chairman, and the chairmen of the committees on code of principles of professional conduct, co-ordination of Institute activities, economic status of the engineer, Institute policy, legislation affecting the engineering profession, publication, and Sections.

Other matters were discussed, reference to which may be found in this or future issues of ELECTRICAL ENGINEERING.

## Weston Library Willed to Newark Engineering College

By the terms of the will of the late Doctor Edward Weston (A'84, M'84, HM'33, past-president) the Newark (N. J.) College of Engineering is to receive his general and technical library with a sum sufficient to provide for housing and maintaining it. The library is reported to contain complete sets of the proceedings of scientific societies not only in America, but from many foreign countries. In addition to his library, Doctor Weston willed the college the drawings and designs for his many patents and discoveries and much data accompanying them of great general interest and historical value. The college is planning to gather together this material and arrange it in such manner as to form a proper record of Doctor Weston's contribution to science and technology.

Doctor Weston was a member of the original board of trustees of the Newark Technical School, predecessor of the Newark College of Engineering, in which capacity he served for many years. Although forced to retire from the board because of increasing business obligations, he maintained an active interest in the college until his death, which occurred on August 20, 1936. A biographical sketch of his career appeared in the September 1936 issue of ELECTRICAL ENGINEERING, page 1049.



New automobile showroom in Chrysler Building, New York, N. Y., has distinctive lighting

## AIEE Officers to Be Nominated Soon

In accordance with the Institute's by-laws, the national nominating committee of the AIEE will meet during the winter convention, New York, N. Y., January 25–29, 1937, for the purpose of nominating national officers to be voted upon by the membership in the spring of 1937. Members of the national nominating committee, named in accordance with the Institute's by-laws, are as follows:

*Representing the Board of Directors*

O. B. Blackwell — A. C. Stevens
N. E. Funk — J. B. Whitehead

(One additional member to be appointed)

*Representing the 10 Geographical Districts*

1—T. H. Morgan, Worcester Polytechnic Institute, Mass.
2—W. E. Wickenden, Case School of Applied Science, Cleveland, Ohio.
3—E. B. Meyer, Public Service Electric and Gas Company, Newark, N. J.
4—E. E. George, Tennessee Electric Power Co., Chattanooga, Tenn.
5—K. L. Hansen, Harnischfeger Sales Corporation, Milwaukee, Wis.
6—A. L. Turner, Northwestern Bell Telephone Company, Omaha, Neb.
7—J. W. Ramsay, University of Texas, Austin.
8—H. S. Lane, Pacific Gas and Electric Company, San Francisco, Calif.
9—R. E. Kistler, Pacific Telephone and Telegraph Company, Seattle, Wash.
10—C. V. Christie, McGill University, Montreal, Quebec, Can.

The provisions of the AIEE constitution and by-laws relating to nomination of officers were given in ELECTRICAL ENGINEERING for November 1936, page 1278, wherein members were invited to submit suggestions for nominations not later than December 15, 1936. The methods whereby nominations also may be made independent of the nominating committee were given in that item. Briefly, independent nominations may be made by a petition of 25 or more members sent to the national secretary at Institute headquarters, not later than March 25, to be placed before the nominating committee for inclusion in the ballot of such candidates as are eligible. Petitions for the nomination of vice-president may be signed only by members within the District concerned.

## New York Gathering Honors Memory of Rudolph Diesel

In commemoration of the 40th anniversary of the introduction of Diesel power into the United States, some 250 or more leaders in American business, industry, engineering, research, and education gathered at the Waldorf-Astoria Hotel in New York City, December 2, for a special luncheon which coincided with "Diesel Day" at the then current annual power show in New York.

Diesel, Paris-born Bavarian refrigerating engineer, had specialized in the study of thermodynamics and was much impressed with the Carnot theory of a perfect engine, the continued study of which subject led him toward his ultimate development. In 1892 he obtained his first German patent covering claims for both simple and compound Diesel engines, the suggested fuel being coal dust. Later patents included the use of petroleum oils and the employment of high-pressure air to inject the oil charge into the cylinder. Early development, however, was slow, and it was Fate's decree that never during the inventor's lifetime did his engine become generally recognized as an important source of power. Doctor Diesel disappeared from a ship while en route from Germany to England, during September 1913, on the eve of his engine's career.

In 1896, Adolphus Busch of Anheuser-Busch fame acquired the American Diesel license, and built in St. Louis, Mo., a 60-horsepower 2-cylinder unit, which, placed in service in 1898, is said to be the first Diesel engine in the world to be put actually into industrial service. In the interim, re-

search and industrial progress, with their by-products of improved knowledge of thermodynamics and vastly improved materials of construction have permitted the development and improvement of the Diesel engine to a point where the new horsepower placed in service during 1936 is estimated at 2,100,000.

Chairman of the committee of arrangements was Gordon Rentschler, president of The National City Bank of New York; master of ceremonies was Radio-Commentator John B. Kennedy. Feature speakers, each of whom spoke briefly from the point of view of his own business activities, included: Edward B. Pollister, president, Busch-Sulzer Brothers Diesel Engine Company; Capt. Edward V. Rickenbacker, vice-president, Eastern Air Lines; Col. Robert H. Morse, president, Fairbanks-Morse & Company; Thomas H. Beck, president, Crowell Publishing Company; C. L. Cummins, president, Cummins Engine Company; Edward G. Budd, Edward G. Budd Manufacturing Company (streamlined trains); R. U. Blasingame, president, American Society of Agricultural Engineers; David S. Sarnoff (via radio from Chicago) president, Radio Corporation of America; B. C. Heacock, president, Caterpillar Tractor Company; and Charles F. Kettering (via radio from Detroit) vice-president in charge of research, General Motors Corporation, who emphasized the extent of the internal combustion engine market in America, by pointing out that during 1936 some 200,000,000 horsepower in new motors cars had been manufactured.

## Insulation Stability Research to Be Extended

Engineering Foundation, with the sponsorship of the AIEE, has appropriated $5,000 for an experimental research on the stability of impregnated paper insulation. The work is to be done in the school of engineering of The Johns Hopkins University, Baltimore, Md., under the direction of Doctor J. B. Whitehead (A'00, F'12, past-president) professor of electrical engineering.

This work will be an extension of that completed several years ago by Doctor Whitehead and associates on the stability of impregnated paper as related to the physical properties of the impregnating oil. The new work will include a similar series of accelerated life tests as related to variations in the physical and chemical properties of the paper.

The present appropriation and plans are for a period of a year, but it is expected that both will be continued a second year.

## Noble Prize Awarded to Institute Member

The Alfred Noble Prize for 1936 has been awarded to Abe Tilles (A'30, M'36) instructor in electrical engineering at the University of California, Berkeley, for his paper "Spark Lag of the Sphere Gap." This paper, which received the Institute's 1935 Pacific District prize for best paper, was published in ELECTRICAL ENGINEERING for August 1935, pages 868–76, and was presented at the AIEE Pacific Coast convention, Seattle, Wash., August 27–30, 1935. An item regarding Doctor Tilles is given in the personal columns of this issue. Presentation of the award will be made at the AIEE 1937 winter convention.

The Alfred Noble Prize was instituted in 1929 in honor of Alfred Noble, past-president of the American Society of Civil Engineers and the Western Society of Engineers, and consists of a $500 cash award and an engraved certificate. The award is made to a member of any grade of either the American Society of Civil Engineers, the American Institute of Mining and Metallurgical En-

## Ambrose Swasey Receives Hoover and VDI Medals



Ambrose Swasey (center), "Knight of the Kindly Heart," Honorary Member of the Institute, founder and patron of The Engineering Foundation, as he appeared at the Astor Hotel in New York City, December 2, 1936, celebrating his ninetieth birthday by receiving simultaneously the Hoover Gold Medal, highest American engineering award, and the Gold Medal of the Verein Deutscher Ingenieure, outstanding German award. At Mr. Swasey's right is Herbert Hoover (HM'29), for whom the medal was named and to whom in 1930 its first award was made "for distinguished public service." Mr. Swasey is the second to receive the award. At Mr. Swasey's left is Dr. Gano Dunn, past-president of the Institute, and chairman of the Hoover Medal board of award. Other details pertaining to the award and its recipient were given in the November 1936 issue of ELECTRICAL ENGINEERING, pages 1278–9 and 1288.

In connection with the presentation ceremonies, Doctor Dunn outlined medallist Swasey's long and colorful career. Mr. Hoover amplified this in his "tribute to Mr. Swasey as an engineer for his 70 years of active service to engineers and to humanity," stating that the "sum of Mr. Swasey's contributions has brought more comfort and more security to more human beings than have come from any one other individual." Incidentally, Mr. Hoover flung an engineer's challenge to engineers by stating emphatically that "the engineer no longer can hold himself to design and administration, but must range out into broader fields if humanity's problems of today are to be solved satisfactorily."

gineers, The American Society of Mechanical Engineers, the American Institute of Electrical Engineers, or the Western Society of Engineers, for a technical paper of particular merit accepted by the publication committee of any of the foregoing societies for publication, in whole or in abstract in any of their respective technical publications, provided the author, at the time the paper is accepted in practically its final form, is not over 30 years of age. The recipient of the prize is selected by a committee of 5 members, consisting of one representative of each society, the award being based upon papers published by the societies within the 12 months preceding July 15 of each year.

The first award of the Alfred Noble Prize was made in 1931, and the second award, in 1932, was made to F. M. Starr (A'30).

# Letters to the Editor

**CONTRIBUTIONS to these columns are invited from Institute members and subscribers. They should be concise and may deal with technical papers, articles published in previous issues, or other subjects of some general interest and professional importance. ELECTRICAL ENGINEERING will endeavor to publish as many letters as possible, but of necessity reserves the right to publish them in whole or in part, or reject them entirely.**

**ALL letters submitted for consideration should be the original typewritten copy, double spaced. Any illustrations submitted should be in duplicate, one copy to be an inked drawing but without lettering, and other to be lettered. Captions should be furnished for all illustrations.**

**STATEMENTS in these letters are expressly understood to be made by the writers; publication here in no wise constitutes endorsement or recognition by the American Institute of Electrical Engineers.**

## Engineering Education—Opinions and Influencing Factors

*To the Editor:*

In their closing discussion on their paper "Engineering Education—Opinions and Influencing Factors" (see ELECTRICAL ENGINEERING, October 1936, page 1147), Professors King and Eshbach raise certain questions that should be answered. One of these points was discussed in my paper "A New General Engineering Curriculum" as presented before the electrical engineering conference of the Society for the Promotion of Engineering Education in Madison, Wis., in June 1936 (see *Journal of Engineering Education*, volume 26, number 10, June 1936, page 826).

The members of the committee that worked out the details of this new general engineering curriculum, debated at length concerning the choice of a proper descriptive name for this new curriculum. They felt that "basic" engineering most nearly described the content, but recognized the fact that this term had no generally accepted meaning in either the engineering world or in industry. At the same time, the committee realized that "general" engineering, in its ordinary usage, connoted considerable emphasis upon managerial studies, and usually a wide range of electives in liberal amounts. Finally, it was decided that perhaps it was best at first to label it, in the college catalog, as "general engineering" with the subtitle description of "composite course including the basic essentials of civil, electrical, industrial, and mechanical engineering."

It was recognized immediately that professional society activities would be a necessary concomitant of the academic program of study. A local General Engineering Society was formed and started functioning immediately after the curriculum was opened. Meetings are held just as frequently as those of the student branches of the various national engineering societies. Also, the General Engineering Society participates jointly with the other student engineering societies in the activities of the local engineering society, which includes in its membership students from all engineering departments. Senior students in general engineering are encouraged to attend in rotation the meetings of the student branches of the 4 national societies sponsored by the 4 co-operating departments, in addition to the meetings of their own General Engineering Society. In this way they get well acquainted with national professional engineering societies and should have every incentive for associating with one of the national engineering societies as soon as they become placed in industry.

Respectfully yours,

ALBRECHT NABTER (A'23, M'30)
Professor and Head of Electrical Engineering Department, Oklahoma Agricultural and Mechanical College, Stillwater

## The Measure of an Engineer

*To the Editor:*

In his response, in receipt of the Lamme medal, Doctor Vannevar Bush stated that engineers were responsible and honest people, but too often inclined to mind their own business. ("The Measure of an Engineer," ELECTRICAL ENGINEERING, August 1936, page 854.)

Such modesty and a minding of his own business are very practical guides to the engineer's conduct in his social community. Viewing socio-economic matters of the past and present he is not so much inarticulate as incoherent, as would be a medical person should he presume to speak on such matters. Let the engineer stick out his neck too far, he will receive, as descriptive of society's understanding of his stimuli, such trivia as:

**". . . but think of his power. Think of the temptation of playing with his switchboard just for the fun of it. In his place and at his age I do not think I could have resisted it."**

This appeared in an article "Notes on the Conventions," by R. deR. deSales, published in *Atlantic Monthly*, September 1936 issue.

There is a wide gulf between the ideas of Doctor Bush and those of M. deSales. Remember, however, the latter is a journalist. He writes for the general public. He thus reflects their viewpoint. What he asks us to "think" the public in general thinks. Note that there is no reference to responsibilities on the part of the technician he refers to, but merely to the hilarious effect that might capriciously be brought about by a wholesale confusion.

To get some further notion of the public mind and its relation to any sort of science, let us assume M. deSale's attitude and apply the words to one or 2 other classes of persons. First, let us think of medical doctors: ". . . but think of his power. Think of the temptation of playing with his patient just for the fun of it. In his place . . . etc." "An unthinkable and monstrous idea!"—thus we could expect to hear from common men filled with a thumping indignation.

But let us continue with possible other changes in the original quotation. Though the thought intrigues, we pass charitably over the substitution of "plaintiff," or "defendant" or "witness" for "switchboard." Rather put "printing-press" in its place, meantime thinking "journalist" instead of "engineer." M. deSales himself would doubtless be among the most notable in rightly professing that inherent responsibility which the true journalist feels.

Yet it cannot be too clearly stated that his original words represent a popular conception of the mischievous possibilities inherent in a position of control and assigned as admissible to engineers' mentalities. It represents the popular mind's notion of the mental set of scientists. These are the persons whom the public suspects of being that vast impersonal THEY in vexatious control of present-day developments and operations.

So, in all sincerity, I beg those who are capable to give us further encouragement along the line of Dr. Bush's "central function" thesis. The engineer needs encouragement to apply the principles of scientific action to human affairs rather than feeling pressure to rush himself uncritically at the "success" demands of a business-based social order. He needs his backbone stiffened so that he may courageously focus back the ills of society on itself by applications of science, not to try to use it to produce any sort of palliatives. In war, physicians attend the wounded, even though in their hate of war they know that larger mass death would sooner terminate hostilities. Such behavior is an aspect of scientific method applied to human behaviors. The public considers such action worthy.

The proper rôle of an engineer at a political convention is likewise a scientific one. If the proceedings are consequential, well and good. Should they be so much twaddle, it is his true office to let that fact appear. But in the cheerful disorder of his mind Johnny Q. Public is a long way from any such realization.

Yours very truly,

J. ANDREW DOUGLAS (A'18, M'29)
Physics and General Science Teacher, Murphy High School, Mobile, Alabama

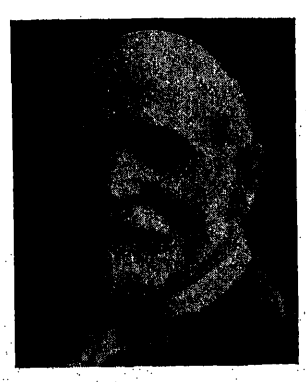
# Personal Items

ALEX DOW (A'93, F'13, member for life) president, Detroit (Mich.) Edison Company, has been awarded the AIEE Edison Medal for 1936 "for outstanding leadership in the development of the central station industry and its service to the public." The medal, which was founded by friends and associates of the late Thomas A. Edison (A'84, M'84, HM'28), and is awarded annually for "meritorious achievement in electrical science, electrical engineering, or the electrical arts," will be presented to Doctor Dow during the Institute's winter convention at New York, N. Y., January 25–29, 1937. Doctor Dow was born in Glasgow, Scotland, in 1862, and although he is not a graduate of a technical school, he has received the honorary degrees of master of engineering (1911) and doctor of engineering (1924) from the University of Michigan and doctor of science (1935) from the University of Detroit. During the period 1874–82, he was employed as junior clerk and stenographer in a railroad office and in the offices of a steamship company in Liverpool, England. In 1882 he came to the United States, and was employed in various departments of the Baltimore and Ohio Railroad Company. Later he was transferred to the Baltimore and Ohio Telegraph Company to take charge of local line and instrument maintenance, with some construction and experimental work on telephones. In 1888 he was employed by the Brush Electric Company, Cleveland, Ohio, as installation electrician in the Chicago (Ill.) office, becoming district engineer in that office in 1889. In 1893, he accepted the opportunity to design and supervise the construction of the original public lighting plant of the city of Detroit, and in 1896 he became vice-president and general manager of the Edison Illuminating Company of Detroit. This company was succeeded by the Detroit Edison Company in 1903, and Doctor Dow was retained as vice-president until 1913, when he was made president. He became a naturalized citizen in 1895. Doctor Dow has been a leading pioneer in the United States in the engineering, rate making, and general operation of the electric light and power utility, and is given credit for both the engineering and financial success of his enterprises. He has supervised the design and construction of several generating stations of the Detroit Edison system, and he is called the father of the so-called "big" steam boiler in the United States, having installed 2,350-horsepower boilers at a time when 600- to 750-horsepower units were commonly considered large. He was the first to adopt the underfeed stoker for large installations, and much of the earlier development of this type of equipment was made in his power plants. In addition to his electric utility activities, Doctor Dow served the city of Detroit as the engineer member of the Board of Water Commissioners from 1916 to 1921, and again from 1925 to 1927. He is a member of The American Society of Mechanical Engineers (president 1928), American Society of Civil Engineers, the Institution of Electrical Engineers (Great Britain), and the Detroit Engineering Society (charter member and past-president). He has recently been elected an honorary member of both the ASME and the ASCE. For his paper "On the Schooling of Engineers" (published in the December 1934 issue of ELECTRICAL ENGINEERING, pages 1589–91), he was awarded the AIEE 1935 national prize for best paper in public relations.

O. E. BUCKLEY (M'19, F'29) director of research for the Bell Telephone Laboratories, Inc., New York, N. Y., has been elected executive vice-president. Doctor Buckley was born at Sloan, Iowa, August 8, 1887, and received the degrees of bachelor of science from Grinnell College (1909) and doctor of philosophy from Cornell University (1914). In 1936 the honorary degree of doctor of science was conferred upon him by Grinnell College. Doctor Buckley was an instructor in physics at Grinnell College during 1909–10, an assistant in physics at Cornell University 1910–12, and instructor 1912–14. He was then employed in the engineering department of the Western Electric Company until he was given charge of the signal corps laboratory of the U. S. Army in Paris, France, during 1917–18. After he returned to the company (from which Bell Telephone Laboratories, Inc., later was derived) he engaged in work on continuously loaded cables. In 1927 Doctor Buckley was made assistant director of research, and 6 years later became director of research, a position in which he had charge of fundamental studies in a great variety of fields. Since 1926 Doctor Buckley has been a member of the Institute's committee on electrophysics, and from 1929–31 he was its chairman. During the period 1929–31 he was a member of the meetings and papers committee (now technical program) and since 1934 he has been a member of the committee on research. He is a member of the Franklin Institute, American Physical Society, and American Association for the Advancement of Science.

O. B. BLACKWELL (A'08, F'17, vice-president) formerly manager of staff departments, Bell Telephone Laboratories, Inc., New York, N. Y., has been elected vice-president of the laboratories with responsibility for the development of communication apparatus and telephone systems. Mr. Blackwell was born at Bourne, Mass., August 21, 1884. Receiving the degree of bachelor of science from Massachusetts Institute of Technology in 1906, he immediately entered the engineering department of the American Telephone and Telegraph Company. In 1914 he became transmission and protection engineer, and with the formation of the department of development and research in 1919 he became transmission development engineer. When that department was consolidated with Bell Telephone Laboratories in 1934, Mr. Blackwell was appointed director of transmission development. In 1935 he was made manager of staff departments. In his new position as vice-president he will have charge of the apparatus development, systems development, and protection development departments. His individual contributions to the communication art have been to the practical theory of transmission and crosstalk and to many problems which have arisen in transmission development. Mr. Blackwell has served on the Institute's committee on communication 1918–26 (chairman 1922–25) and from 1935 to the present time; in 1936 he was elected a vice-president representing the New York City District and was appointed a member of the standards committee. He is a member of the plant co-ordination committee and the joint sub-committee on development and research of the Edison Electric Institute and Bell System, and a member of the standards council of the American Standards Association.

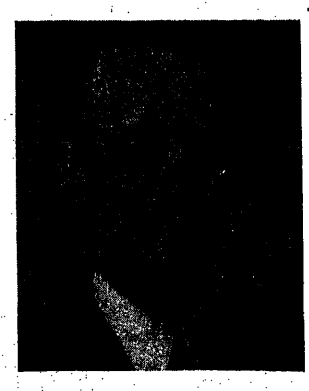
E. W. BOEHNE (A'29) engineer in the large oil circuit breaker engineering department of the General Electric Company, Philadelphia, Pa., has received honorable mention in connection with the selection by Eta Kappa Nu, honorary electrical engineering society, of America's outstanding young electrical engineer for 1936 (see page 193). Mr Boehne was born at Laramie, Wyo., June 2, 1905. Following graduation in 1926 from the Agricultural and Mechanical College of Texas, Mr. Boehne entered the General Electric Company at Lynn, Mass., for a year and then undertook graduate work at Massachusetts Institute of Technology, receiving the degree of master of science in 1928. He was one of 2 men from that institution selected to take the advanced course



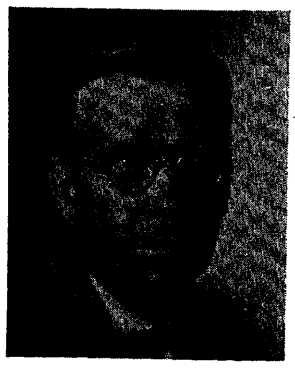
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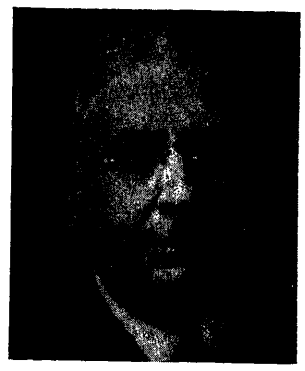
O. E. BUCKLEY



O. B. BLACKWELL



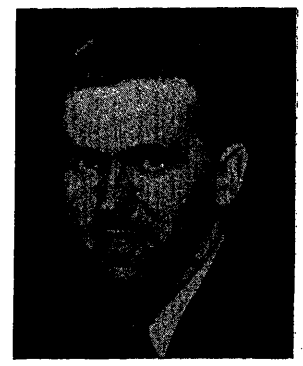
M. J. KELLY



J. H. HERRON



F. M. STARR



ABE TILLES

in engineering of the General Electric Company at Schenectady, N. Y. Since 1933 he has been in the switchgear plant of that company at Philadelphia. He has specialized in the protection of electrical equipment from surges due to lightning and switching, his early work on the calculation of arrester performance in connection with choke coils being notable. He was closely associated with the design of 287-kv circuit breakers for the Boulder Dam-Los Angeles transmission line, and is the author of several Institute papers. Mr. Boehne is a member of the Franklin Institute, and is interested in the activities of the Roerich Society, whose aim is "world peace through the arts."

M. J. KELLY (M'26, F'31) vacuum tubes and transmission instruments director, Bell Telephone Laboratories, Inc., New York, N. Y., has been appointed director of research. He was born at Princeton, Mo., February 14, 1894, and received the degrees of bachelor of science (1914) and master of science (1915) from the University of Missouri. In 1919 he received the degree of doctor of philosophy from the University of Chicago and in May 1936 he received an honorary degree of doctor of engineering from the University of Missouri in recognition of his contributions to communication engineering. Doctor Kelly joined the engineering department of the Western Electric Company, now Bell Telephone Laboratories, in 1919 and since then has been continuously engaged in researches in electronics and in the development of thermionic devices of all types. In 1922 he was placed in charge of the vacuum-tube development of the laboratories. In 1935 in addition to that work he was placed in charge of the development of transmitters and receivers for telephone instruments. Now, as director of research, he is in charge of all of the research activities of the laboratories. Doctor Kelly has served on the Institute's committees on communication and standards since 1934.

J. H. HERRON (M'35) president, The James H. Herron Company, Cleveland, Ohio, has been elected president of The American Society of Mechanical Engineers for the year 1936–37. Mr. Herron was born at Girard, Pa., January 4, 1875, and received the degree of bachelor of science in electrical engineering at the University of Michigan in 1909. From 1889 to 1897 he was employed in Erie, Pa., and subsequently was assistant engineer in charge of power for the Cambria Steel Company, Johnstown, Pa.; vice-president and chief engineer of the Bury Compressor Company, Erie; manager of the Motch & Merryweather Machinery Company, Detroit, Mich.; and chief engineer and works manager of the Detroit Steel Products Company. Since 1909 he has been president of The James H. Herron Company, engineers and chemists. He is also president of the Paragon Laboratories, director of the Baldwin Farms Land Company, and secretary of the National Engineering Inspection Association. He is the author of articles on metallurgical subjects published in technical periodicals, and is the inventor of the air-compressor inlet-valve unloader and of numerous devices for use with air compressors and metallurgical furnaces. Mr. Herron has served The American Society of Mechanical Engineers as manager (1922–25) and as vice-president (1934–36), and was president of the Cleveland Engineering Society during the year 1917–18. His other society affiliations include the American Society of Civil Engineers, American Institute of Mining and Metallurgical Engineers, American Chemical Society, American Society for Testing Materials, British Iron and Steel Institute, Society of Automotive Engineers, American Concrete Institute, and American Association for the Advancement of Science.

F. M. STARR (A'30) central station engineer, General Electric Company, Schenectady, N. Y., has been named by Eta Kappa Nu, honorary electrical engineering society, as America's outstanding young electrical engineer for 1936. Details of the award are given elsewhere in this issue. Mr Starr was born at Fowler, Colo., February 26, 1905, and was graduated with special honors from the University of Colorado in 1928 with the degree of bachelor of science in electrical engineering. He then joined the General Electric Company, entering on the test course at Schenectady, N. Y. The following year he entered the engineering general department and for the past 5 years has been a member of the central station engineering department. Mr. Starr's contributions to the electrical art have been chiefly in the field of central station design and power distribution. His researches and inventions in the devising of equivalent circuits for simulating complex networks resulted in the widespread adoption of new and more exact methods for calculating system performance under both normal and emergency conditions. His later work in establishing methods for detecting faults on ungrounded lines, and his study on the design, operation, and economics of various types of distribution systems, particularly networks, have also attracted wide attention. Mr. Starr has presented several papers before the Institute and received the Alfred Noble prize for his paper on equivalent circuits presented in 1932. The degree of electrical engineer was conferred upon him in 1933 by the University of Colorado in recognition of his work.

L. H. HILL (A'22, M'29) who has been assistant engineer in charge of transformer design for the Allis-Chalmers Manufacturing Company at Milwaukee, Wis., has been appointed engineer-in-charge of the transformer division. Mr. Hill was born at Toms River, N. J., March 8, 1899, and received the degree of electrical engineer from Cornell University in 1922. During the period 1920–22 he served as an instructor at the university, and following graduation accepted the position of design engineer in the transformer engineering department of the Westinghouse Electric & Manufacturing Company. In 1928 he became manager of the transformer division of the American Brown Boveri Electric Corporation at Camden, N. J., having charge of engineering and sales for the division. This company was absorbed by Allis-Chalmers Manufacturing Company in 1931, at which time Mr. Hill was made assistant engineer in charge of transformer design. Recently Mr. Hill was appointed vice-chairman of the national convention committee preparing for the 1937 summer convention of the Institute at Milwaukee.

ABE TILLES (A'30, M'36) instructor in electrical engineering at the University of California, Berkeley, has been awarded the Alfred Noble Prize for 1936, as reported elsewhere in this issue. The award was made for his paper "Spark Lag of the Sphere Gap," which was presented at the AIEE Pacific Coast convention, August 27–30, 1935. Doctor Tilles was born at New York, N. Y., March 10, 1907. In 1928 he received the degree of bachelor of science in mechanical engineering and electrical engineering with highest honors

from the University of California. In 1932 he received the degree of master of science in electrical engineering, and in 1934 that of doctor of philosophy in electrical engineering. During the period 1928–30 he was employed in the testing laboratories of the Bureau of Power and Light, Los Angeles, Calif., and in 1930 was for a time engaged in work for the testing and research laboratories of the California State Division of Highways at Sacramento before joining the faculty of the University of California as an associate. He was appointed instructor in 1933, specializing in electric power transmission and telephone transmission lines and transmission networks. Doctor Tilles received the annual best paper prize of the Pacific District at the 1936 AIEE summer convention for the same paper for which he now receives the Noble prize. He is counselor of the University of California Branch, and a member of Eta Kappa Nu and Sigma Xi.

ROSCOE SCHAEFFER (A'32, M'36) formerly resident electrical engineer for the Byllesby Engineering and Management Corporation, Oklahoma City, Okla., has been transferred to the Oklahoma Gas and Electric Company, Oklahoma City, as superintendent of engineering of that company. Mr. Schaeffer was born at Ludlow, Ill., in 1892, and was graduated from Iowa State College in 1915, with the degree of bachelor of science in electrical engineering. Upon graduation he served briefly as assistant superintendent of a small municipal power plant before entering the employ of the General Electric Company, Schenectady, N. Y., in 1916, serving first as a test engineer and subsequently as an assistant foreman and an assistant to the electrical superintendent of the Schenectady works of that company. In 1919 Mr. Schaeffer accepted a position as assistant engineer on standards with the Remy Electric Company, Anderson, Ind., where he remained for one year before affiliating himself with the William A. Baehr Company, Chicago, Ill., as resident engineer in charge of transmission-line construction at Ada, Okla. In 1923 he became assistant to the construction superintendent of the Oklahoma Gas and Electric Company, and later was made assistant to the general superintendent of operation of that company before being transferred to the Byllesby Engineering and Management Corporation in 1926.

C. G. VEINOTT (A'28, M'34) electrical engineer, Westinghouse Electric & Manufacturing Company, Springfield, Mass., has received honorable mention in connection with the selection by Eta Kappa Nu, honorary electrical engineering society, of America's outstanding young electrical engineer for 1936 (see page 193). Mr. Veinott was born at Somerville, Mass., February 15, 1905, and received the degree of bachelor of science in electrical engineering from the University of Vermont in 1926. He then entered the student course of the Westinghouse company at East Pittsburgh, Pa., and since then has been engaged chiefly with the problems of rotating machinery, making notable contributions. He was transferred to the small-motor engineering department at Springfield in 1929, and has been associated with the development of new methods of analysis of losses in single-phase motors, noise prevention studies, and new means of calculating single phase and polyphase induction motors. Mr. Veinott holds patents for disk-type thermostatic protection of motors, and has actively participated in the design and development of fractional-horsepower motors. Recently he was appointed to have charge of sales and engineering on all fractional-horsepower motors for fans and blowers. Mr. Veinott is the author of a number of papers, some of which have been presented to the Institute. He has been a member of the Institute's electrical machinery committee since 1934, and has been active in the work of the Springfield Section, of which he is now chairman.

J. M. TODD (M'32) consulting electrical engineer, New Orleans, La., has been elected a vice-president of The American Society of Mechanical Engineers for the year 1936–37. He was born at Franklin, La., May 25, 1896, and received the degrees of bachelor of engineering (1918) and mechanical engineer (1930) from Tulane University. He served (1918–19) as a lieutenant in the U.S. Army, seeing service in England and France, and in 1919 became chief engineer of the Marrero, La., plant of Penick and Ford, Inc. From 1921 to 1928 he was associated as assistant engineer with A. M. Lockert & Company, mechanical engineering contractors in New Orleans. He has since been retained as consultant in mechanical and electrical problems by the Orleans Parish School Board, the Board of State Engineers, the city of New Orleans, and Tulane University. Mr. Todd has been a member of the Institute's membership committee since 1935, and is a past-president of the Louisiana Engineering Society.

A. C. SELETZKY (A'29, M'35) assistant professor of electrical engineering, Case School of Applied Science, Cleveland, Ohio, has received honorable mention in connection with the selection by Eta Kappa Nu, honorary electrical engineering society, of America's outstanding young electrical engineer for 1936 (see page 193). Doctor Seletzky was born at Novostavtzy, Volynia, Russia, May 29, 1905. In 1927 he received the degree of bachelor of engineering and in 1930 that of doctor of engineering from The Johns Hopkins University, and in the latter year became an instructor in electrical engineering at Case School of Applied Science. He was made assistant professor in 1933. Doctor Seletzky is noted for his research work, which ranges from new analyses of various types of electric circuits and bridges to methods of magnetic analysis, thermionics, power transmission circuits, and a-c circuit theory. Doctor Seletzky is a second lieutenant in the Ordnance Reserve of the U.S. Army and has worked at Watertown Arsenal. He is the author of a number of AIEE papers and of papers published by the Franklin Institute. Since 1933 he has been a member of the AIEE committee on instruments and measurements, and is now serving as counselor of the Branch at Case School of Applied Science and as chairman of the membership committee of the Cleveland Section.

E. W. BURBANK (A'25, M'30) district manager, Allis-Chalmers Manufacturing Company, Dallas, Texas, has been elected a manager of The American Society of Mechanical Engineers for the year 1936–37. He was born at Sunbury, Ohio, February 15, 1889, and received the degree of bachelor of engineering from Tulane University in 1911. He then entered the employ of the Allis-Chalmers company as a student apprentice. Between 1913 and 1916 he was engaged in the experimental design and development of hydraulic machinery and in conducting extensive tests on this type of equipment. In 1916 he was transferred to the sales department and was sent to New Orleans, La., as sales engineer becoming district manager at Dallas 5 years later. He is a member of the American Petroleum Institute and the Dallas Technical Club.

P. L. BELLASCHI (A'29, M'34) section engineer in charge of transformer engineering, Westinghouse Electric & Manufacturing Company, Sharon, Pa., has received honorable mention in connection with the selection by Eta Kappa Nu, honorary electrical engineering society, of America's outstanding young electrical engineer for 1936 (see page 193). Mr. Bellaschi was born at Piedmont, Italy, February, 13, 1903, and came to the United States with his parents in 1913. In 1926 he received the degree of bachelor of science in electrical engineering from Massachusetts Institute of Technology and, following a year in the Westinghouse student course, received the degree of master of science in electrical engineering in 1928. Since that time he has been with the Westinghouse company in various capacities. Mr. Bellaschi is well known for his work in the field of lightning investigation, and has made many important contributions and discoveries. Many papers based on his researches have been published, both in the United States and in Europe. In 1936 he received a Westinghouse award of merit in recognition of his work in high-voltage research. Mr. Bellaschi has been active on the committees of the Sharon Section of the Institute. He is a member of the Associazione Elettrotecnica Italiana.

G. H. DUNSTAN (A'28) formerly assistant professor of general engineering at the University of Southern California, Los Angeles, now is enrolled as a graduate student at the University of Iowa, Iowa City. Mr. Dunstan is specializing in hydraulic engineering.

VINCENT HACKETT (A'36) student engineer, General Electric Company, Schenectady, N. Y., has been transferred to the Philadelphia, Pa., works of that company.

H. J. MASSHARD (A'24) formerly with the International Paper Company, New York, N. Y., now is employed by the Scott Paper Company, Chester, Pa.

# Obituary

CHARLES LEGEYT FORTESCUE (A'03 F'21) consulting transmission engineer, Westinghouse Electric & Manufacturing Company, East Pittsburgh, Pa., died December 4, 1936. Doctor Fortescue was born at York Factory, Manitoba, Canada, November 7, 1876, and received his earlier education at a private school in England. In 1898 he received the degree of bachelor of science from Queen's University, Kingston, Ont., and in that year joined the Westinghouse Electric & Manufacturing Company as an apprentice. The university conferred upon him a doctor's degree in 1931. From 1901 to 1918 he was in the transformer engineering department, and from 1918 to 1926 he was manager of the porcelain, insulator, and transmission engineering department. Since 1926 Doctor Fortescue had been consulting transmission engineer. Perhaps the best known of the many contributions to the engineering art that are credited to Doctor Fortescue is the development of the mathematical system known as "symmetrical coordinates" or "symmetrical components" and application of it to the solution of problems involving polyphase systems. For this work he was awarded the gold medal of the Franklin Institute in 1931. Other fields of his work were studies of stability and lightning protection. Doctor Fortescue also is credited with many improvements in transformer design, advancement of the art of measurement of high voltage by the sphere spark gap, development of basic principles for the form and proportions of insulating surfaces, and contributions to the design of transmission systems, receiving nearly 200 patents. He is said to have developed the first commercial 100,000-volt transformer, and advanced the theory that direct strokes were the cause of trouble on transmission lines. Many papers on various subjects were presented by him before the Institute, and others were published elsewhere. Doctor Fortescue had been a member of the Institute's committee on power transmission and distribution since 1932, serving previously from 1925 to 1929. He also had been a member of the committees on telegraphy and telephony (now communication) 1914–17, and electrophysics 1916–17 and 1920–31.

CLINTON JESSE AXTELL (A'09, M'30) assistant engineer of the control division, transportation engineering department of the General Electric Company, Erie, Pa., died October 16, 1936. He was born at Axtell, Kans., April 4, 1883, and was graduated from Kansas State College in 1904. For a short time he was employed by the Jackson (Mich.) Light and Power Company, then entered the testing department of the General Electric Company at Lynn, Mass. In 1907 he was transferred to Schenectady, N. Y., remaining until 1910. Between 1910 and 1913 he was employed by the Commonwealth Power Company of Michigan, the International Railway Company, Buffalo, N. Y., and the Cleveland (Ohio) Railway Company. He then returned to the General Electric Company in the railway department division, becoming assistant engineer of the division in 1930. He made many important contributions to the development of railway equipment and was an authority on electric control for all types of transportation vehicles including ships and naval equipment.

A. W. RUSSELL (A'31) chief engineer of the Hollywood mill, Buckeye Cotton Oil Company, Memphis, Tenn., died recently according to word just received at Institute headquarters. Mr. Russell was born December 22, 1876, at Little Rock, Ark. During the period 1910–19 he was chief engineer of the Little Rock (Ark.) Railway and Electric Company. In 1923 he was appointed chief engineer of the National Cotton Seed Products Corporation, where he remained until he entered the employ of the Buckeye Cotton Oil Company in 1929, as supervisor of power in the Memphis mills of that company. He was appointed chief engineer of the Hollywood mill in 1933.

# Membership

## Recommended for Transfer

The board of examiners, at its meeting on December 2, 1936, recommended the following members for transfer to the grade of membership indicated. Any objection to these transfers should be filed at once with the national secretary.

**To Grade of Fellow**

Bennett, C. E., electrical engineer, Federal Power Commission, Washington, D. C.
Bossard, G. L., president and director of engineering research, General Kontrolar Company Inc., Dayton, Ohio.
Lane, F. H., manager, engineering and construction, Byllesby Engineering and Management Corporation, Chicago, Ill.
MacNaughton, A. K., supervising engineer, The Commonwealth and Southern Corporation of New York, Birmingham, Ala.
Watson, A. E., associate professor of electrical engineering emeritus, Brown University, Providence, R. I.
5 to Grade of Fellow

**To Grade of Member**

Beck, Lester E., assistant professor of electrical engineering, Purdue University, West Lafayette, Ind.
Bodicky, A., underground engineer, Union Electric Light and Power Company, St. Louis, Mo.
Brady, G. B., assistant division superintendent, Oklahoma Gas and Electric Company, Enid, Okla.
Dueland, R., electrical engineer, Parsons, Klapp, Brinckerhoff and Douglas, New York, N. Y.
Dutton, T. D., district plant engineer, American Telephone and Telegraph Company, Washington, D. C.
Gerell, G. W., relay engineer, Union Electric Light and Power Company, St. Louis, Mo.
Hoyle, E. R., electrical engineer, Sinclair Oil and Refining Company, Houston, Texas.
Musgrove, A. M., Jr., assistant engineer, Public Service Electric and Gas Company, Englewood, N. J.
Nuttall, A., electrical engineer, Trinidad Leaseholds Ltd., Pointe-a-Pierre, B. W. I.
Stone, E. W., assistant superintendent, electric testing department, Central Illinois Light Company, Peoria, Ill.
Talley, T. J., 3rd, technical employee, American Telephone and Telegraph Company, Philadelphia, Pa.
Watts, F. W., vice-president, United Electric Controls Corporation, Hoboken, N. J.
Weiser, R. G., assistant engineer, Brooklyn Edison Company, Brooklyn, N. Y.
13 to Grade of Member

## Applications for Election

Applications have been received at headquarters from the following candidates for election to membership in the Institute. If the applicant has applied for direct admission to a grade higher than Associate, the grade follows immediately after the name. Any member objecting to the election of any of these candidates should so inform the national secretary before Jan. 31, 1937, or March 31, 1937, if the applicant resides outside of the United States or Canada.

Allen, R. T., Jr., Consumers Power Company, Jackson, Mich.
Andrews, N. R. (Member), National Sugar Refining Company of New Jersey, Long Island City, N.Y.
Armstrong, D. K., Union Oil Company, Oleum, Calif.
Armstrong, H. R., Detroit (Mich.) Edison Company.
Barrow, L. G. (Member), Brooklyn (N. Y.) Edison Company, Inc.
Behar, M. F. deM., (Member), Instruments Publishing Co. Pittsburg, Pa.
Bose, C. C. (Member), Indiana Bell Telephone Company, Indianapolis.
Bowen, R. E., Jr., City Light & Water Division, Memphis, Tenn.
Brandt, T. F., (Member), Ohio Brass Co. Barberton
Campbell, S. M., Cleveland Electric Illuminating Company, Ohio.
Capel, C. C., Indiana Bell Telephone Company, Indianapolis.
Dausman, O. D., Indiana Bell Telephone Company, Indianapolis.
Denison, H. C., Oklahoma Gas and Electric Company, Oklahoma City.
Dixon, A. R. American Tel. & Tel. Co., New York, N. Y.
Dotterweich, W. A. (Member), Consumers Power Company, Jackson, Mich.
Dunnewold, L. J., Indiana Bell Telephone Company, Indianapolis.
Dublin, M., Department of Docks, North River, New York, N. Y.
Falk, K. K. (Member), Bendix Products Corporation, South Bend, Ind.
Ferguson, B. (Member) 319 Homebuilders Bldg. Phoenix, Ariz.
Foster, C. D., Portland (Ore.) General Electric Company.
Green, I. V., Indiana Bell Telephone Company, Indianapolis.
Griffith, H. D., Westinghouse Electric & Manufacturing Company, Springfield, Mass.
Gruenberg, A. T., Gruenberg Elec. Co. Inc., New York, N. Y.
Heathman, E. J., Southwestern Bell Telephone Company, Bristow, Okla.
Henson, C. A., Pacific Gas and Electric Company, Sacramento, Calif.
Hyland, G. A., Westinghouse Electric and Manufacturing Company, Wilkes Barre, Pa.
Jack, C. R., 715 S. W. King Ave., Portland, Ore.
Johnson, J. E., Philadelphia (Pa.) Electric Company.
Johnson, W. C., Allis Chalmers Manufacturing Company, Chattanooga, Tenn.
Jones, D. J. (Member), Vapor Car Heating Company, Chicago, Ill.
Kanouse, E. L., Los Angeles (Calif.) Bureau of Power & Light.
Killoran, J. M., The Cleveland (Ohio) Electric Illuminating Company.
Langhauser, G. E. (Member), New York and Queens Electric Light and Power Company, Flushing, N. Y.
Larlee, D. H., Brooklyn (N. Y.) Union Gas Company.
Langhus, L., Cenral Electric and Telephone Company, Sioux City, Ia.
Lehman, A. J., Freeport Sulphur Company, Freeport, Texas.
Lincks, G. F., General Electric Company, Pittsfield, Mass.
Linders, J. R., Cleveland Electric Illuminating Company, Ohio.
Linke, H. M., Spruce Falls Power and Paper Company Ltd., Kapuskasing, Can.
Low, A. A. (Member), Brooklyn (N. Y.) Edison Co. Inc.
Mancib, A. S. (Member), Weston Electric Institute Corporation, West Somerville, Mass.
Markus, H. F., Arsenal Technical Schools, Indianapolis, Ind.
Mascaro, W. O., Atlantic Refining Company, Philadelphia, Pa.

McDowell, J. A., Sherwin Williams Company, Dallas, Tex.
Meyer, J. E., General Laminated Products Inc., New York, N. Y.
Meyer, J. M., Meyer Instrument Company, San Francisco, Calif.
Moody, W. S., General Electric Company, Schenectady, N. Y.
Muehlig, R. E., Westinghouse Electric & Manufacturing Company, Boston, Mass.
O'Brien, E. W. (Member), Southern Power Journal, Atlanta, Ga.
Packer, W., 1826 E. 82nd St., Cleveland, Ohio.
Pefferly, W. J., Phelps Dodge Copper Products Corporation, Detroit, Mich.
Personeus, L. H., Puget Sound Power and Light Company, Seattle, Wash.
Pierson, W. H., Croft Place, R. F. D. 3, Huntington, L. I., N. Y.
Powers, C. F., C. F. Powers Company, Cleveland, Ohio.
Risseeuw, E. J., Allis-Chalmers Manufacturing Company, Milwaukee, Wis.
Rivero, A. (Member), New York (N. Y.) Edison Company.
Robinson, W. F., Pacific Telephone and Telegraph Company, Portland, Ore.
Rockwell, F. H., United Light and Power Engineering and Construction Company, Kansas City, Mo.
Royal, A. B., Louis-Allis Company, Milwaukee, Wis.
Schoenfeld, S. S., Department of Parks, Bronx, N. Y.
Sessions, A. P. (Member), Southern California Edison Company, Ltd., Los Angeles, Calif.
Shepherd, R. H., R. H. Shepherd Company, Vancouver, Can.
Snowden, W. H., *Electrical West*, San Francisco, Calif.
Stahl, C. D., Oklahoma Gas and Electric Company, Ardmore.
Stanley, L. L., Klein & Saks, New York, N. Y.
Steinback, E. T., Homestake Mining Company, Lead, S. D.
Stinchcomb, L. M. (Member), H. B. Sherman Manufacturing Company, Battle Creek, Mich.
Stokien, A., Brooklyn (N. Y.) Edison Company, Inc.
Swenson, C. R., Indiana Bell Telephone Company, Indianapolis.
Taylor, A. Y., Rural Electrification Administration, Washington, D. C.
Thompson, J. K., France Manufacturing Company, Cleveland, Ohio.
Uphouse, W. F. (Member), Southwestern Bell Telephone Co. St. Louis, Mo.
Waag, H. B., North Eastern Coustruction Co. New York, N. Y.
Wald, S., 2715 Webb Avenue, New York, N. Y.
Williams, H. F., Bussmann Manufacturing Company, St. Louis, Mo.
Williams, N. W., CCC-SCS Iowa No. 18, Clariton, Iowa.
Wood, A. H., Virginia Electric and Power Company, Richmond, Va.
77 Domestic

Foreign

Lucas, F. N., Bardez Elec. Supply Co. Ltd., Mapuca, Bardez Goa, Portuguese India.
Robinson, J. E. L. (Member), Ferranti Ltd., Hollinwood, Lancashire, England.
Simmonds, J. C., University College, Nottingham, Eng.
Sreenivasaiengar, M., International General Electric Company (India) Ltd., Bombay, India.
4 Foreign

# Engineering Literature

## New Books in the Societies Library

Among the new books received at the Engineering Societies Library, New York, recently, are the following which have been selected because of their possible interest to the electrical engineer. Unless otherwise specified, books listed have been presented gratis by the publishers. The Institute assumes no responsibility for statements made in the following outlines, information for which is taken from the preface of the book in question.

SCIENTIFIC BASIS OF ILLUMINATING ENGINEERING. (Electrical Engineering Texts). By P. Moon. N. Y. and Lond., McGraw-Hill Book Company, 1936. 608 p., illustrated 10x6 in., cloth, $5.00. A textbook on the engineering of lighting. Presents the details of current practice and a thorough treatment of the scientific fundamentals. The text is based on courses at the Massachusetts Institute of Technology.

Die SCHLAUCHELEKTRODE zur LICHTBOGENSCHWEISSUNG von KUPFER. By W. Lessel. Berlin, VDI-Verlag, 1936. 57 p., illustrated, 8x6 in., paper, 3.80 cm. Describes a new process for arc welding copper for which several important advantages are claimed.

RADIO AMATEUR'S HANDBOOK. 14th ed. American Radio Relay League, West Hartford, Conn., 1936. 536 p., illustrated, 10x7 in., paper, $1.00 in U.S.A.; cloth, $2.50 in all countries. A reference book for amateurs, intended to provide accurate information on the practical design and construction of sending and receiving apparatus and the operation of amateur radio stations.

PRINCIPLES of ELECTRICAL ENGINEERING, Theory and Practice. By G. C. Bialock. 2 ed. N. Y. and Lond., McGraw-Hill Book Company, 1936. 584 p., illustrated, 9x6 in., cloth, $4.00. Provides a course in electrical theory and practice adapted to the needs of students who are preparing for work as civil, mechanical, or chemical engineers, but it may also be used by students of electrical engineering as an introduction.

Great Britain. Mines Dept. REPORT OF H. M. ELECTRICAL INSPECTOR of MINES for the Year 1935. London, His Majesty's Stationery Office, 1936. 78 p., illustrated, 10x6 in., paper (obtainable in British Library of Information, New York, $0.45). Presents statistics upon the use of electrical mining machinery and upon the accidents resulting from the use of electricity in mines.

ELEMENTS of PROBABILITY. By H. Levy and L. Roth. Oxford, England, Clarendon Press; N. Y., Oxford University Press, 1936. 200 p., illustrated, 9x6 in., cloth, $5.00. Presents an elementary treatment of the subject and provides a detailed criticism of the various self-contained theories of probability.

Das ELEKTRISCHE EISENBAHNWESEN der GEGENWART. (Elektrische Bahnen Ergänzungsheft, Jahrgang 1936.) Ed. by W. Wechmann. Berlin, Verlag für Sozialpolitik, Wirtschaft and Statistik, 1936. 212 p., illustrated, 12x8 in., paper, 6 rm. Contains 9 lectures by various authorities on the electrical railway.

EINFÜHRUNG in die KLASSISCHE ELEKTRODYNAMIK. By J. Fischer. Berlin, Julius Springer, 1936. 199 p., illustrated, 10x7 in., cloth, 13.80 rm. Presents the classic theory of electrodynamics, intended for advanced students.

BEITRAG zur BERECHNUNG von MASTFUNDAMENTEN. By H. Fröhlich. 3 ed. Berlin, Wilhelm Ernst and Sohn, 1936. 81 p., illustrated, 10x7 in., paper, 7.50 rm. (5.65 rm. in U.S.A.). Provides a study of the design of foundations for the masts and towers of transmission lines.

INDUSTRIAL DUST. By P. Drinker and T. Hatch. N. Y. and Lond., McGraw-Hill Book Co., 1936. 316 p., illus., 9x6 in., cloth, $4.00. Discusses the problem of dust control in its relation to the health of workmen, and presents methods for designing and operating dust-control equipment.

ENGINEERING ALLOYS, Names, Properties, Uses. By N. E. Woldman and A. J. Dornblatt. Cleveland, Ohio, American Society for Metals, 1936. 622 p., tables, 10x6 in., lea., $10.00. Contains the trade names, manufacturers, composition, properties, and uses of 8,200 engineering alloys.

ELEMENTS of MECHANICS. By H. A. Erikson. 3 ed. N. Y. and Lond., McGraw-Hill Book Co., 1936. 269 p., illus., 8x6 in., cloth, $2.25. A text based on a course at the University of Minnesota.

DESCRIPTIVE GEOMETRY PROBLEM BOOK. By F. W. Bubb. N. Y., Macmillan Co., 1936. Diagrs., 8x11 in., paper, $1.75. Contains 300 problems on detachable sheets of white paper.

PUBLIC UTILITY INDUSTRIES. By G. L. Wilson, J. M. Herring, and R. B. Eutsler. N. Y. and Lond, McGraw-Hill Book Co., 1936. 412 p., illus., 9x6 in., cloth, $3.50. Affords a survey of the economic, legal, and social characteristics of public utility enterprises.

TEXTBOOK of ILLUMINATION. By W. Kunerth. 2 ed. N. Y., J. Wiley and Sons, 1936. 276 p., illus., 10x6 in., lea., $3.00. A short course in illumination, intended for undergraduates.

TELEVISION with CATHODE RAYS. By A. H. Halloran. San Francisco, Pacific Radio Publishing Co., 1936. Illus., 7x5 in., lea., $2.75. The operating principles of the cathode-ray tube and its application to television are explained in terms that can be understood by the amateur radio operator and radio service man.

PHYSIK und TECHNIK der ULTRAKURZEN WELLEN, v. 2. By H. E. Hollmann. Berlin, Julius Springer, 1936. 306 p., illus., 9x6 in., cloth, 33 rm. Describes the practical applications of ultra-short waves, and discusses reception, detection, and transmission.

INDUCTIVE CO-ORDINATION of ELECTRIC POWER and COMMUNICATION CIRCUITS. By L. J. Corbett. San Francisco, J. H. Neblett Pressroom Ltd., 500 Sansome St., 1936. 161 p., illus., 9x6 in., cloth, $3.00. Discusses the factors involved and suggests methods by which detrimental effects can be remedied. Written from the point of view of the power engineer, but considers the problems of the communication engineer also.

HEAVISIDE'S OPERATIONAL CALCULUS, as applied to Engineering and Physics. (Electrical Engineering Texts.) By E. J. Berg. 2 ed. N. Y. and Lond., McGraw-Hill Book Co., 1936. 258 p., illus., 8x6 in., cloth, $3.00. Contains appendices in which various numerical problems are solved. Additional information on the theory of the use of the "unit function" is given.

Der ERDSCHLUSS in HOCHSPANNUNGSNETZEN. By H. Weber. Munich and Berlin, R. Oldenbourg, 1936. 107 p., illus., 10x7 in., paper, 5.80 rm. Discusses the phenomena accompanying grounds in 3-phase distribution systems and the methods of preventing them. Intended for operating engineers and students.

ELEKTROTECHNIK und WITTERUNG. By U. Retzow. Berlin, Julius Springer, 1936. 121 p., 9x6 in., paper, 6.60 rm. Discusses the effects of weather in electrical engineering, including the influence of meteorological elements on overhead lines, the use of wind for generating electricity, influence of altitude on power stations, and disturbances of radio transmission.

Die ELEKTRISCHE KRAFTÜBERTRAGUNG, v. 3, pt. 1. Bau und Betrieb des Kraftwerkes. By H. Kyser. 3 ed. Berlin, Julius Springer, 1936. 573 p., illus., 10x6 in., cloth, 45 rm. Devoted to the mechanical equipment of electric power plants from a practical point of view for the designer and operator.

ELECTRONICS and ELECTRON TUBES. By E. D. McArthur. N. Y., John Wiley and Sons, 1936. 173 p., illus., 9x6 in., $2.50. Describes the fundamental principles governing the action of all electron tubes; mathematics is used sparingly. A chapter is devoted to electron tube construction. Much of the book has appeared serially in the *General Electric Review*.

ELECTRICAL LABORATORY EXPERIMENTS, Theory and Practice. By V. Karapetoff and B. C. Dennison. N. Y., John Wiley and Sons, 1936. 487 p., illus., 9x6 in., lea., $4.00. An abridgment of Karapetoff's "Experimental Electrical Engineering," prepared to meet the demand for a less comprehensive book with the same general method of treatment but better adapted to the average undergraduate course.


**Engineering Societies Library**
29 West 39th Street, New York, N. Y.

MAINTAINED as a public reference library of engineering and the allied sciences, this library is a cooperative activity of the national societies of civil, electrical, mechanical, and mining engineers.

Resources of the library are available also to those unable to visit it in person. Lists of references, copies or translation of articles, and similar assistance may be obtained upon written application, subject only to charges sufficient to cover the cost of the work required.

A collection of modern technical books is available to any member residing in North America at a rental rate of five cents per day per volume, plus transportation charges.

Many other services are obtainable and an inquiry to the director of the library will bring information concerning them.

# Industrial Notes

**Corning Glass Expands.**—To meet the increased production demands, plant facilities of the fibre products division of the Corning Glass Works are being enlarged, and work is well under way in the erection of 3 new buildings having a total area of 46,000 sq. ft. L. W. W. Morrow, formerly editor of the "Electrical World," was recently appointed general manager of this division. Principal applications of the new glass fibre include building insulation, refrigerator linings and air conditioning filters. Potential markets include wire and cable covering and innumerable textile applications to which an inorganic thread or cloth made of glass can be applied. The new glass cloth is heat resistant, waterproof, and non-corroding.

**Copperweld Appointment.**—Roy C. Raasch has recently been appointed field representative for the Copperweld Steel Co., with headquarters at Chicago, Ill. For the past few years he has been in the engineering department of a large utility company.

**Tower Order to Blaw-Knox.**—According to a recent announcement, the Blaw-Knox Co., Pittsburgh, Pa., has received an order for approximately 2000 tons of transmission towers (which will number about 250) for a 220,000 volt line of the Pennsylvania Water & Power Co. of Baltimore.

**New Connector.**—Burndy Engineering Co., Inc., New York City, has announced an addition to their line of grounding connectors "Groundem," type GH. This low-cost connector is for use in joining a ground lead to a driven rod or pipe. Its construction permits it to be slipped over the top of the rod as a one-piece assembly, or, in the event that the rod or pipe has been splayed from driving, it may be readily disassembled and slipped around the conductors. The Groundem is constructed entirely of noncorrosive copper alloys, making it resistant to underground conditions. It is installed with an ordinary wrench and is made in three sizes, each of which will take a range of rod and wire diameters.

**Pacific Electric Now Home Owned.**—According to a recent announcement, the interest of the General Electric Co. in the Pacific Electric Manufacturing Corp., has been purchased by Joseph S. Thompson, president of the latter company. Some eight years ago General Electric secured a virtual half interest in the west coast company, but with the sale of the stock the latter is now an entirely independent organization. It operates a factory occupying two city blocks in San Francisco and a small branch maintenance and storage plant at Gary, Ind. Incorporated in 1906, it is engaged in the manufacture of high voltage air break switches, oil circuit breakers, high voltage fuses and kindred apparatus.

**Calculating Board Kept Busy.**—With increasing loads racing toward the capacity of equipment, many power companies find it necessary to solve quickly new generation and distribution problems. Five companies wishing to determine accurately the added power needed and the load limits and stability of their systems have recently engaged the Westinghouse a-c calculating board to analyze their problems. During the past year eighteen major system studies, involving plants up to 500,000 kva capacity, have been completed on this uniquely efficient board. These systems included eight utilities, six government projects, two industrial plants and two foreign power systems. This is the largest a-c calculating board built to date, and with its 300 circuits it can readily duplicate, by miniature replica, any power system in this country. With its aid, system stability, power factor correction, load-voltage regulation studies and the best location for new generating, transformer and line equipment are readily determined.

# Trade Literature

**Distribution Capacitors.**—Bulletin 3381, 16 pp. Describes the use of "Permittors" (capacitors) for power factor correction in distribution circuits. Products Protection Corp., New Haven, Conn.

**Meters.**—Catalog Sec. 42–210, 16 pp. Describes various types of polyphase detachable meters, applications, construction, operation, adjustment, outline dimensions and wiring diagrams. Westinghouse Electric & Mfg. Co., E. Pittsburgh, Pa.

**Stopwatches.**—Folder. Describes and illustrates 40 different types of stopwatches for industrial and laboratory use. Circular describes stopwatch repair service. A. R. & J. E. Meylan, 268 W. 40th St., New York.

**Motor Repair Supplies.**—Catalog 49, 48 pp. Describes insulation, wire, tools and supplies for the motor repair shop. Prices are included. Reading Electric Co., 227 W. Van Buren St., Chicago, Ill.

**Circuit Breakers.**—Bulletin GEA-2450, 4 pp. Describes type AE-1 air circuit breakers for industrial and central station auxiliary service; 250 volts d-c; 600 volts a-c; 15–600 amperes, 20,000 amperes interrupting rating. General Electric Co., Schenectady, N. Y.

**Measuring Instruments.**—Catalog-type broadside "Power Plant Measuring Instruments, Telemeters, and Automatic Controls." Specific applications are illustrated in electrical generation and transmission, steam generation and distribution, hydro- and diesel power generation, in which the equipment is used. Leeds & Northrup Co., 4962 Stenton Ave., Philadelphia, Pa.

**Oilostatic Transmission System.**—Bulletin, 16 pp. Describes the Bennett Oilostatic transmission system, in which the insulated power cables are installed in buried metal pipe filled with oil maintained under a constant high pressure. Includes details of construction, cable design, cable splices, terminals, pressure maintaining equipment, etc., as well as a detailed outline of all information required to make a study of an Oilostatic application. The Okonite-Callender Cable Co., Paterson, N. J.

**Monel Metal.**—Bulletin, 48 pp. The publication has been prepared primarily as a guide book to Monel and other non-ferrous nickel alloys in the fields of engineering applications. It also covers the corrosion resistance and other properties of these metals. Twenty sub-divisions are included, each devoted to specific problems in fields from hydroelectric and steam power plants to highway maintenance, refrigeration and automobiles. The booklet also describes some of the newer forms of the alloy, including "K" and "S" Monel, etc. International Nickel Co., 67 Wall St., New York City.

**Synchronous Motors.**—Bulletin 1154A, 28 pp. Describes the construction and applications of modern, coupled and engine-type synchronous motors that may now be obtained with torque characteristics suitable for practically any drive, fifty horse power or over, where the squirrel cage induction motor could be used. It deals with the increasing usage of this type of motor due to its uniform high efficiency, at fractional as well as at full loads, and at all speeds, together with its all important function of power factor correction. Allis-Chalmers Mfg. Co., Milwaukee, Wis.

**Industrial Wiring Survey.**—Bulletin, 40 pp. This publication has been designed to facilitate investigation of the condition of the electrical equipment and wiring in industrial plants from the standpoint of ability to carry load, surplus or spare capacity, system defects, safety, deterioration and obsolescence. It gives the logical procedure for making such a survey, provides convenient space for recording findings, and includes recommendations for plans or plot sketches of the existing layout. It is stated that such a study will disclose the weaknesses, if any, in the electrical system, and become a permanent record for determining what parts of the system may be extended under pressing conditions. Anaconda Wire & Cable Co., 25 Broadway, New York City.

**New Clip-On Ammeters.**—Bulletin, 4 pp. Describes a complete new line of dual range clip-on ammeters now available. Originally introduced some 6 years ago, this instrument was at first available only in the standard 0–100/500 ampere combination. Recently additional low and high range combinations have been added to the line so that it is now stocked in 4 standard low range combinations and 3 high range combinations. With these instruments it is possible to measure currents from 1/5 ampere up to 1,000 amperes without opening the circuit or shutting down the equipment under test, or removing insulation from the conductors. The instruments are supplied with fully insulated clips as well as Bakelite handles and may be used with equal safety on insulated or bare conductors. Many minor improvements have been incorporated in the new line. Ferranti Electric, Inc., 30 Rockefeller Plaza, New York City.

# Electrical Engineering

Registered U. S. Patent Office

## *for February 1937—*

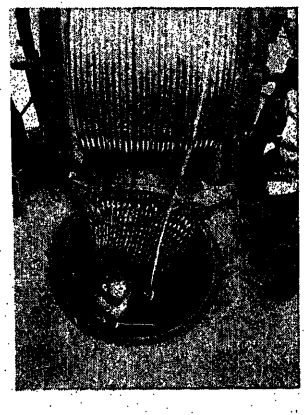

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## The Cover

**Coaxial communication cable being drawn into conduit**

Photo courtesy New Jersey Bell Telephone Co.




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# High Lights

**Water-Level Control.** Control of the water level in a model of the Cape Cod (Mass.) Canal and the automatic recording of water level at several points during studies of flow were accomplished electrically by utilizing the capacitance between the water itself and a plate suspended above it, together with suitable vacuum-tube amplifiers, grid-controlled arc-discharge tubes, and Selsyn motors (*pages 237–44*).

**Engineers and Economics.** Successful economic planning is most hopefully to be looked for if the planners are guided by the approach and method characteristic of an engineer. However, individuals combining this with other essential traits are regarded as rare (*pages 206–07*).

**Japanese Progress.** The characteristics of the Japanese people, their educational system, and cultural and industrial development are reported by a visitor to Japan who finds that country well-equipped to compete with the western world (*pages 208–15*).

**Electrical Machinery.** Reactance of end connections and eddy currents in rotor bars are the subjects of 2 papers in this issue. In one the use of image conductors in iron, of Rayleigh insulating partitions, and of images of conductors in these partitions are shown to afford an attack on the problem of end-connection reactance (*pages 257–60*). The other paper shows that from oscillograms of eddy currents in the rotor bars of a squirrel-cage induction motor, the magnitude of the power loss caused by eddy currents, and its variation with load, may be determined (*pages 253–6*).

**Switchboards.** The power plant at Boulder Dam has been equipped with switchboards notable for their size and for the combination of designs and methods that heretofore have been used individually but seldom together (*pages 224–36*).

**Lightning Investigation.** Data obtained from the measurement of lightning currents in tower structures, counterpoises, and ground wires on a 132-kv line indicate that stroke currents rarely exceed 150,000 amperes and that adequate shielding of lines at station entrances is necessary (*pages 245–52*).

**Stability.** A comprehensive review of the subject of stability of large power systems is presented in a report of an AIEE subcommittee. A summary of the recent practices regarding stability features of many power systems throughout the United States is included (*pages 261–82*).

**Tube Nomenclature.** A committee of the American Standards Association is attempting to simplify the nomenclature of electronic tubes, and toward that end has obtained an agreement by 2 large manufacturers to abandon trademark rights to several names. A tabulation indicating the initial step is given in this issue (*page 284*).

**Unemployment Among Engineers.** Unemployment data from 52,589 engineers throughout the United States, obtained in the 1935 survey of the engineering profession conducted by the United States Bureau of Labor Statistics shows that more than 1/3 of all engineers reporting were unemployed at some time during the years 1929–34; half of these were unemployed for more than a year. The largest proportion unemployed at any one time was about 11 per cent (*pages 216–23*).

**Correction.** An error in photoengraving shifted from its correct position the center vertical scale of figure 11 of the paper "Pole Flexibility as a Factor in Line Design" by Howard P. Seelye and Myron Zucker, as reproduced on page 97 of the January 1937 issue. The corrected figure is shown here.

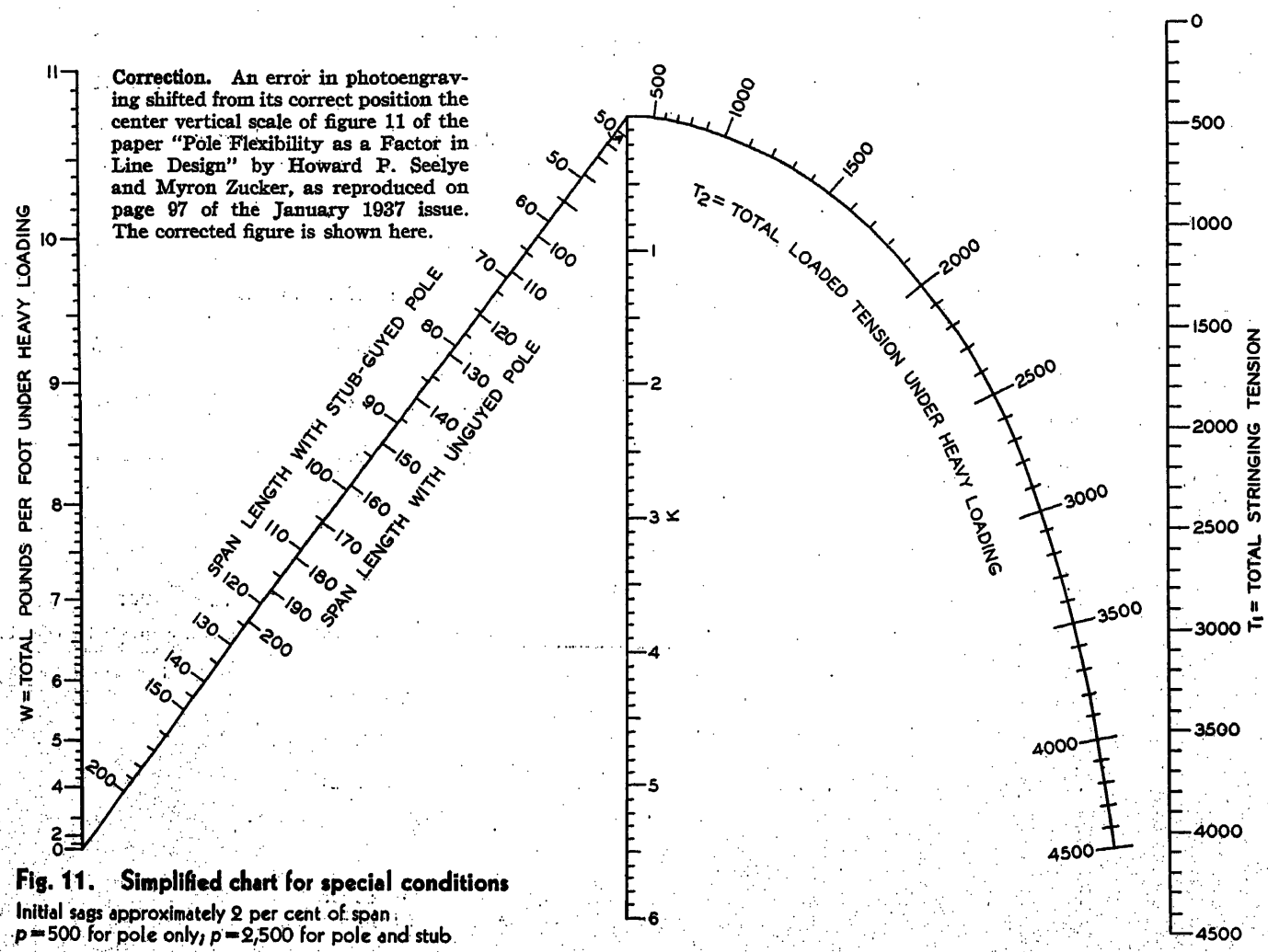



**Fig. 11. Simplified chart for special conditions**

Initial sags approximately 2 per cent of span.
$p = 500$ for pole only; $p = 2{,}500$ for pole and stub.

Statements and opinions given in articles and papers appearing in ELECTRICAL ENGINEERING are the expressions of contributors, for which the Institute assumes no responsibility. Correspondence is invited on all controversial matters. ¶ Subscriptions—$12 per year to United States, Mexico, Cuba, Porto Rico, Hawaii, Philippine Islands, Central and South America, Haiti, Spain, Spanish Colonies; $13 to Canada; $14 elsewhere. Single copy $1.50. ¶ Address changes must be received by the fifteenth of the month to be effective with the succeeding issue. Copies undelivered because of incorrect address cannot be replaced without charge. ¶ ELECTRICAL ENGINEERING is indexed annually by the Institute, weekly and monthly by *Engineering Index*, and monthly by *Industrial Arts Index*; abstracted monthly by *Science Abstracts* (London). ¶ Copyright 1937 by the American Institute of Electrical Engineers. Number of copies this issue—20,850.

# Electrical Engineering

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# The Challenge of 1937

1936 is now history. Whatever we have accomplished, or failed to accomplish, is written into the records and we cannot change it. The engineer is interested in history as a guide to the future, but what most intensely interests him is that which he may accomplish in the future. Every keen-minded member of the American Institute of Electrical Engineers is greatly interested in the future accomplishments of the organization.

We are not satisfied with the performance of our organization, and I hope that we never will be. The greatest stimulus to future accomplishment is a sane and healthy dissatisfaction with the past.

Although not satisfied, we can secure a certain degree of comfort through comparison. I think that we will not suffer in comparison with other technical societies. They too wish to accomplish more than they have in the past. In a broader sense, are we entirely satisfied with affairs throughout the world? Are we entirely satisfied with affairs in our own country? Yet is it not the best country in which we can live? Likewise is not our organization the best one available to us for our professional advancement? Our problem is to make it the best organization possible.

With privilege comes responsibility. It is the privilege of the Institute to represent professionally the electrical engineers of America, and this high privilege implies a deep responsibility of which we should ever be conscious.

During the last year, have we adequately represented the electrical engineering profession in our technical activities? I think we have, but I know that we can do better in 1937. A greater participation of the Sections in the national technical activity is desirable. This does not mean that each Section must set up a technical committee corresponding to each of the national technical committees, but rather that each Section has the privilege of selecting 1, 2, or more technical committees in the work of which that Section is particularly interested. This opportunity is a real challenge to each Section for 1937. I would suggest that the Sections start by selecting the one technical committee in the work of which they are most interested, and organize within the Section a corresponding technical committee. In this way it is possible for every Section to contribute to the national technical activity. The chairman of such a Section technical committee would be a very logical nominee by the Section for membership on the corresponding national technical committee the following year.

Has the Institute in 1936 effectively embraced its opportunity in advancing the professional standing of its members? Here lies another challenge for 1937.

Should there be a gradual and intelligent broadening of the sphere of Institute activities? This deserves very earnest consideration. As one example of what can be accomplished, I was very favorably impressed by a paper "The Engineer's Responsibility to Society" which was presented by a student member at a recent Branch conference held in Pittsburgh, Pa.

Are we satisfied with the 1936 record of members added to our rolls? Before answering, let us consider why a professional engineering society desires addition to its membership. If there be electrical engineers who are qualified for membership but who are not members, the society will be more truly representative of the electrical engineering profession if they were offered the opportunity of joining. If they would then participate in the activities of the organization, it is obvious that the organization would more nearly measure up to its opportunities. The increased financial support from such new members would enable the organization more successfully to carry on all its work. The challenge of 1937 will not be successfully met unless every qualified electrical engineer is offered the opportunity of enrolling in our ranks.

I firmly resolve to do all in my power to meet the inspiring challenge of 1937, and I ask every one of our more than 15,000 members to make the same resolution.



PRESIDENT AIEE

# Engineers and Economics

By MORRIS E. LEEDS
FELLOW AIEE

**The characteristics of engineering that should give the engineer a stronger sense of economic and social responsibility than is sometimes felt by those in other professions are discussed in this article, which suggests that an engineering approach should be made to economic problems.**

MANY individual engineers undoubtedly feel a peculiar sense of obligation to make some contribution to the solution of our economic difficulties, and I think we may safely say that engineers collectively in their organizations share that feeling. The individual sense of responsibility is manifested by numerous writings and statements of men in the profession. As a result of collective efforts we have had the reports of the committee of the American Engineering Council on the relation of production, distribution and consumption, out of which grew a real, though unsuccessful, effort on the part of the Engineering Foundation and the American Engineering Council to plan for such work under engineering auspices with an even broader committee, including representatives of labor and the public.

Of course, engineers are not the only groups that have made such efforts. Many reports addressed to aspects of economics have been issued, representing trade organizations, chambers of commerce, etc., but these have generally concerned themselves quite narrowly with the needs of those for whom they spoke and have assumed, if they considered it at all, that the general welfare would coincide with their own. They do not show the disinterested breadth of view which led the engineers' committee to state as its objective:

"The selection and recommendation of such governmental, financial, and business policies as will maintain in the United States a standard of living that is high, broadly distributed, and free from severe fluctuations."

I wish to discuss particularly those characteristics of engineering which in my judgment should give the engineer a stronger sense of economic and social responsibility than is felt by his brethren of industry and the other professions.

There are those who say that his responsibility is a natural consequence of his conspicuous success. Pursuing his work along the lines of the definition now more than a century old—"the art of directing the great sources of power in nature for the use and convenience of man"—the engineer has done his full part in providing us very rapidly with such a wealth of machinery for producing goods and services and providing transportation and communication, that this good fortune has come on us more quickly than we have learned to manage it, and, lacking that management skill, has become temporarily and in part a misfortune. It is argued that the engineer having contributed so largely to this condition now has the obligation to extend his art to the field of social and political economy so as to make his other contributions an unmixed blessing. There is something in this viewpoint, but responsibility in that sense belongs also to scientists, inventors, perfecters of management, and other innovators. To my thinking, the chief reason for the engineer's responsibility lies in his possession of an approach and method which have been so perfected that they are uniquely valuable for producing practical results under imperfectly understood and complicated circumstances, where, as in the economic realm, traditional methods fail and it is not obvious how to proceed.

The essentials of the engineering approach and method, I take it, are these:

A clear conception and precise statement of the objective to be achieved.

A consideration, as thorough as practicable, of all the factors—be they physical, social or psychological—which will influence or may be employed in getting the desired results; and on the basis of this knowledge—

The formulation of the most effective plans for achieving results that can be developed in the allowable time.

This may seem to many of you to be little more than elementary common sense. Good sense I believe it to be, but common I think it is not.

I have just now referred to this approach and method as uniquely characteristic of the engineer, and taking these steps all together I believe they are. Others may clearly conceive and precisely define their objectives, but in practical affairs that is rare.

Business men for the most part work in fields where experience, tradition, and the pressure of circumstances serve to guide their plans and policies.

Scientists weigh the facts pertinent to their subject perhaps more thoroughly than do engineers, but they seek perfection of classification and description, extension of knowledge and theory, rather than the development of workable plans—and that is a highly significant distinction. Moreover, they are not hampered by a date on which the report is due, while the engineer is almost always limited in that respect. I have heard it said recently that a recognized authority, who has published extensively on the business cycle, has said that he needs 5 years more before he will be in a position to

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MORRIS E. LEEDS is president of the Leeds and Northrup Company, Philadelphia, Pa.

talk definitely about controls. Contrast that viewpoint with, let us say, a bridge engineer. His plans must be ready in a certain time; and if a new material which promises lighter and better structure cannot be sufficiently time-tested to be used safely, he must plan a heavier one known to be safe.

I know of no science, trade, or profession other than engineering that has perfected an approach and method that are so clearly right for dealing with our muddled economics.

Let me explain at this point that when I speak of economic plans I am not talking of something new and strange. Any measure for getting an economic result, such as a tax bill or a tariff act, is an economic plan; and any discussion by which such bills are formulated is economic planning of a sort.

We do not want planning of the Russian type, or except for emergencies, even that of our own War Industries Board. With us economic plans will become effective only as they commend themselves to our people and their legislative representatives. Planning for democratic acceptance *is* going on continuously in an unorganized way through public discussion, in magazines, pamphlets, and books, and a great amount of useful educational work is being done which ranges in value from the ephemeral and trivial to the publications of such men as Maynard Keynes and those of such bodies as the Brookings Institution and the National Bureau of Economic Research. But in spite of this extensive discussion, we still seem far from agreement as to the best means of dealing with our very serious unemployment situation, for instance, and this is only one of a number of important subjects on which we do not have a united or settled opinion. Let me illustrate by reminding you of a few of them.

**How can taxes be levied so as to bring in the desired revenue and distribute the burden equitably?**

**How shall they be apportioned between the states and the nation?**

**Should taxes be used for other purposes than to raise revenue, as the import taxes are used to encourage domestic production?**

**Can they be planned to moderate instead of intensify the business cycle?**

**Will prosperity be enhanced by a policy which excludes practically everything that we can produce in our own country, or by one that encourages a large exchange with other countries; or if by some intermediate position, how shall that position be determined?**

**How are we to maintain balance between production and consumption; between agriculture and industry, etc.?**

**At various stages of national wealth, what proportion of the total should be expended publicly by government?**

**What about foreign debts, credit and finance?**

It is in connection with this complex situation that economic plans are to be developed, and in order to be effective they must have popular democratic acceptance. I repeat that success is most hopefully to be looked for if the planners are guided by the engineer's approach and method. Thus guided:

**1. They would clearly envisage their objective and would probably state it in some such language as the engineers did, that is, a level of national prosperity that is high, widely and fairly distributed, and free from serious interruptions.**

**2. They would take into consideration all the factors, be they physical, social, or psychological, which will influence or may be employed in getting the desired results. This will include an understanding of the conditions necessary for getting popular acceptance.**

**3. On the basis of the available knowledge they would present the best practical plan for achieving the results that the time available permitted. The time factor is important. The plan must be one that can be put through at some specific time, and one that will work after it is enacted, with conditions as they are.**

It may be questioned whether those who have attained proficiency in some branch of their profession will thereby be best fitted to translate this fundamental engineering attitude to such an alien field as economics. An essential condition is that all the pertinent factors, including the social and the psychological, be taken into consideration. Perhaps the engineer, who has become accustomed to and has chiefly dealt with the dependable phenomena of the physical world, would thereby be unfitted for dealing with economic phenomena in which human will and emotion and mass psychology play so large a part. The practice of engineering will not in itself familiarize one with the vast body of economic fact and theory.

This is my conception of the kind of men who would best qualify for economic planning. They will be men who understand the engineering approach and method, whether trained in the profession or out of it. They will be men who have so risen above any particular industry or profession, through which they have achieved eminence, that they will be able to see society and its needs as a whole. They should have the steadiness and dependability which come from successful adjustment of their own affairs to practical conditions, and, along with those qualities, should be marked by a high degree of social idealism. A rare type! There are many men who have the first of these qualifications; many who have the second; few who combine them. Of the few men whom I know or know about who seem to have these qualifications, one is an engineer, another was a lawyer and is now a judge, and a third is a business man.

So I conclude, you see, that it is not the vast knowledge of the engineer nor the skills and techniques of the profession, useful as these may be, that put him in position to make a uniquely valuable contribution to the art of dealing with complex economic situations, but I believe he can make such a contribution by passing over into the field of economic practice his habitual way of looking at and dealing with problems, which leads him to see clearly what he wants to accomplish, to take into account systematically all the factors and circumstances which will influence results, and then plan so that the objective may be achieved as nearly as possible by the time wanted and under existing conditions.

It is interesting to consider how the engineering profession might make this contribution. Individual engineers can emphasize the engineering method in their own discussion of economic subjects and urge it in connection

(*Concluded on page 215*)

# Industrial and Cultural Japan

By DUGALD C. JACKSON
PAST-PRESIDENT, AIEE

**Education and industrial development in the Japanese Empire are here described as seen by the author during his visits to that country, in which he recently delivered a series of lectures under the Iwadare Foundation.**

JAPAN and its industries present a picture of interest and significance from many angles. The facts and opinions outlined in this paper were secured in 2 visits to Japan 6 years apart and each of some weeks' duration, a considerable part of the time of each visit having been spent in observing as a matter of personal interest the education and the industry in that engaging country.

## Characteristics of the Japanese People

The population of the Japanese empire is now counted as about 95,000,000 people. These are included in the islands of Japan proper and in Chosen (Korea), which is a peninsula of the Asiatic mainland, the island of Taiwan (Formosa), and a few small islands. It is a notably literate population, vying with the United States in the percentage of literacy. The Japanese people are full of sentiment for their ideals in art and literature, for their interpretation of heroes and heroism, and for the beauties of nature as exhibited in Japan; but they also are realists—shrewd and practical.

Americans generally have heard much of the sentimentalism of the Japanese people and have heard little of the other side of their nature and habits. The exaggerated sentimentality of Pierre Loti's writings and the sympathetic interpretation of Lafcadio Hearn have influenced American thought on one side only, and we have not secured a balanced view of this people. There is a degree of reason in this. Even the British poet laureate, Masefield, mystically traces in glamorous words the lure of the broad Orient in his poem describing the stores of the Eastern Merchants:

"We have been told that in the East are things
Flame-guarded by the Phoenix' burning wings,
The Sunstones of the Everlasting Kings;

"The Moonstones from the Woman of the Sea,
The Changestones that compel Eternity
To that which *is*, but yet can never be.

* * * * *

"And silks, that the worm spins and man refines,
Silk of the East with sunlight in its lines
That, at each turn, with other color shines."

* * * * *

In the light of such delightful legends it was easy for Americans to fall under the spell proclaimed by the sentimentalists. It was also easy for a pragmatic people to miss the truth on the other side. We did so in distress over an embarrassing influx into California of low-class coolies, a third of a century ago, and we assumed a patronizing attitude toward the Japanese because some of our citizens (in contact with an inferior class) confused that class with the entire race and dubbed the race inferior.

The recent strong place in the world of affairs that has been assumed by the Japanese nation emphasizes the importance of a fuller examination of the facts and a better understanding by Americans of the Japanese people, their ambitions and their ideals.

In their original feudal stage the Japanese authorities seem to have had neither desire for, nor strong antipathy toward, contact with foreigners. However, clashes with western traders and western proselytizers, who refused to yield to feudal regulations, led to exclusion of foreigners from Japanese soil and the prohibition of almost all trading contacts or privileges. Lasting several hundred years (during which the expostulations of western nations were rebuffed), this state of affairs was disturbed by Commodore Perry of the United States Navy who, in 1853, on behalf of our Government, made approaches to the Japanese authorities for the purpose of establishing mutual relations of friendly nature between the 2 nations and their citizens. Contact having been made, he then temporarily withdrew.

Commodore Perry returned to Japan in 1854, and this time succeeded in opening restricted diplomatic and commercial relations for the United States. European nations joined with America in this opening of Japan anew to foreign intercourse. Our earliest official commercial agent, Townsend Harris, was fortunate in his qualities of forbearance in a somewhat hostile setting, tolerance toward (to him) strange religious beliefs, and competence of imagination for picturing the points of view of alien peoples. The European nations were not so free from the arrogance that arose from an assumed superiority of intellectual level. Neither have we Americans been at all times free from arrogance since the days of Commodore Perry and Townsend Harris, but Harris has stood (in the imagination of the Japanese people) as a representative of the friendly qualities of the American people. We likewise have touched the hearts of the Japanese at other times and by other means, of which a notable example arose through the noble manner, as well as the magnitude,

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of our aid to Japan on the occasion of that cataclysmic Yokohama-Tokyo earthquake and conflagration of 1923, which destroyed over 100,000 lives and rendered 1¾ millions of people homeless. The cost to Japan of reconstruction which followed that disaster is estimated at more than 5 billion yen.

Through such relations the informed Japanese feel a deep sense of gratitude toward the United States and its people. But this is offset by the sense of resentment which rests on the whole Japanese population, for what they consider our not infrequently patronizing attitude toward them due to racial differences.

Now the Japanese nation has come to vie with the western nations in diplomacy, industry, education, and international commerce. They started on their career in these fields short of 70 years ago. Their progress in industrial affairs during the 70 years, while in competition with the most active industrial developments of the western world, proves them to be a people of intellectual power rivaling the intellectual powers of their western competitors, as was foreseen by Theodore Roosevelt in 1906. We of the United States are their most important customers in international trade. They are high in order of importance among our customers. Our greatest commercial importation from them is raw silk. Their purchases from us include much cotton, but (although they have become great industrialists themselves) also include considerable machinery and other products of manufacture.

## Japanese Education

It is time for the American people to awaken to the fact that the Japanese are a highly educated people possessing intellectual powers rivaling our own and inventive genius in government and industry which has become matured and capable by experience. Japan is a nation with which (as in the case of other strong nations) we are having and will continue to have commercial rivalries and causes of friction demanding tactful adjustment; but it is a nation which cannot afford serious differences with us, nor can such differences become acute without loss to ourselves.

For satisfactory acquaintance between the peoples of 2 nations it is desirable that each of the peoples shall know something of the educational processes carried on in the other nation. Only through such knowledge can truly friendly relationships grow up and be maintained; and only through such knowledge can misconceptions arising from false diplomacy or errors of commercial processes be avoided, or (if occurring) can be prevented from becoming causes of friction. If one knows the processes of education of a people, one may, in a sense, claim to know the characteristics of that people. The writer's observations in his 2 visits to Japan, 6 years apart, each of some weeks' duration, as already said, added to a long life spent in American industry and engineering education, indicate a definite lack of understanding among the Americans and the Japanese people regarding the processes of education in the other nation. In each nation there are but few individual exceptions to this lack. It is also notably true that the Americans lack understanding of the Japanese civilization and that the Japanese (except for a relatively few individuals among the whole) equally lack a conception of the American land or the lives of its people. Space available gives but little opportunity to deal with these features, but the importance of the matter justifies as full an outline as practicable.

In 1868 the Japanese Emperor Meiji shook off the control of the Shogun and took full administrative control in the nation. Feudalism was overthrown. The Meiji Emperor was a man of force and character with a will for the betterment of his people. With the advice and aid of commissions of able Japanese statesmen sent to Europe and America to gather data and formulate recommendations, a parliamentary government was formed, financial and commercial processes were outlined, and education for the masses was established.

By 1872 a unified plan for elementary, intermediate, and higher education was outlined for Japan, following rather clearly the French standards in the elementary and intermediate processes. By 1880, attendance at school by children up to certain ages was made compulsory. These educational processes established under the Meiji Emperor have reasonably well fulfilled the expectation for old Japan which is set forth in the Imperial Proclamation, which reads: "Henceforward education shall be so devised that there shall be no ignorant family in the land and no family with an ignorant member."

The elementary educational processes have been modified from time to time since the early establishment of general education, and various later doctrines which have served well in Europe and America have been introduced, besides modifications which seem best suited to the national requirements of the Japanese people. In no land is the welfare of the school children more cherished than in Japan, and solicitous attention is given to their physical welfare as well as their intellectual welfare. As an evidence of the results of care for the physical welfare, statistics are given which



**Edison memorial at Yawata, site of original source of bamboo for incandescent-lamp filaments; Professor Jackson is in the center of the group**

show that the stature of the children is increasing in height compared with earlier groups. The children also are taken on visits to beauty centers (which are so numerous in Japan), to notable temples and shrines, to museums of art, and to centers of creative thought.

It is now characteristic of the schools that the children work at desks, sitting on benches, instead of following the old Japanese custom of sitting on the floor with little tables before them. The children are usually in uniform dress, which is determined by government, those for the boys corresponding to trousers and jacket suits such as we often see in the west, and for the girls, to skirt and blouse suits, such as we also see in the west. These garments are much more convenient for wear during active exercise or when sitting at the desks than the old-time kimono garments, although the latter are commonly worn at home on account of their relative comfort.



**Ancient flowering cherry tree in Kyoto, said to be 400 years old**

The elementary education covers a period of a half-dozen years or more. The instruction is done in the Japanese language and no foreign language is taught in most of the elementary schools. The children follow educational processes that are not particularly different from those of the western world but much more attention is given to bringing the pupils in contact with the national ideals than we usually find in the western schools. Indeed, the attention which is given to the health of the children and the supervision of their athletic exercises match our best efforts; and the children's organized visits to seats of great national reputation and natural beauty, and to important shrines and temples, excel the corresponding procedures which we find in the west.

Through these processes, the children grow up in Japan with a wonderful appreciation of the beauties and the symmetries of nature and art in their country, besides being educated in the usual fashion that we associate with literacy. The selection of school teachers is made under rigorous requirements relating to preparation for the teaching work.

Secondary education is carried on equally scrupulously in Japan, although a much smaller percentage of the children transfer from the elementary education into the secondary education than we now find in America. That is, the compulsory education in Japan only applies (for most part) to the elementary portion and the age at which children are released from the compulsion is several years younger than it is in certain of our states. In thinking of these things, however, we must remember that the statutes of Japan apply to the whole nation, with the exception of special provisions made for Chosen and Taiwan, while in the United States we have requirements of different scope in the different states.

For the secondary education, one finds schools of general education (usually referred to as middle schools) and also vocational schools, all of excellent grade. In these schools a foreign language is included, which is usually English, French, or German. Since the emphasis is on English, it is possible for an English-speaking visitor to Japan to find a considerable competency in English among the Japanese, and it is almost always easy to find an interpreter. The structure of the Japanese language is so markedly different from English or any other of the western languages that the usual visitor from the west is not quickly tempted to try to learn something of the native language, as he is when visiting in western countries which are neighboring on his own.

Among the vocational schools there are very adequate groups which deal with the particular problems of agriculture, industry, and commerce.

The university program of Japan now is quite extensive. There are in old Japan 6 Imperial universities, and one each in Chosen and Taiwan. These universities, supported by the government, are all of fine order. They are reinforced by many other universities, higher scientific schools, higher commercial schools, research institutes, and other higher institutions which have not yet reached (or are not intended for) the scope required for designation as Imperial universities, which designation is conferred under statute by the Ministry of Education. Some of the institutions other than Imperial universities are the result of private endowments, but many are sup-

ported by government funds in a manner similar to the support of Imperial universities. Some are sustained for limited purposes, such as education and research in the fields of medicine, engineering, agriculture, or other fields of special import, or as institutes of research in particular branches of science. Important research in fields of science, with emphasis on applied science, is also fruitfully supported by government ministries and by private industrial organizations. An official organization, which is somewhat analogous to our National Research Council, is supported by the government.

While schooling is compulsory through adolescence, the admissions to Imperial universities and other government-supported institutions of higher education and research are usually by competitive examination accompanied by rigorous limitation in the numbers of students accepted. Consequently the numbers of students in the universities and higher professional schools are apparently less, proportionally, than we have in America. This seems notably true of the engineering classes, medical classes, and classes of students in other professional branches; but the standards of work in these branches are established on an admirably high level. For intermediate work in these branches there are available a certain proportion of polytechnic schools, commercial schools, schools of practical agriculture, and such like.

Education in science is recognized by the Japanese government and people to be a feature of great importance during the expansion of the Japanese industries which now is going on. A country coming in the last part of the nineteenth century, as a novice, to develop a western type of education in science and an active participation in industrial production, appropriately may give first encouragement to rigorous education and research in improved applications of science, and rely at first on the already established nations for the production of fundamental, new, discoveries on which to build further. This is especially true where ready money is not easily forthcoming for budgets. The wisdom of the Japanese led them originally to that practice, but they are now established in full appreciation of the advantages to themselves of supporting a suitable part of the world's work of research in the fundamental aspects of science. They do the latter without lessening their attention to further creative work in the useful applications of science or lessening their enthusiasm for art and literature.

## Japanese Industrial Development

Japan is deeply affected by the electric forces set up by industrialization, which draw people into increasingly populous urban areas. Tokyo, the national capital, is associated with Yokohama and 2 intervening smaller industrial municipalities to make an industrial area of continuous urban population, which is the third largest continuous urban population in the world, being exceeded only by New York and London. This is Japan's greatest center of commerce, finance, industry, and dipolmacy. The seat of the Imperial government (with its imperial residence, its ministries, and parliament house) is located in Tokyo. The area is one of great intellectual and commercial activity.

Osaka is another center of great industrial and business activity, like Chicago, with several million inhabitants. Nagoya is still another large and important industrial municipality. In addition, industrial activity is widely spread over the home islands of Japan. The continuing repute that the Japanese are solely copyists and cannot become creative industrialists is belied by the factories scattered through a wide area in which are manufactured a variety of originally designed products, often made on Japanese machine tools, Japanese looms, and other Japanese machinery.



**A very old Japanese bridge of wood, bronze, and iron, reputed to have been built in 1673**

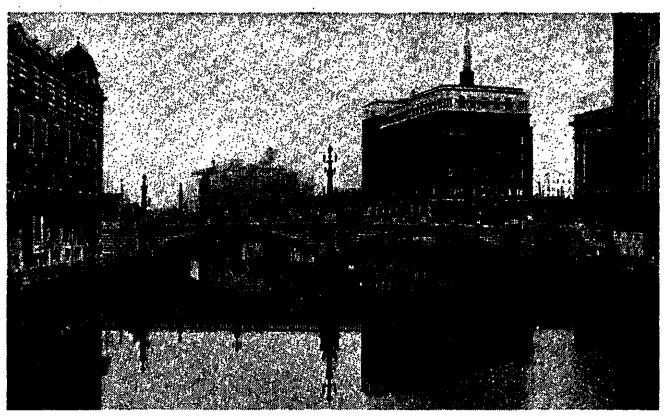
The Japanese build their own ships and now bid for ship construction for other nations. They build their own railroad motive-power and rolling stock. They design and manufacture their own electrical machinery. They are beginning the manufacture of automobiles. They manufacture their own steel, although most of the

A panoramic view of the Inawashira power development, one of those which provide hydroelectric power to the Tokyo Electric Company



iron ore and much coal must be imported. They are rapidly developing in the field of chemical manufacture. They are notable in the manufacture of textile goods and ceramic goods. And so on it runs through a wide range of manufactured commodities and specialties. The Japanese are pressing for an increased export trade. They are keen competitors, and we must be sagacious as well as alert in protecting our trade situation, even in our home markets, if we are to succeed in doing so without serious friction.

The Japanese were copyists (indeed, they were assiduous copyists) in the early days of their era of industrialization, as we also were copyists when we were young in industrialization, and the Germans were copyists (often to the distress of American makers of machine tools and other machines) in the early days of their industrialization. Like these other nations, the Japanese have become competent to stand, industrially, on their own feet although the nation woefully lacks possession of sources of many needed raw materials.



A view in reconstructed Tokyo, showing the Sumida River

It is difficult for Americans, living in a continental country possessing sources of raw materials for almost the gamut of our needs, to appreciate the gravity of the situation for an insular nation which lacks in essential supplies, and to further appreciate the pressure for expansion which that situation imposes. In fact, it is even difficult for citizens of Great Britain, a nation that has met such a situation by the development of a surpassingly great sea-borne commerce, to view sympathetically the efforts of a growing industrial nation in seeking to assure its position by gaining a like status.

The Japanese have demonstrated their ambition and their ability, and we must face the fact that they are competent, and also insistent, as competitors for world trade in manufactured products. They came late into this trade as competitors, but they entered it seriously and with the intent to stay. For illustration, with one exception of a wooden ship, no ship of more than 1,000 tons had ever been built in Japan before 1895. Now at least 4 of their competent group of shipyards and navy yards have built ships up to 30,000 tons.

The Japanese are industrious workers and very thrifty. In the agricultural areas, the farm families live from the produce of tiny (in our ideas) farms of from 1 to 3 acres, which they intensively cultivate in every available square foot. Earnings of daughters and sons who have gone into industrial employment bring some ready money to the pockets of farmers, and (to the farmers) the profitable export of manufactured products seems a life line. In their opinion, this life line must be maintained and the nation must be strong in military power and in shipping in order that the life line shall be maintained. The farmers' families work long hours over their crops, but the hours of industrial workers are limited by law to weekly hours that compare on all-fours with those in American factories.

Japan is not a nation of great *per capita* wealth. It is difficult to secure reliable estimates of such wealth, but the Japanese government has published certain estimates which, converted into dollars on the present basis of exchange, make a sorry comparison with our estimated *per capita* wealth. However, such a comparison is superficial and inconclusive. A yen (Japan's principal money unit) buys in Japan about as much food, shelter, and clothing of the character demanded by Japanese as a dollar buys in this country to meet our needs, and on this basis of comparison for the yen Japan possesses *per capita* wealth which is in keeping with that available in several of the important European countries. Although the ratio with our status, even on this basis, may still be low, the Japanese possess a fair amount of working capital, and the development of further capital is progressing with considerable speed.

The exigencies of military expansion are absorbing a great deal of money for nonproductive uses, and the public debt is expanding. When doubt is expressed of the wisdom of this policy, attention is politely directed to the extraordinary magnitude of our "New Deal" expenditures. Pertinent as is this retort, there nevertheless is a difference which weakens the analogy. Of the total present Japanese funded debt, public and private, perhaps one-quarter as much has been borrowed abroad as at home and the debt service siphons a good deal of wealth away from the country. Establishing textile mills and other industrial establishments abroad, as the Japanese have done in China, also draws wealth from its native land, and diverts wages from homeland wage earners. Increased profits accruing to the homeland may not offset these disadvantages in the case of a country which is without excess of wealth, but the Japanese have proved to be astute in commerce and finance and their wisdom may enable them to avoid undue difficulty from the situation.

## Present Status of Japanese Industry

The World War had a great influence on Japanese industry, and nations meeting Japan in lively competition



A scene in Tokyo illustrating the charm of Japanese architecture

for world's trade in manufactured products can lay much of Japan's present industrial stature to the impulse arising out of the demands of that war. Up to 1914 the industrial situation in Japan had been for a decade or more in a state of expansion at a moderate rate, but during the World War, Japanese industries embraced the opportunity for very rapidly expanding their world trade, and industrial production bounded upward accompanied by rapid expansion of plant and enlargement of the number of industrial employees. The principles of mass production, guided by scientific management, were adopted in many localities. Manufacture of iron and steel, electrical machinery, machine tools, textile goods, ceramic goods, chemical goods, matches, portland cement, paper, and other commodities were all pressed forward, as also was the preparation of foodstuffs.

The homeland (that is old Japan, which consists of the islands of Honshū, Kyushū, Shikoku, Hokkaidō, and accessory islands), possesses some 48,000 kilometers of coast line, indented with some 1,900 harbors, of which 153 are important. The great industrial cities are located on these harbors, and deep water is directly alongside many factories. A great deal of local transportation of goods is therefore by water, and shipping is of large importance. Bounties for ship building and subsidies for ship operation have been part of government policy.

Electric power, generated both by fuel and water, has been largely developed, and power transmitted at 154 kv serves the larger centers. It is estimated that $6^{3}/_{4}$ million horsepower in firm power and $13^{1}/_{2}$ million horsepower in 6-months' power may be secured from water power when the potential hydroelectric plants are all developed. As coal is of reasonable price, much fuel-generated power is associated with the water power. If any reader desires more specific information regarding the Japanese electrical industries, he may refer to my very brief article relating to them which was published in *Electrical World*, July 18, 1936. It is said that seven-eighths of the houses of the homeland use electricity, but the domestic use of kilowatt-hours is actually small because of the few lamps installed in most houses and the low wattage of those installed, and modest incomes preclude the general purchase of electric household appliances.

Mining is a very old art in Japan, and a long list of minerals are mined; but, of the more important mineral ores and commodities, the supply from Japanese soil is insufficient for present industrial demands and importation has to be resorted to. Nevertheless, Japan now is producing most of its own requirements in iron and steel, using mostly imported iron ore and some imported coal.

Industrial wages of Japan are small (when converted to American money at the rates of international exchange) compared with wages in this country, but (as previously pointed out) this makes an inconclusive comparison. In comparison with cost of food, clothing, and shelter in the 2 countries, the Japanese working people are as well paid as our working people were some decades ago, and in the many plants, of many varieties of production, which I have visited, the working people look healthy, well fed, contented, and interested in their work. Our manufacturers who feel the pinch of Japanese competition must come to understand that the Japanese accomplishments are not secured by oppression or exploitation of the working people. Acumen and good management, associated with an as yet relatively very low cost of living, make the combination that has brought the Japanese competition to success. Aid to export business given by the government has also contributed its advantages to the Japanese exporters.

As to the manufacturing processes of the Japanese, they are good. They have been greatly improved during the past half-dozen years. Accuracy in mass production is secured in the factories. Committees participate in



A Japanese private garden at Kyoto

international standards conferences and set standards of construction and manufacture for Japan. Refined testing machines, measuring instruments, and other instruments of precision of Japanese manufacture are now generally available. Research laboratories, working devotedly on the problems within their respective fields, are a general feature of the industries, the government ministries, and departments of universities.

As household industries were developed in feudal times and have continued to the present time, many items of industry are still produced in this informal manner. Such products are likely to be of variable quality, or of low grade, and the government is reported to have plans for putting all such products through tests and inspection in case the products are intended for exportation. This has already been done, for perhaps a dozen years, for raw silk, and may now be in practice for other commodities.

## Ethics and Religion of the Japanese

Shintoism and Buddhism are the religions most influential in Japan, but Shintoism is easily the first in influence, being bound up with the cult of the 3 sacred objects (the sword, the jewel, and the mirror), and the divine paternity of the Emperor. The Japanese are fundamentalists on the divine descent of the Emperor, and their ethics are bound up with that tenet. This gives an aspect to Japanese ethics which is not found in the ethics recognized in western nations, or recognized among the Chinese whose ethics came down through the illuminating interpretation of Confucius.

Perhaps part of the friction between the Americans and the Japanese arises from this component of ethics which lacks mutuality. We compose 2 peoples with present-day cultural ideals somewhat alike, with ethics similar in the main, but with one deeply modifying aspect which pertains to the beliefs of the people of one of the nations. The highest ideal of a Japanese citizen is sincerely bound up in loyalty to the Emperor and the welfare of the nation. The honor of the Japanese individual lies there first. Man-to-man relations and commercial relations trail after, as a matter of fundamental religion.

The western world has been in diplomatic and commercial relations with Japan and the Japanese for only about three-quarters of a century. This is a short time within which to secure mutual understanding between 2 self-reliant and ambitious peoples who live in such diverse situations and are of such diverse antecedents. Suddenly established extreme and continuous intimacy requires time for making adjustments before understanding is established and frictions are overcome. This situation of sudden intimacy has been imposed on the relations of the peoples of the United States and Japan by the intimacies due to steam-power transportation and new modes of quick communication. Sufficient time has not yet elapsed for the roughnesses of contact to be smoothed and softened by experience and adjustment.

Can the causes of friction between our 2 nations be eradicated?

In the realm of science, a theory is a statement which is equivalent to the explanation of any relationships which have been discovered to exist between measured apparent facts. This serves as a guide in seeking out additional relationships. The situation in international affairs, unhappily, is too complex for fitting a theory to guide the adjustment of relationships. In the example of these 2 great nations, our differences can only be adjusted by continued mutual observation, self-restraint, tolerance, and good sense, which lead to mutual respect and appreciation.

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## Engineers and Economics

(*Continued from page 207*)

with discussion by others. But the situation is so vast and complicated and has so many divisions which interact on each other that it seems to be beyond individual effort and to call for the kind of mass attack which our great industries use in their research and engineering departments for dealing with their physical problems. The telephone industry furnishes outstanding illustration of what I mean. Theodore Vail, and the able men who succeeded him, appear to have set for themselves the ideal goal of producing communication machinery through which anyone anywhere in the world may talk to anyone anywhere else, and they have gone an amazing distance toward the realization of that goal. That has involved dealing with a vast complexity of subjects which range from elementary engineering to advanced and difficult mathematics and physics. How far would the art have progressed by now if the leaders of the industry had contented themselves with development by the tedious and uncertain processes by which we have been satisfied for the most part and until recently, to allow our knowledge of economics to translate itself into working plans? They organized for the attack on their problem great research and engineering establishments, staffed them with the ablest men they could command, and backed them financially on a magnificent scale.

A few similar organizations for mass attack on the economic problem are already in existence. The National Bureau of Economic Research and the Brookings Institution, already referred to, are 2 outstanding illustrations. Others, such as the Falk Foundation, The Twentieth Century Fund, and the National Industrial Conference Board, might be mentioned. In varying degrees numerous other organizations deal with limited areas of applied economics. Graduate schools of business administration, management societies, trade associations, etc., are in this class. It is a common experience of engineers, as they rise in their profession, to find themselves drawn more and more into management and administration, and through these interests into association with organizations of the kinds just mentioned. Here they have an opportunity to carry the engineering approach into a field where it is much needed, and to help build on the basis of economic theory and knowledge a socially useful art of economics.

# Unemployment in the Engineering Profession

**Reporting further upon the results of the 1935 survey of the engineering profession conducted by the United States Bureau of Labor Statistics, at the request and with the co-operation of American Engineering Council, this article* presents the Bureau's analysis of the unemployment data obtained.**

AS FAR as is known, the recent depression was unique in its disastrous repercussions upon professional groups. Unemployment has for decades been recognized as a major form of insecurity affecting wage earners, and fairly reliable data concerning this have been made available from time to time. Precise knowledge as to the extent of the depression's impact upon professional workers, however, has been lacking.

As a result of a survey of the engineering profession undertaken in May 1935 by the United States Bureau of Labor Statistics, at the request of American Engineering Council, it may now be said that at the end of 1932 more than $^1/_{10}$ of the engineers were simultaneously unemployed, that at one time or another between the beginning of 1930 and the end of 1934 more than $^1/_3$ of the engineers had some period of unemployment, and that half of those who became unemployed were out of work for more than a year. Unfortunately, there are no comparable data for the other professions.

From the 52,589 reports from professional engineers throughout the country, the following summary analysis of unemployment, including work relief and direct relief, may be presented:

1. Between the end of 1929 and 1932, the percentage of engineers who were unemployed increased from 0.7 to 10.9. At the end of 1934 the percentage was 8.9.

2. At no time was direct relief extensive among engineers, but the development of work-relief programs after 1932 became an important factor. Although 10.9 per cent of all engineers reporting were unemployed on December 31, 1932, less than $^1/_{15}$ of those unemployed were on work relief. On December 31, 1934, 4.0 per cent of all engineers reporting had work relief, that is, almost half the total number of engineers unemployed at that time.

3. The largest number unemployed at any one time was about 11 per cent of the total, but more than a third of the engineers had some period of unemployment within the 5 years, 1930–34.

4. Among those who became unemployed at some time during these 5 years, half were out of employment (except as they found work relief) for more than a year.

5. This experience with unemployment was common to all professional classes of engineers. In 1932 unemployment ranged from 10.1 per cent among chemical and ceramic engineers to 11.6 per cent among electrical engineers. In 1934 approximately 8 per cent of the electrical, mechanical, and industrial and of the mining and metallurgical engineers were unemployed. The percentage of unemployment dropped most among chemical engineers, of whom 6.8 per cent were unemployed in December 1934. There was a slight increase in unemployment among civil engineers from 1932 to 1934.

6. The most marked differences as regards unemployment are those found among the various age groups. The greatest frequency of unemployment was among those who attempted to enter the profession after 1929. Approximately half of them were unemployed at one time or another from 1930 to 1934. Older engineers, who were already professionally established prior to 1929, were less frequently unemployed, though even among those with 20 or more years of experience $^1/_4$ had some unemployment.

7. When the older engineers became unemployed, however, unemployment lasted longer than it did with the younger engineers. Thus, the median period of unemployment for engineers graduating in 1925–29 was 12.1 months, whereas the median for those graduating prior to 1905 was 23.1 months.

8. The effect of this longer period of unemployment among older engineers was cumulatively to produce a higher percentage of unemployment among older engineers than among younger engineers. Thus, in December 1934, 11.5 per cent of the engineers 53 years of age or more were unemployed, in contrast to an average of 7.3 per cent of the younger engineers who were exposed for the same period to the risk of possible unemployment.

9. The type of education the professional engineer had received did effect variations on both the incidence and severity of unemployment. These factors were very much less for postgraduates than for engineers with other types of education. But as between engineers with first degrees in engineering and those whose college course was incomplete or who had attended noncollegiate technical schools, the differentials were very slight.

10. The influence of regional location on unemployment was practically negligible, whether considered from the point of view of differentials in incidence or of severity of unemployment.

The sources of these data are the replies received to a questionnaire mailed to 173,151 engineers. One question called for employment status on each of 3 dates, thus giving a cross section as to employment, unemployment, work relief, and direct relief on December 31, 1929, 1932, and 1934. From these reports the general trends of unemployment have been traced. A second question related to the number of months of unemployment over the 60-month period January 1, 1930, to December 31, 1934. Consequently, it is possible to measure the incidence and severity of unemployment, work relief, and direct relief for 5 years of the depression, as well as at other dates.

In keeping with the other analyses of this survey, these subjects, wherever warranted, are so presented as to determine their significance when related to (1) type of education, (2) professional class, (3) age, and (4) regional location.

## Unemployment at End of 1929, 1932, and 1934

The first part of the discussion will be concerned with trends in unemployment. For the country as a whole

* Essential substance of an article prepared by A. F. Hinrichs, chief economist, and Andrew Fraser, Jr., of the Division of Wages, Hours, and Working Conditions, Bureau of Labor Statistics, United States Department of Labor, which article was published in the January issue of the *Monthly Labor Review*. This is the second of a series of summary articles covering the results of this survey. The first article dealt with the educational qualifications of the engineer, and was published in the *Monthly Labor Review* for June 1936 (page 1528); also reprinted as Bureau of Labor Statistics Serial No. R 400. The essential substance of the first article was published in the August 1936 issue of ELECTRICAL ENGINEERING, pages 863–7. A detailed report of the survey will be published later in bulletin form by the Bureau of Labor Statistics.

there was an appreciable decrease in unemployment among professional engineers between December 31, 1932, and December 31, 1934. Thus, while the proportion unemployed on December 31 rose from 0.7 per cent in 1929 to 10.9 per cent in 1932, it had declined to 8.9 per cent by 1934 (table I).

The decreases in unemployment among engineers from 1932 to 1934 must not be thought to imply an increase in the proportion engaged in engineering employments. While a larger proportion[1] of the engineers were employed in 1934 than in 1932, the gain, if all professional classes are considered in combination, occurred in nonengineering work. Increases of nonengineering employment were particularly important to electrical engineers. Only in the case of mining and metallurgical engineers was there a large increase in the percentage reporting engineering employment.

The most striking fact in table I is the narrow range in the proportions of unemployment among the various professional groups for each of the 3 periods. This is especially true for 1932 with a range of from 10.1 per cent for the chemical and ceramic engineers group to 11.6 per cent for the electrical engineers.

ships occurred in 1934, although, for all but civil engineers the decrease in unemployment was marked.

There is no clear evidence in table I of a relationship between the extent of unemployment among those engineers whose college work was incomplete, or who attended noncollegiate technical schools, and those who had first degrees.

### Age

The outstanding feature of table II is that a larger proportion of the older engineers remained unemployed on December 31, 1934, than was true of those graduating from 1905 to 1932. Further inspection of table II shows very clearly that by December 1934 many of the older engineers were still unable to obtain work; and there is a very strong presumption that the preference in new hirings was given to the younger man. This is partly explicable on the grounds that, first, the older engineers probably were in a better position financially to weather the continuing depression, and second, that the available professional employment opportunities were of such a

**Table I—Per Cent of Engineers of Each Professional Class Unemployed* on December 31, 1929, 1932, and 1934, by Type of Education**

| Professional Class‡ | Per Cent Unemployed on Dec. 31— | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 1929 | | | | | 1932 | | | | | 1934 | | | |
| | | Others with— | | | | | Others with— | | | | | Others with— | | |
| | All Types of Education | Postgraduates | First Degree Graduates | College Course Incomplete | Noncollegiate Technical Course | All Types of Education | Postgraduates | First Degree Graduates | College Course Incomplete | Noncollegiate Technical Course | All Types of Education | Postgraduates | First Degree Graduates | College Course Incomplete | Noncollegiate Technical Course |
| All engineers | 0.7 | 0.5 | 0.7 | 0.9 | 1.1 | 10.9 | 8.1 | 11.5 | 10.4 | 11.1 | 8.9 | 6.3 | 9.1 | 10.3 | 10.0 |
| Chemical and ceramic | 0.5 | | 0.4 | 1.6 | | 10.1 | 6.5 | 11.3 | 7.9† | 25.0† | 6.8 | 3.2 | 7.7 | 5.8† | 23.8† |
| Civil, agricultural, and architectural | 0.7 | 0.5 | 0.7 | 0.8 | 1.4 | 10.5 | 9.4 | 10.8 | 10.2 | 11.7 | 10.8 | 9.6 | 10.9 | 11.9 | 13.3 |
| Electrical | 0.8 | 0.8 | 0.3 | 0.6 | 1.4 | 11.6 | 8.5 | 12.5 | 9.6 | 10.3 | 8.0 | 5.7 | 8.2 | 9.3 | 8.6 |
| Mechanical and industrial | 0.7 | 0.5 | 0.8 | 0.9 | 0.4 | 11.3 | 6.4 | 11.8 | 11.9 | 10.5 | 7.5 | 4.5 | 7.9 | 8.2 | 6.3 |
| Mining and metallurgical | 2.1 | 0.7 | 2.1 | 2.1 | 3.8 | 10.9 | 9.3 | 12.0 | 8.3 | 9.6 | 8.3 | 7.0 | 8.8 | 8.4 | 11.2 |

* Including those on direct relief and work relief.
† These figures are believed to be without significance.
‡ The total numbers of engineers in the various classes reporting unemployment is not shown in this article, but will become available in a statistical appendix to be included in the complete report to be published by the Bureau of Labor Statistics. While the percentage of unemployment was 1/5 less in 1934 than in 1932, the number of engineers reporting employment in 1934 was 48,124 as against 40,721 in 1932, due to the entrance of new persons into the profession. The number reporting unemployment dropped from 4,448 in 1932 to 4,288 in 1934, a decline of less than 4 per cent. Due to the overrepresentation of recent college graduates in the sample and the high percentage of unemployment among them, the total number reporting unemployment in 1934 should not be compared with the total number reporting unemployment in 1932.

### Education

The type of education the engineer had received affected the extent of unemployment (table I). Thus, in 1932 the proportion of all postgraduates who were unemployed was only 2/3 that of graduates with a first degree in engineering. Among chemical engineers and mechanical engineers, the difference in favor of the postgraduates was greatest. The smallest difference occurred among civil engineers. The same characteristic relationnature as not to be in keeping with their experience or their customary salary status.

In summary, this analysis of trends shows that: (1) there was a distinct improvement in the unemployment status of professional engineers between December 31, 1932, and December 31, 1934; (2) there were but slight differences in the incidence of unemployment among the various professional classes in 1932 and, except for civil engineers in 1934; (3) engineers who had received postgraduate degrees fared better than engineers with other types of training; and (4) as between older and younger engineers, the former not only felt the effect of the drop in business activity earlier than the latter but unquestionably were still lagging, at least until December 31,

1. It should be emphasized that increases and decreases referred to are with reference to a shifting total sample. See footnote to table I.

1934, in the return to professional activity. In general, it may be said that in this period of contraction of business activity, the inexperienced newcomer had greater difficulty in securing a professional status than any other class, that those with 5 to 25 years' experience fared best as regards unemployment, and that there was little difference (except for chemical engineers) in the percentages of unemployment at a given date between those with less than 5 years' experience and those with more than 25 years' experience.

In a period of expansion the younger and the more inexperienced engineers have a definite advantage. The normal method of recruitment at the bottom is followed. It is to be noted from table II that by December 31, 1934, the percentage of unemployment in all professional classes showed little variation between the age groups that entered the profession as late as 1932 and those with an upper limit of 53 years of age. However, there is evidence that in the 4 largest professional classes unemployment continued to be relatively high among the group of engineers who were more than 53 years of age in 1934.

## Incidence and Duration of Unemployment Among Professional Engineers, 1930–34

The preceding discussion presented unemployment data as of given dates, but gave no measure either of the number who were unemployed at other times during the 5-year period or of the length of unemployment. Light is shed on these points by the data obtained as to the period of unemployment, that is, the number of months during which the engineers were on work relief[2] or were without work of any kind. The data in this section therefore afford a measure of the gross or over-all period of displacement from regular employment, without regard to the mitigating effects of various types of relief.

More than 35 per cent of all the engineers reporting were unemployed at one time or another within these 5 years, as against about 11 per cent who were unemployed on December 31, 1932. The percentage who reported unemployment at some time during the 5 years, January 1, 1930, to December 31, 1934, with a classification by age and type of education, is shown in table III. The slightly lower incidence of unemployment for the "other" engineers is explicable on 2 grounds: (1) As a statistical "freak," arising out of slight differences in the age distribution of graduates and "other" engineers; and (2) the longer experience record of "other" engineers, for the graduate sample is especially heavily weighted by newcomers to the profession during the depression period 1930–34. For each particular age group shown in the table there is a slightly higher percentage of unemployment.

It is evident from table III that unemployment was greatest among the newcomers to the profession and decreased with the age of the engineer. In all professional groups there appeared an age beyond which there was apparently a common risk of unemployment. That age varies among the several professional classes. For civil engineers it was 43 years, whereas for electrical, and mechanical and industrial engineers it occurs after 33 years of age.

It may be noted that for the 2 youngest age groups the percentages affected by unemployment are practically the same for all 3 types of education, with roughly half the engineers who entered the profession during the depression period reporting some period of unemployment.

These findings seem definitely to extend the conclusions reached earlier as regards the influence of educational background. Table I showed less unemployment in 1932 and 1934 among those with post-graduate degrees than among those with first degrees, but there were no decisive differences between first-degree graduates and "other" engineers. It may now be stated that this was not due to the age composition of the 2 groups, for when age is considered (table III) the college graduate does appear to have an advantage.

For further consideration of the incidence of unemployment by age, the data in table III are shown for 2 distinct groups of engineers, those entering the profes-

**Table II—Per Cent of Engineers in Each Professional Class Unemployed* on December 31, 1929, 1932, and 1934, by Age or Year of Graduation†**

| Approximate Age in 1934 of "other" Engineers | Year of Graduation of Graduate Engineers | Per Cent Unemployed on Dec. 31— All Classes | Chemical and Ceramic | Civil, Agricultural, and Architectural | Electrical | Mechanical and Industrial | Mining and Metallurgical |
|---|---|---|---|---|---|---|---|
| **1929** | | | | | | | |
| 53 and over‡ | Prior to 1905 | 1.9 | 0.7 | 1.7 | 2.2 | 1.8 | 3.6 |
| 43–52 | 1905–14 | 0.7 | 0.5 | 0.9 | 0.3 | 0.6 | 2.2 |
| 33–42 | 1915–24 | 0.4 | 0.5 | 0.4 | 0.3 | 0.2 | 1.3 |
| 28–32 | 1925–29 | 0.4 | 0.3 | 0.3 | 0.4 | 0.6 | 0.5 |
| 25–27 | 1930–32 | | | | | | |
| 23–24 | 1933–34 | | | | | | |
| **1932** | | | | | | | |
| 53 and over‡ | Prior to 1905 | 10.9 | 3.9 | 11.2 | 10.0 | 11.3 | 12.8 |
| 43–52 | 1905–14 | 8.7 | 7.0 | 8.8 | 7.1 | 9.6 | 9.6 |
| 33–42 | 1915–24 | 8.0 | 5.0 | 8.9 | 6.6 | 8.7 | 6.0 |
| 28–32 | 1925–29 | 10.6 | 8.8 | 10.2 | 9.9 | 11.9 | 12.4 |
| 25–27 | 1930–32 | 16.6 | 15.8 | 14.7 | 20.2 | 15.6 | 17.5 |
| 23–24 | 1933–34 | | | | | | |
| **1934** | | | | | | | |
| 53 and over‡ | Prior to 1905 | 11.5 | 5.9 | 12.3 | 11.4 | 10.2 | 14.2 |
| 43–52 | 1905–14 | 8.1 | 4.1 | 9.0 | 7.3 | 7.7 | 7.5 |
| 33–42 | 1915–24 | 7.0 | 4.4 | 8.9 | 5.5 | 6.0 | 6.2 |
| 28–32 | 1925–29 | 7.0 | 5.5 | 9.2 | 5.3 | 6.0 | 7.5 |
| 25–27 | 1930–32 | 8.0 | 4.9 | 11.5 | 6.9 | 5.8 | 6.1 |
| 23–24 | 1933–34 | 13.9 | 11.9 | 18.0 | 14.6 | 10.4 | 10.7 |

* Including those on direct relief and work relief.

† In order to obtain a datum whereby direct comparisons could be made between engineers with and without degrees, the median age of graduation among the several professional classes was computed. This was found to be 23 years. Consequently, the data were so tabulated to permit of groupings by years of graduation and corresponding year of birth for each of the periods 1929, 1932, and 1934. In this table engineers with college degrees in the years indicated are combined with "other" engineers of the ages given in the table.

‡ The criticism has been made that the percentages of unemployment shown here relate to the indefinite group of those "53 and over." The figures would presumably be smaller if the group were closed at 62 years of age. It is quite certain from the contour of the percentages both in 1932 and 1934 that the percentage continues to rise with age. It is also certain that the high percentages shown are due to the persistence of unemployment when it occurs, rather than to a rising risk of unemployment.

2. Excluding work on P.W.A. projects and in nonrelief administrative positions in the public service.

sion during the depression years 1930–34 and the 4 older groups who had entered the profession prior to 1929. These 4 older groups had a common experience as regards the period during which they were exposed to the risk of unemployment. However, the younger engineers were exposed to a shorter period of risk, a factor of great importance when the length of their employment is considered. They were also subjected to the necessity of making their way into the profession under singularly difficult conditions. Length of exposure appears to have been a factor even as regards the general incidence of unemployment, for a slightly larger proportion of those who graduated in the period 1930–32 were unemployed during this 5-year period than was the case for those graduating in 1933–34.

For the 4 older groups, all entering the profession before 1930, the largest percentage of unemployment occurred among those who entered slightly before the beginning of the depression. There appears to have been no greater incidence of unemployment among engineers 53 years of age and over than there was among those 43 to 52 years of age. Therefore, relating this analysis to the preceding discussion of table II, it can only be concluded that the higher percentage of unemployment for the oldest age groups as of December 31, 1932, and December 31, 1934, is due not to the more frequent occurrence of unemployment but to the greater length of the period of unemployment when loss of position occurred.

These findings as regards the extent of unemployment among engineers in general are confirmed by the analysis of the separate professional classes of engineers shown in table IV.

**Table III—Percentage Distribution, by Age and Type of Education, of All Engineers Reporting a Period of (Gross*) Unemployment, 1930–34**

| Item | Age (in Years) in 1934 | College Graduates: Per Cent Reporting Unemployment |
|---|---|---|
| All graduating classes | | 37.8 |
| Entered profession during 1930–34: | | |
| Graduated in— | | |
| 1933–34 | 23–24 | 47.1 |
| 1930–32 | 25–27 | 53.5 |
| Entered profession in 1929 or earlier: | | |
| Graduated in— | | |
| 1925–29 | 28–32 | 36.0 |
| 1915–24 | 33–42 | 27.1 |
| 1905–14 | 43–45 | 23.8 |
| Prior to 1905 | 53+ | 23.5 |

| Item | Age (in Years) in 1934 | Other Engineers With— College Course Incomplete | Other Engineers With— Non-collegiate Technical Course |
|---|---|---|---|
| | | Per Cent Reporting Unemployment | |
| All years | | 35.4 | 35.6 |
| Entered profession during 1930–34: | | | |
| Born in— | | | |
| 1910–14 | 20–24 | 47.9 | 48.2 |
| 1905–09 | 25–29 | 49.5 | 49.8 |
| Entered profession in 1929 or earlier: | | | |
| Born in— | | | |
| 1900–04 | 30–34 | 39.0 | 41.4 |
| 1895–99 | 35–39 | 33.4 | 34.1 |
| Prior to 1895 | 40+ | 30.4 | 32.3 |

* Includes periods both of direct relief and work relief.
This table does not show the percentage of unemployment among engineers with only a secondary-school education, for their number was too small to warrant classification by age. The percentage of unemployment among all such engineers was 22.6.

## Periods of Unemployment

"Gross unemployment" is used in this section to cover periods of work relief or periods without work of any kind. The figures show the median periods of unemployment.[3]

Table V shows the median periods of unemployment, by age, education, and professional classes, during the 5-year period. In connection with the age classifications shown it is important to remember the period of exposure to the possibility of unemployment.

There are significant differences in the period of unemployment as between the various age groups of engineers and as between engineers with different types of educational background. There are real differences between the several classes of engineers, but professional class had a less marked influence on the average period of unemployment than either age or educational background.

The influence of educational background appears to be persistent whether the data are classified for each of the professional classes or for all engineers combined. However, the difference of almost 5 months in the median period shown in table V as between all college graduates without regard to age and all those whose college course was incomplete exaggerates the spread. It may be that there was no spread in the case of the older engineers; the impossibility of making identical age groupings prevents any other conclusion than that, in the case of older engineers, educational background is no longer a determining factor. Comparison of the median period of unemployment in similar brackets beginning with the engineers who were approximately 30 years of age in 1934 indicates that unemployment lasted only 1 or 2 months longer in the case of those with an incomplete college record. Although in the case of the 2 youngest groups of engineers the college graduate appears to have had some advantage, there is reason to believe that the difference between an average period of $7\frac{1}{2}$ months for the graduates of the classes 1933–34 and $12\frac{1}{2}$ months for those 20 to 24 years of age with an incomplete college record is due in large part to the fact that the latter group had a longer work history and consequently a longer period of exposure. For civil engineers classified on an age basis there was also a persistently longer period of unemployment for those with an incomplete college record.

As between the 2 types of "other" engineers, the difference of 1 month in the average appears to arise from the experience only of the younger engineers. For those over 35 years of age in 1934, there was no difference. In the younger age groups the differences ranged from 1.3 months to 2.5 months, and in all cases, those with an

3. In other words, the middle point, half the engineers having had a longer period and half a shorter period of unemployment.

**Table IV—Percentage Distribution, by Age and Professional Class, of Graduate and College-Incomplete Engineers Reporting a Period of Gross Unemployment,* 1930–34**

| Graduating Class or Year of Birth | Age (in Years) in 1934 | Per Cent Reporting Unemployment: Graduate Engineers — Chemical and Ceramic | Civil, Agricultural, and Architectural | Electrical[a] | Mechanical and Industrial | Mining and Metallurgical |
|---|---|---|---|---|---|---|
| All graduating classes | | 33.5 | 41.8 | 36.9 | 35.0 | 33.9 |
| Entered profession during 1930–34: | | | | | | |
| Graduated in— | | | | | | |
| 1933–34 | 23–24 | 40.3 | 55.1 | 48.9 | 40.7 | 45.6 |
| 1930–32 | 25–27 | 44.3 | 59.7 | 54.7 | 48.5 | 54.7 |
| Entered profession in 1929 or earlier: | | | | | | |
| Graduated in— | | | | | | |
| 1925–29 | 28–32 | 29.8 | 41.9 | 31.3 | 34.2 | 33.7 |
| 1915–24 | 33–42 | | 34.4 | 19.6 | 25.4 | |
| 1905–14 | 43–52 | 15.1 | 26.8 | 17.2 | 24.7 | 23.9 |
| Prior to 1905 | 53+ | | 27.0 | 17.1 | 23.3 | |
| **Engineers With College Course Incomplete** | | | | | | |
| All ages | | † | 39.1 | † | ‡31.2 | † |
| Entered profession during 1930–34: | | | | | | |
| Born in— | | | | | | |
| 1910–14 | 20–24 | † | 55.9 | † | ‡41.8 | † |
| 1905–09 | 25–29 | † | 57.3 | † | ‡42.0 | † |
| Entered profession in 1929 or earlier: | | | | | | |
| Born in— | | | | | | |
| 1900–04 | 30–34 | † | 43.5 | † | ‡34.4 | † |
| 1895–99 | 35–39 | † | 37.8 | † | ‡29.3 | † |
| Prior to 1895 | 40+ | † | 33.3 | † | ‡26.3 | † |

* Includes periods both of direct relief and work relief.
† Included with mechanical and industrial.
‡ Includes chemical and ceramic, electrical, and mining and metallurgical.
a. The high general average for electrical engineers shown in the table is due to an especially high rate among the newcomers to the profession.
It should be noted that in the case of all graduate engineers, it was necessary to make certain combinations of professional classes. Thus, a small number of ceramic engineers were combined with chemical engineers. Civil, agricultural and architectural engineers were combined, but the group was dominated by civil engineers. Mechanical and industrial engineers were combined, as were also mining and metallurgical engineers. In the case of the "other" engineers there were too few cases of noncollegiate technical-school graduates to warrant tabulation of the period of unemployment by both age and professional class; hence, only the data for those whose college course was incomplete are tabulated. This group has been divided to distinguish civil, agricultural, and architectural engineers from mechanical and all other types of engineer. Inasmuch as the unemployment experience of civil engineers differed from that of all other classes, this grouping into 2 categories makes possible general comparisons between the unemployment experience of graduate engineers and those with an incomplete college course. The percentages of these various professional classes of engineer who reported unemployment at some time during the 5-year period, 1930–34, are shown here by the age groupings heretofore shown.

incomplete college course had the shorter period of unemployment.

The average length of the period of unemployment increased with age. Whether the differential for noncollegiate technical-school graduates of these ages is real, or is due to certain peculiarities of the sample, cannot be said; but for all professional classes of engineers there was also a slight increase in the average period of unemployment among those who graduated before 1925 as compared with those who graduated later. By and large, however, those engineers who were 30 to 40 years of age and became unemployed were unemployed for 12 to 14 months, but within these limits age was not an important factor.

It is interesting to note that the engineer who entered the profession during the period 1930–32 had an average period of unemployment almost identical with th the engineers who had entered just prior to the depr This was true in spite of the fact that the younger m a shorter period of exposure to unemployment; lack of experience obviously militated against absorption.

In general, it may be said that the average pe unemployment for graduate engineers tended to i from about 1 year for those who graduated b 1925–29 to almost 2 years for those who graduate to 1905. The older engineer suffered from unemplo because of its greater length when it occurred rathe because of its greater frequency. Although the p tion of those who became unemployed over the period was only ⅔ as great for the oldest group as for the youngest group to enter the profession p 1930, when unemployment did occur it tended twice as long in the case of the older engineer.

Comparison of the severity of unemployment the professional classes is confined to those 4 age that had entered the profession prior to 1930, for av could not be shown for all age classes of chemic ceramic engineers, as the number of those over 3 of age was too small to allow of subdivision. It is ent, however, that the average period of unemplo was not more than ⅔ as long for chemical and c engineers as for the various other classes. The of unemployment of mining and metallurgical em was probably somewhat shorter in the various age fications than it was for the 3 larger professional cla

The general averages indicate comparatively difference, as regards the period of unemplo between civil engineers and electrical and mecl and industrial engineers.

Although unemployment occurred more freq among civil engineers than in any other engineering its severity was slightly less than for the other class

The median periods of unemployment cited show enough the differences among the various groups. as these average periods were, they still fall short veying the full picture. This may be gathered table VI, which shows the percentage of enginee reported varying periods of unemployment. It only engineers with college degrees received in 1 earlier years, without regard to professional class.

## Public Relief Among Professional Engineers, 1930–34

In the majority of cases engineers survived w public assistance their periods of unemployment 1930 to 1934. This was especially true of thos entered the profession prior to 1930.

The first data to be considered are with refere direct relief. Fewer than 1 per cent of the en reported themselves to have been unemployed on I ber 31, 1929. At that time there were no wor projects and none of the engineers reported ther as on direct relief.[4] Nearly 11 per cent of all en reported themselves as unemployed on Decemb

1932; 31 engineers reported themselves as on direct relief—less than 1/10 of 1 per cent of all the engineers and 1/2 of 1 per cent of the number reporting unemployment.

For the 5-year period as a whole, receipt of some direct relief was reported by 0.8 per cent of all engineers with college degrees and about 2 per cent of those who attended noncollegiate technical schools or who did not complete their college courses.[5]

Engineer's training was required in the administration of many of the projects designed to benefit other groups in the community. There was also a large increase in nonrelief forms of public employment. This was of particular benefit to civil engineers, of whom 8.5 per cent were employed by the Federal Government on December 31, 1929, and 18.6 per cent were so employed on December 31, 1934. For civil engineers the increase in this form of employment was greater than the increase in work relief.

Despite the increase in public employment, work-relief projects were the main source of assistance to those who were unemployed. On December 31, 1932, when nearly 11 per cent of the engineers were unemployed, only 0.7 per cent were on work relief. Two years later 4.0 per cent of all engineers were on work relief, which was approximately half of the total number of engineers unemployed at that time.

The reports for December 31, 1934, show striking differences in the extent of work relief as between civil engineers and other professional groups. At that time 6.6 per cent of all civil, agricultural, and architectural engineers were on work relief, as compared with only 2.3 per cent of all the other professional classes combined. The difference probably reflects chiefly the development of work programs that called especially for the civil engineer's training; it also reflects the fact that the total amount of unemployment among civil engineers in their normal fields increased from 1932 to 1934, whereas it decreased in the other professional classes. The greater amount of work relief among civil engineers balanced their more widespread unemployment. There was comparatively little difference between civil engineers and the other professional groups as regards the net amount of unemployment on December 31, 1934; those entirely without work (including work relief) formed 4.2 per cent of the civil engineers as compared with 5.3 per cent of the other types combined.

Work relief was slightly more common among engineers without college degrees than among those who were college graduates. The situation with reference to direct relief has already been noted. Among the civil engineers 6.2 per cent of the college graduates, as against 7.9 per cent of the others, were on work relief on December 31, 1934. For the 5 years as a whole, 18.4 per cent of the graduate civil, agricultural, and architectural engineers group reported a work-relief experience, whereas 19.6 per cent of this same group of professional classes with an incomplete college course so reported.

Comparison of the proportions receiving work relief at the close of 1932 and 1934 indicates that the older engineers were favored prior to 1932, while the more recent graduates were being favored in 1934. In 1932 the group graduating in the period 1930–32 had a larger proportion of its membership unemployed than any of the other age classes, but the proportion on work relief (0.6 per cent) was slightly less in December 1932 than the proportion among the older engineers (0.8 per cent of those graduating from 1915–29 and 0.7 per cent of those graduating prior to 1915). Among the civil, agricultural, and architectural engineers the difference in favor of the older groups was marked, work relief being reported for only 0.5 per cent of those graduating from 1930 to 1932 as against 1.0 per cent of those graduating from 1915 to 1929. By

**Table V—Median Period of Gross Unemployment,* by Age, Type of Education, and Professional Class, 1930–34**

| Graduating Class | Age (in Years) in 1934 | Period of Gross Unemployment (in Months) of—: Graduate Engineers: All Classes | Chemical and Ceramic | Civil, Agricultural and Architectural | Electrical | Mechanical and Industrial | Mining and Metallurgical |
|---|---|---|---|---|---|---|---|
| All graduating classes | | 11.4 | 9.4 | 11.8 | 11.5 | 11.1 | 12.3 |
| Entered profession during 1930–34: | | | | | | | |
| Graduated in— | | | | | | | |
| 1933–34 | 23–24 | 7.5 | 7.0 | 7.9 | 7.7 | 7.1 | 6.0 |
| 1930–32 | 25–27 | 11.9 | 10.6 | 11.9 | 13.2 | 11.1 | 11.9 |
| Entered profession in 1929 or earlier: | | | | | | | |
| Graduated in— | | | | | | | |
| 1925–29 | 28–32 | 12.1 | 11.1 | 12.2 | 12.4 | 12.0 | 11.7 |
| 1915–24 | 33–42 | 13.4 | | 12.9 | 14.1 | 15.2 | |
| 1905–14 | 43–52 | 17.8 | 11.4 | 17.0 | 20.7 | 18.5 | 17.4 |
| Prior to 1905 | 53+ | 23.1 | | 22.9 | 25.3 | 22.2 | |

| Year of Birth | Age (in Years) in 1934 | Period of Gross Unemployment (in Months) of—: Other Engineers: College Course Incomplete: All Classes | Civil, Agricultural, and Architectural | Mechanical and others | Noncollegiate Technical Course |
|---|---|---|---|---|---|
| All ages | | 16.3 | 15.8 | 16.9 | 17.3 |
| Entered profession during 1930–34: | | | | | |
| Born in— | | | | | |
| 1910–14 | 20–24 | 12.5 | 13.8 | 11.4 | 15.0 |
| 1905–09 | 25–29 | 14.0 | 13.9 | 14.3 | 15.3 |
| Entered profession in 1929 or earlier: | | | | | |
| Born in— | | | | | |
| 1900–04 | 30–34 | 14.2 | 13.2 | 15.1 | 16.0 |
| 1895–99 | 35–39 | 14.6 | 14.1 | 15.3 | 14.7 |
| Prior to 1895 | 40+ | 19.4 | 18.3 | 22.0 | 19.2 |

* Includes periods both of direct relief and work relief.
No figure is shown in the table for engineers with a secondary-school education, for its significance is not certain. The median period for such engineers was 12.4 months.

4. In this survey, work relief is defined as emergency employment, usually made available on the basis of need, by such agencies as C.W.A., F.E.R.A., and W. P. A. It does not include engineering work on P. W. A. projects, which should have been reported either as a form of private employment or as Government employment for those engineers working in the Public Works Administration itself. It also does not include engineers hired for strictly administrative work by the various relief administrations. There was some overreporting of work relief and a corresponding underreporting of public employment. Direct relief refers to direct financial or other assistance from any public authority.

5. In New York City, direct relief appears to have been more extensive through the Professional Engineers Committee on Unemployment than through public agencies.

December 31, 1934, this situation had been reversed and there was a larger proportion on work relief among the recent college graduates than among those who had entered the profession prior to the depression. This was especially true of the civil engineers, for whom work relief on December 31, 1934, was reported for 9.4 per cent of those graduating in 1933–34 and 8.3 per cent of those graduating in 1930–32, in comparison with only 6.5 per cent of those graduating in 1915–29 and 4.9 per cent of those graduating prior to 1915. In the other professional groups no real differences between the early and late graduating classes appears. Of the engineers in professions other than the civil-engineering group, who graduated during the years 1930–32, 2.2 per cent were on work relief, but 3.2 per cent of those graduating in 1933–34 reported work relief. In this connection it must be recalled that in 1934 there was a larger proportion of unemployed among those graduating in 1933–34 than among the other age groups.

Thus far, in this section, the discussion of work relief has been confined to the reports for specific dates. For the 5-year period as a whole, a larger number of engineers had some experience with work relief. For all types of engineer, irrespective of background, about 1/8 reported some period of work relief, but very wide differences were shown in the extent of work relief for civil engineers and for other types of engineers. Thus, among engineers with an incomplete college course, 19.6 per cent of the civil-engineer group reported some work relief, whereas classified by year of graduation in the 3 professional groups of civil, electrical, and mechanical engineering.

The differences in the length of the period between the various professional classes are small and show no particular regularity. Essentially, the periods are the same both for civil engineers and for mechanical engineers, though the average period was perhaps somewhat shorter in the case of electrical engineers. Little difference is shown between those who graduated from 1915–29 and those who graduated prior to 1915, but apparently those who graduated prior to 1930 had a slightly longer period of work relief than those who graduated in 1930–32.[6]

Thus far in this discussion, those reporting work relief have been regarded as unemployed. More than 4/5 of those who reported a period of work relief also reported a period of unemployment. However, among the 5,349 engineers with college degrees who reported a period of work relief, 966 reported a period of work relief but no period of unemployment. This situation calls for some explanation though it does not change the general outline of the conclusions reached. There seems to be a slight overreporting of work relief and, therefore, a slight overestimate of unemployment due to the method of adding together periods of unemployment without work of any kind and periods of work relief to determine the gross frequency and period of unemployment. There is also a corresponding underreporting of nonrelief public employment. In this discussion, it is necessary to distinguish 3 age groups, those graduating in 1929 or earlier,

**Table VI—Percentage Distribution of Engineers Graduating From College Prior to 1930, by Period of Unemployment**

| Year of Graduation | Total Reporting in Survey | Total Reporting Unemployment at Any Time During 1930–34 | | Per Cent Whose Reported Unemployment (in Months) Was— | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Number | Per Cent | Under 6 | 6 and under 12 | 12 and under 18 | 18 and under 24 | 24 and under 30 | 30 and under 36 | 36 and under 42 | 42 and under 48 | 48 and over |
| All years prior to 1930 | 24,853 | 6,965 | 100.0 | 21.0 | 21.6 | 16.5 | 12.8 | 9.5 | 7.1 | 5.1 | 3.2 | 3.2 |
| 1925–29 | 6,499 | 2,340 | 100.0 | 23.9 | 25.7 | 19.4 | 13.4 | 7.9 | 4.0 | 3.2 | 1.6 | 0.9 |
| 1915–24 | 8,298 | 2,245 | 100.0 | 23.3 | 22.9 | 16.1 | 11.4 | 9.4 | 7.3 | 4.4 | 3.0 | 2.2 |
| 1905–14 | 6,602 | 1,570 | 100.0 | 17.7 | 18.8 | 14.0 | 13.8 | 11.4 | 8.7 | 7.2 | 3.7 | 4.7 |
| Prior to 1905 | 3,454 | 810 | 100.0 | 12.8 | 11.7 | 14.4 | 13.1 | 10.6 | 12.0 | 8.3 | 7.0 | 10.1 |

only 7.5 per cent of those in the other professions considered together so reported. Among college graduates work relief was reported by 18.3 per cent of the civil engineers and only 10.9 per cent of the mining and metallurgical engineers. For the other professional classes, the percentages were 9.3 for electrical engineers, 8.7 for mechanical and industrial engineers, and 6.6 for chemical and ceramic engineers.

In all professional classes, age was an important factor in the frequency of work relief. Table VII gives for the 3 professional classes civil, electrical, and mechanical engineers, the percentages of those receiving work relief, at any time during the 5 years, 1930–34, classified by age. The figures relate only to college graduates.

The median period of work relief was approximately 5 months, as shown in table VII for college graduates those graduating in 1930–32, and those graduating in 1933–34. Among the more recent graduates little difference is found between civil engineers and all other types of engineers, as regards work relief without unemployment. Of the 1,138 engineers graduating from college in 1933–34 and reporting some work relief, 333 reported no period of unemployment, that is, approximately a third of them appear to have entered directly into work relief. Among those graduating in 1930–32, 281 out of 1,747, or somewhat more than 1/6, reported such an

6. If it is correct to conclude that the major part of the work-relief experience came in the years 1933–34, the differences between the classes graduating in 1930–32 and those graduating earlier are not to be explained in terms of a longer period of eligibility for work relief. It may be pointed out that a shorter period in the case of the classes of 1930–32 is consistent with the earlier conclusion that recruitment was more extensive among this group of engineers than among the older ones. The still shorter period, which is indicated for those who graduated in 1933–34, may well be explained by the fact that they had a shorter period of eligibility for work relief.

experience. This may merely reflect a need for young engineers to staff minor supervisory positions on projects conceived to meet the needs of other groups.

In the case of those civil engineers who graduated in 1929 or earlier years, 242 of the 1,476 who reported work relief did not report a period of unemployment. There are too few cases in the other professional classes to warrant a breakdown, but among all engineers other than civil engineers graduating in 1929 or earlier, 110 out of 988 reported no period of unemployment. Two factors lead to the belief that some of those reporting a period of work relief but no period of unemployment should be separated from the unemployed: (1) It may be noted that this situation was commoner among civil engineers than among the other professional classes, undoubtedly because the training of civil engineers was more extensively required on work-relief projects than was the training of other types of engineer. (2) It seems probable that there was some misunderstanding by engineers replying to the questionnaire and that a few reported

**Table VII—Per Cent of Graduate Engineers, by Year of Graduation and Professional Class, Reporting Work Relief at Any Time, 1930–34, and Median Period of Work Relief**

| Year of Graduation | Per Cent Reporting Work Relief | | | Median Period (in Months) of Work Relief | | |
|---|---|---|---|---|---|---|
| | Civil | Electrical | Mechanical | Civil | Electrical | Mechanical |
| All years | 18.3 | 9.3 | 8.7 | 5.0 | 4.4 | 4.9 |
| 1933–34 | 26.4 | 12.5 | 10.2 | 4.1 | 3.8 | 4.1 |
| 1930–32 | 25.2 | 12.8 | 10.4 | 4.8 | 4.3 | 4.5 |
| 1915–29 | 15.9 | 6.2 | 7.4 | 5.6 | 4.6 | 5.7 |
| Prior to 1915 | 12.4 | 6.3 | 7.6 | 5.5 | 6.5 | 5.6 |

The civil engineers here tabulated do not include architectural and agricultural engineers, nor do the mechanical engineers include industrial.

public administrative employment in connection with work-relief projects as work relief rather than as public employment. It is possible that certain engineers reporting a period of work relief neglected to report a period of unemployment or merged the 2 figures in a single one of a period of work relief.

In general, a period of work relief was associated with a reported period of unemployment. This was true of more than 85 per cent of the engineers, without regard to professional classification, graduated in 1929 or earlier years, who secured work relief. For this group of college graduates, there is a clear relationship between the period of unemployment and entrance into work relief.[7] The percentages in table VIII represent the ratio of the total number of individuals receiving work relief after a given period of unemployment to the total number of unemployed persons who had at least as much as the shortest period of unemployment indicated. Thus, for example, 6 per cent of all civil engineers who reported any period of unemployment whatsoever were placed on work-relief projects after a period of less than 6 months of unemployment, etc.

During the 5-year period, placement on work-relief

**Table VIII—Per Cent of Unemployed Graduate Engineers on Work Relief After Specified Unemployment, 1930–34, by Years of Graduation**

| Year of Graduation | Per Cent of Engineers Who Received Work Relief After Specified Months of Unemployment | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Less than 6 | 6–12 | 12–18 | 18–24 | 24–30 | 30–36 | 36–42 | 42–48 |
| All classes of engineers | 4.3 | 9.3 | 12.6 | 13.7 | 14.9 | 18.4 | 18.0 | 18.8 |
| Civil engineers | 6.0 | 11.9 | 15.7 | 17.9 | 18.1 | 22.1 | 21.2 | 24.6 |
| 1925–29 | 6.3 | 13.8 | 17.4 | 25.8 | 25.2 | 26.0 | 33.0 | 63.0 |
| 1915–24 | 7.2 | 13.5 | 19.5 | 20.9 | 19.8 | 36.0 | 28.0 | 27.0 |
| 1905–14 | 5.9 | 11.0 | 14.4 | 16.6 | 19.0 | 15.6 | 22.0 | 23.0 |
| Prior to 1905 | 1.8 | 6.4 | 9.0 | 8.5 | 10.6 | 16.8 | 13.0 | 18.0 |
| Other professional classes | 2.8 | 7.0 | 9.9 | 10.2 | 12.5 | 15.5 | 15.5 | 14.1 |
| 1925–29 | 2.5 | 7.4 | 10.6 | 11.2 | 13.5 | 19.6 | 20.0 | 20.0 |
| 1915–24 | 3.7 | 7.5 | 12.4 | 12.7 | 11.8 | 19.3 | 20.0 | 8.0 |
| 1905–14 | 2.8 | 7.1 | 8.5 | 9.1 | 15.2 | 14.0 | 10.0 | 19.0 |
| Prior to 1905 | 0.8 | 4.5 | 5.4 | 5.9 | 8.4 | 9.7 | 14.0 | 12.0 |

projects rose steadily as the period of unemployment was lengthened. This increase reflects the actual course of events in these 5 years, but the period was not homogeneous as regards the availability of work relief, which was first inaugurated on a large scale in 1933. Any person unemployed for as little as 6 months in 1931 had virtually no opportunity to secure work relief. On the other hand, a person who became unemployed in July 1931 probably would have found C.W.A. work, after the lapse of 30 months. Therefore, in interpreting the figures shown in table VIII, it must be remembered that longer periods of unemployment increase the probability of work relief merely by carrying over into a period in which work relief became available.

A further and more significant comparison may be made with reference to the availability of work relief to the members of the different groups of graduating classes. For this purpose, these classes should be interpreted as indicating not particularly differences between younger and older engineers, but more especially probable differences in the financial resources of the different groups. In the aggregate, those engineers who graduated prior to 1905 probably had substantially larger financial reserves than those who graduated from 1925 to 1929. In the case of civil engineers, the percentage on work relief was highest for those who graduated from 1925 to 1929. Among the other professional groups, this relationship was less well maintained, although there appeared to be a distinct demarcation between those who graduated prior to and after 1915. The strongest contrast was between those who graduated in the period 1925–29 and those who graduated prior to 1905.

7. For the correlation of the period of unemployment that antedates relief, the following information is available: The total period of unemployment, exclusive of work relief, and the total period of work relief. In order to simplify the presentation, the material is presented as though there were in all cases a sequence of an unbroken period of unemployment followed in certain instances by work relief. It is quite possible that in certain instances the total period of work relief is broken into several stretches interspersed with periods of work relief. In such a case, it would be incorrect to say that work relief followed after 12 months of unemployment if 12 months were the total reported period of unemployment exclusive of work relief. To distinguish several periods of unemployment would have required a greater refinement than it was possible to undertake by the questionnaire method. The extent of the error, which is implied in this assumption, is probably not great, but technically all that can be shown is a relationship between a certain aggregate period of unemployment, exclusive of work relief, and the existence of some period of work relief which may have preceded a period of unemployment or have broken into a period of unemployment.

# Switchboards for Boulder Power Plant

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**Switchboards for the power plant at Boulder Dam are unusual not alone for their size, but also for the combination in one plant of switchboard designs and methods that have been used individually but seldom together. The plan of the power plant and the switchboards and control equipment are described in this paper.**

THE Boulder Power Plant is unusual in many respects, and these unusual features are reflected in the switchboards. Mere "bigness" would not make the switchboards unusual, but other features resulting indirectly from such bigness introduce requirements in the switchboard design which are not commonly encountered. Among the well-known features of this plant are:

Generating units of 3,000, 40,000, and 82,000 kva

Transformer banks up to 165,000 kva and 287.5 kv

Ultimate capacity of 17 major generating units totaling approximately 1,300,000 kva

Among the lesser known or recognized features are:

The generators are disposed along the opposite sides of the river so that the power plant is in effect approximately 1,600 feet long, with the control room in the center. The farthest generator is approximately 700 feet from the control room.

The 287.5-kv substation or switch yard for the City of Los Angeles is approximately 1,500 feet from the control room.

The complete plant will involve 4 major systems, with transmission voltages from 132 kv up to 287.5 kv.

The Boulder Power Plant really represents several large generating stations, tying in with separate outside systems. The individual requirements of these systems must be taken care of with an over-all uniformity in operating practice and switchboard design. Standard, conventional switchboard design has been followed wherever possible. Nevertheless the very features previously mentioned necessitate the combination in one plant of switchboard designs and methods which have been used individually, but seldom together in the same plant.

The initial installation comprises 4 82,500-kva units for the City of Los Angeles, and 1 40,000-kva unit for the Southern Sierras Power Company. The plan adopted for these units will apply in general to the succeeding units. The general plan is to provide a separate switchboard or cubicle near each generator for manual control. There is also a centralized main control desk from which all the generators, transformers, and their related apparatus may be controlled automatically and remotely.

In brief, the City of Los Angeles system involves connecting 2 generators in parallel to a transformer bank, through suitable low-voltage circuit breakers. The transformers are located directly outside the generator room, and the low-voltage circuit breakers are located in suitable switch rooms, directly outside the main building, and as close to the respective generators and transformers as is possible. The high-voltage side of the transformer bank connects to a double-bus outdoor substation, from which are taken the Los Angeles lines. Each generator has 2 breakers in parallel so as to permit maintenance without interruption of service. Provisions are made for connecting a spare generator to a transfer bus, and energizing a transformer therefrom, in order to replace any generator that may be out of service.

## Generator Control Cubicles

The control system is arranged so that the generators may be operated from 2 locations, either the control room or the generator floor. Each generator control cubicle is located in a recess in the river wall of the power plant. It is provided with all the manual control and instrumentation usually associated with a water-wheel generator of like capacity such as circuit breaker, field, and governor controls. At this point the generator can be completely started even to synchronizing and connecting to the bus, controlled, and shut down. This permits and facilitates initial operation, testing, and maintenance, and provides emergency operation in case the main control desks should be out of service. Control is not provided for the high-voltage circuit breakers and disconnecting switches, but suitable signals indicate their connections. The voltage regulator, generator protective relays, and various graphic instruments are also located on this board.

This cubicle also serves as the transfer point for the control circuits coming from the main desk. Therefore, the interposing relays, interposing current transformers, automatic starting relays, and thermal converters for load control and totalizing are located here. A control-transfer switch determines whether the unit can be controlled locally or from the main control desk and thus prevents conflicting, contradictory, or incomplete control. This switch is provided with a cylinder lock to prevent unauthorized operation.

## Main Control Room

The contracts for power privileges established 2

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principal lessees, the City of Los Angeles and the Southern California Edison Company, as the generating agents for generation of all power at Boulder Dam. The City of Los Angeles generates power for itself, the Metropolitan Water District, the cities of Pasadena, Glendale, and Burbank, and the states of Arizona and Nevada. The Southern California Edison Company generates power for itself, and the Southern Sierras Power Company. The main control room is divided into 2 sections to provide for separate operation by the 2 lessees. These rooms are located in the central portion of the power plant at an elevation approximately 70 feet above generator floor level. In the control room for the City of Los Angeles, the main control desk and the station service desk face each other from opposite sides of the room. The auxiliary control room boards are located on the other 2 sides of the room. The operator's desk, supervisory control benches, etc., are located in the center of the room, between the control desks. The equivalent equipment for the Southern Sierras Power Company is located in the adjoining room with provision for future equipment for the Southern California Edison Company.

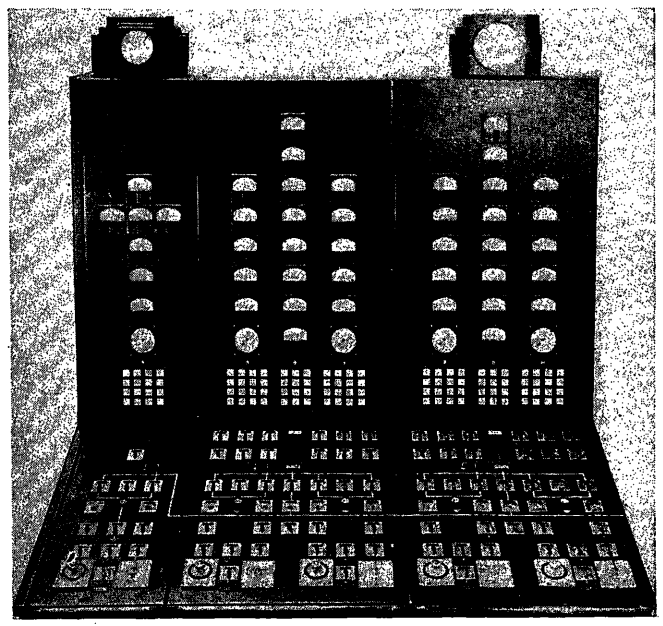


**Fig. 2. Main control desk, showing 3 panels with the control for 5 generators (one future) and 2 transformer banks**

## Main Control Desk

The main control desk centralizes the control of all the main generators, the power transformer banks, and the outgoing feeders. The desk for the City of Los Angeles comprises initially 3 fully equipped sections for the control of 5 generators, 2 transformer banks, and 2 outgoing lines. The initial desk for the Southern Sierras Power Company comprises a single section, mounted separately, for the control of 2 generators with their respective transformers and transmission lines. On account of the large number of units to be controlled, the desks are of the so-called "miniature" type, using Westinghouse type *K* indicating instruments 4 inches wide with scales $3^1/_2$ inches long, and control switches of the Minatrol type. With complete control and instrumentation including lamp indicators, miniature bus, governor controls, etc., the length of the Los Angeles section for the initial equipment of 5 generators, 2 transformers, and 2 lines is only 6 feet.

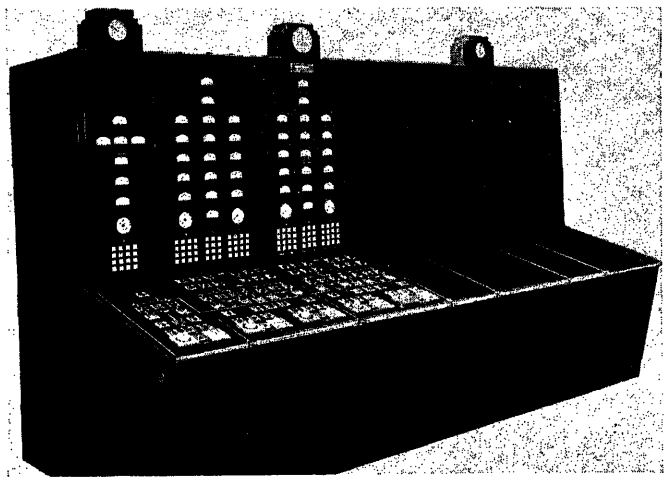


**Fig. 1. Complete main control desk**

Starting from the main control desk is almost completely automatic. The operator selects the breaker with which he plans to connect the generator to the bus, inserts the key for one of the 2 automatic synchronizers, and turns the master control switch to "start." Auxiliaries such as the bearing oil pressure pump, cooling water pump, etc., start automatically and when these are in operation, the turbine gates open. The generator then comes up to full speed, taking full voltage excitation, matches speed with the system and synchronizes, resulting finally in closing the preselected breaker. A synchronizer by-pass button is provided for manual synchronizing when the bus is dead or when the automatic synchronizer is out of service. This performance is carried out through a full complement of preventive interlocks and relays and continuous operation is safeguarded by means of protective relays operating as functions of electrical conditions in the main circuits, temperature, or in failures of the auxiliary devices. With one circuit breaker closed, the parallel breaker can be closed by the operator directly and immediately.

The high-voltage transformer or line circuit breakers can be handled manually, either after the generator has been put on the bus, or preset so that line connection is made on the low-voltage side automatically.

Once on the line, the operator can control the load, voltage, or regulated voltage level, etc., as in a conventional power plant. Shutdown can be made by the operator, or result from the operation of the protective relays. Most of the automatic and pro-

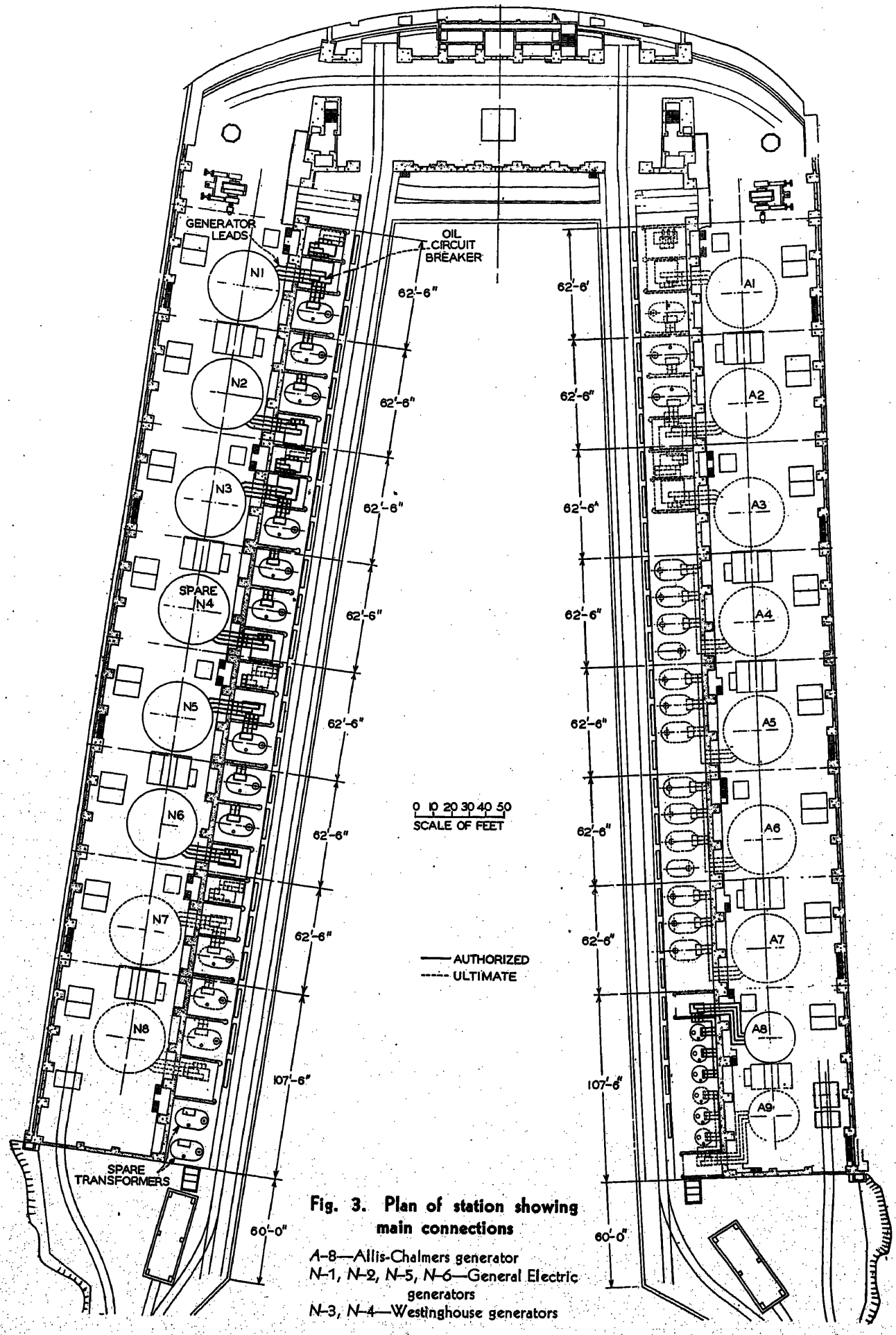



**Fig. 3. Plan of station showing main connections**

*A*-8—Allis-Chalmers generator
*N*-1, *N*-2, *N*-5, *N*-6—General Electric generators
*N*-3, *N*-4—Westinghouse generators

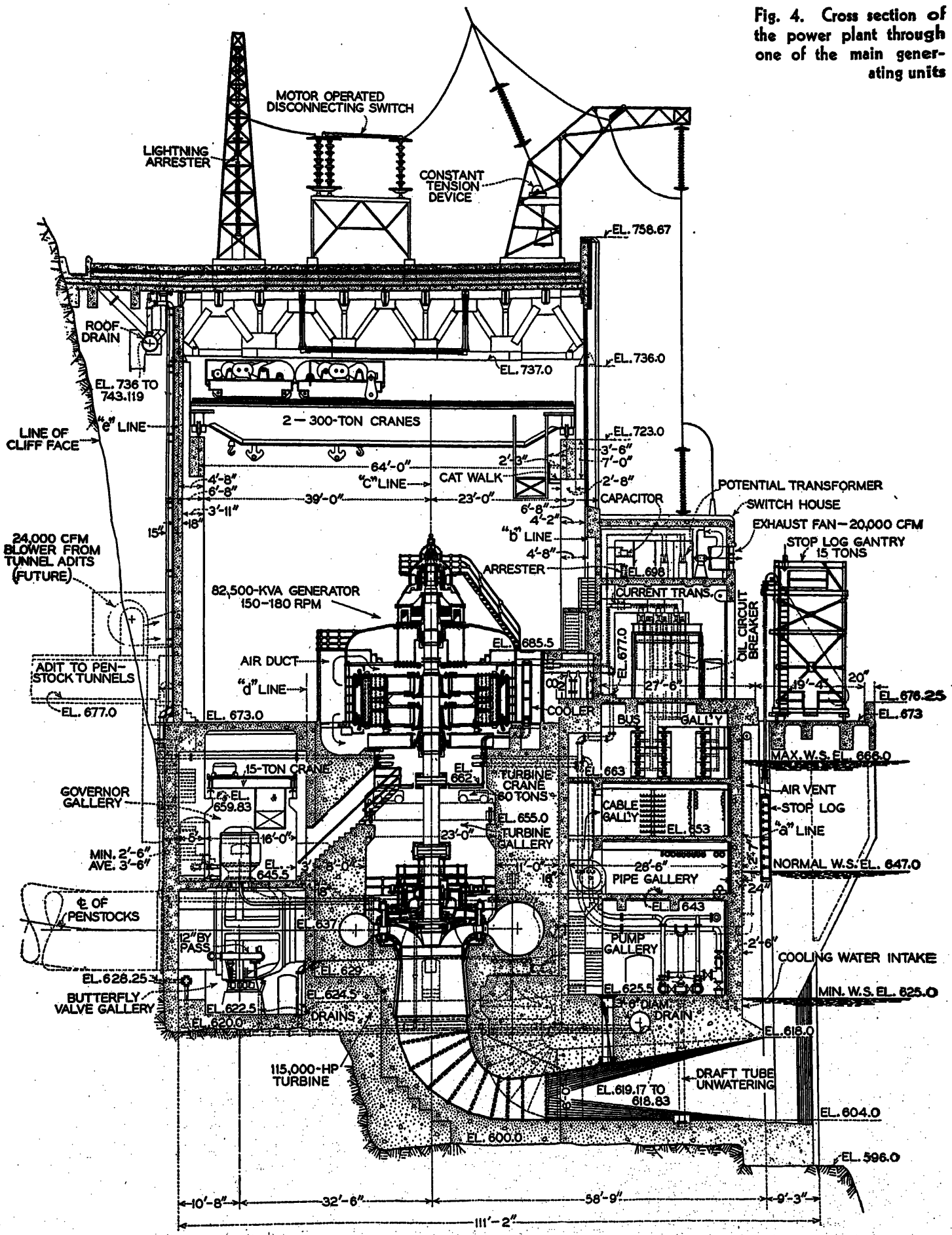



Fig. 4. Cross section of the power plant through one of the main generating units

tective features found only in an unattended station have been incorporated in this control in order to relieve the operator as far as possible from routine duty.

The control desk is constructed of "stretcher leveled" (smoothly finished) steel, with the back fully enclosed and provided with swinging doors. The front lower face is inclined toward the rear so as to facilitate approach to the desk and manipulation of the various controls thereon. Another unusual feature of this desk design is the arching of all internal cross members and corresponding placement of control conductors, so that an inspector can walk along the top of the terminal boards on the lower floor, and readily observe or adjust the apparatus and wiring on the under-inner side of the desk.

## Station Service Control Desk

The station service control desk is similar in construction and equipment to the main control desk. The 3 central sections are of full height, and are for the control of the 2 3,000-kva station service generators and the station service transformer bank. These sections are provided with complete instrumentation and control comparable to that provided for the main generators. Automatic starting, speed matching, and synchronizing are provided for these generators as is the case with the larger generators.

The control desk sections extending from each side of the center are of lower height, because of the relatively fewer instruments required thereon. These sections are for the control of the storage batteries and their charging generators, 2,300-volt feeders to various sections of the plant and to the 460-volt auxiliary transformers for station service. The outside sections, toward the Arizona and Nevada sides respectively, are provided with illuminated signals to indicate normal or abnormal conditions with respect to the various auxiliary services such as control supplies, cooling-water indications, bearing-oil indications, etc.

All controls from the main desk are at 125 volts direct current. These controls operate interposing relays located at their respective generator cubicles, or at the outdoor substation, translating to the heavier currents required for the various devices such as governor controls, and also to the 250-volt d-c control for the circuit breakers and similar apparatus.

For the various indicating and graphic instruments, potential is brought from the generator cubicles at full value of 110 volts. For the current instruments and similar devices, the normal 5-ampere secondary current is stepped down to 0.1 ampere by current transformers located at the generator cubicles or at the switch yard. By this means, the long control and instrument cables from the control desk to the generator cubicles or the switch yard are kept to a reasonable size, and excessive current-transformer burdens are avoided.

## Auxiliary Control Board

There are 2 auxiliary control boards each consisting of a double line of vertical panels, arranged back-to-back with a passageway between. These panels are equipped with the master automatic equipment used for the entire plant, that is, speed matchers and

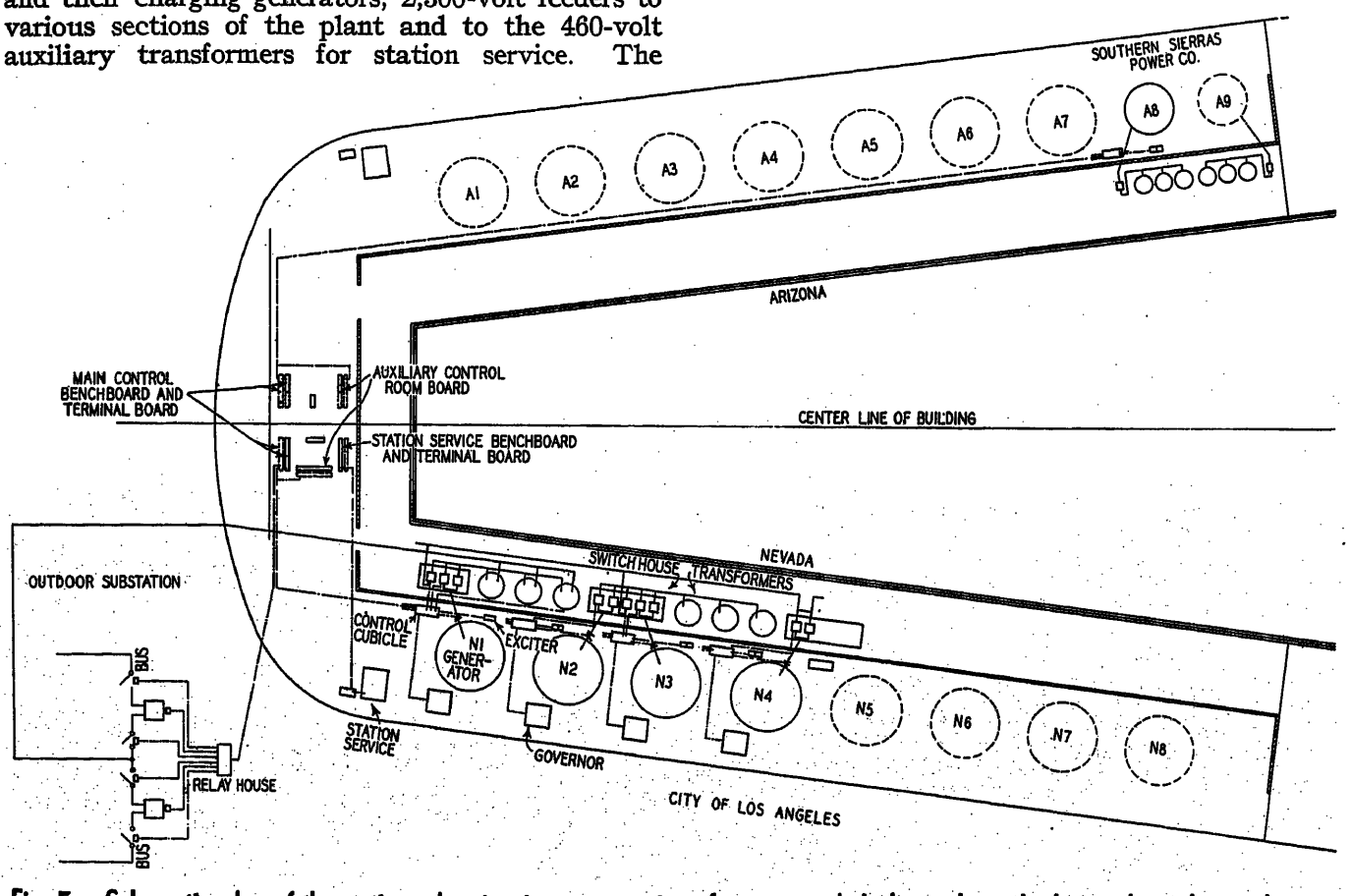



**Fig. 5. Schematic plan of the station, showing interconnections from control desk to the cubicles and outdoor substation**

synchronizers and frequency and load controls; with recording instruments for generator-armature and field-winding temperatures, bearing temperatures, and transformer temperatures; with frequency, totalizing, watt, and reactive kilovolt-ampere recording instruments; and with voltmeters for automatic recording of high voltage during faults.

## Terminal Boards

The control and instrument cables from the various cubicles, switch yard, station service switchgear, and station auxiliary switchgear are brought to terminal boards in a room below the main control room and located directly beneath the control desks or auxiliary boards which they serve. Vertical cables connect directly from the terminal blocks in the terminal boards to the terminal blocks in the switchboards above.

The terminal boards for the control desks are actually double units, mounted back-to-back, and running lengthwise under their respective desks, with a passageway between. Terminal blocks and test switches are mounted on one side, and small circuit breakers for the complete segregation of the 125-volt control circuit in the desks are mounted on the other side. The terminal boards for the auxiliary boards are similar, except that test switches and circuit breakers for control segregation are omitted.

## Control Supply

The control supply for the desks is provided by a 60-cell 125-volt storage battery, with suitable motor-generator charging equipment. The various circuits to the switchboard desk section are supplied through individual circuit breakers. Not only is the supply segregated for each main unit, but also for each distinct part of the unit. The completeness of this segregation may be indicated by the fact that 38 2-pole circuit breakers are required for the control circuits of one desk section controlling 2

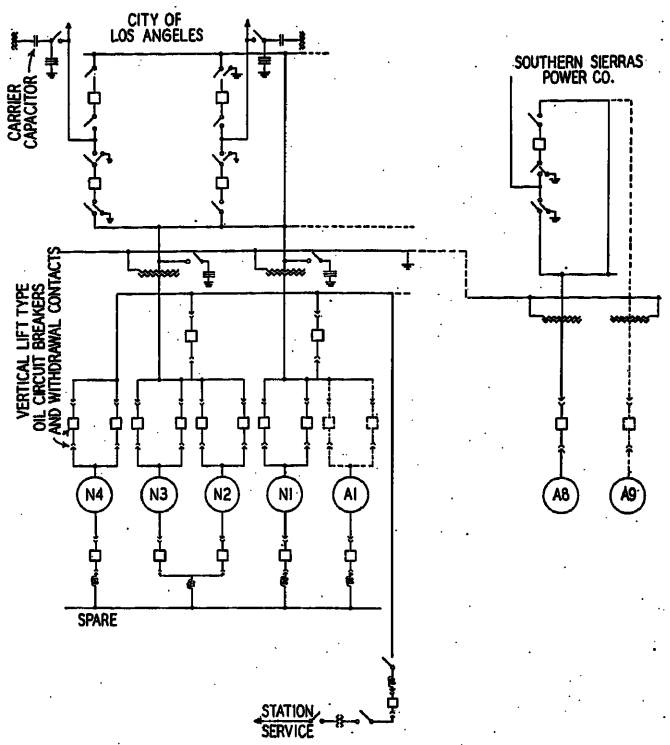



**Fig. 6. Simplified single-line diagram of present equipment**

generators and one transformer. This segregation permits of complete isolation automatically in case of a fault and manually for maintenance purposes. While these circuits are only 125 volts direct current their importance and the possibilities of high short-circuit currents led to the choice of Westinghouse type *AB* automatic thermal-trip circuit breakers of 250-volt d-c rating and 10,000-ampere rupturing capacity.

Oil circuit breakers and similar apparatus are operated from 120-cell 250-volt batteries, one for each wing of the power plant, and for the switch yard. These control circuits are similarly segregated, not

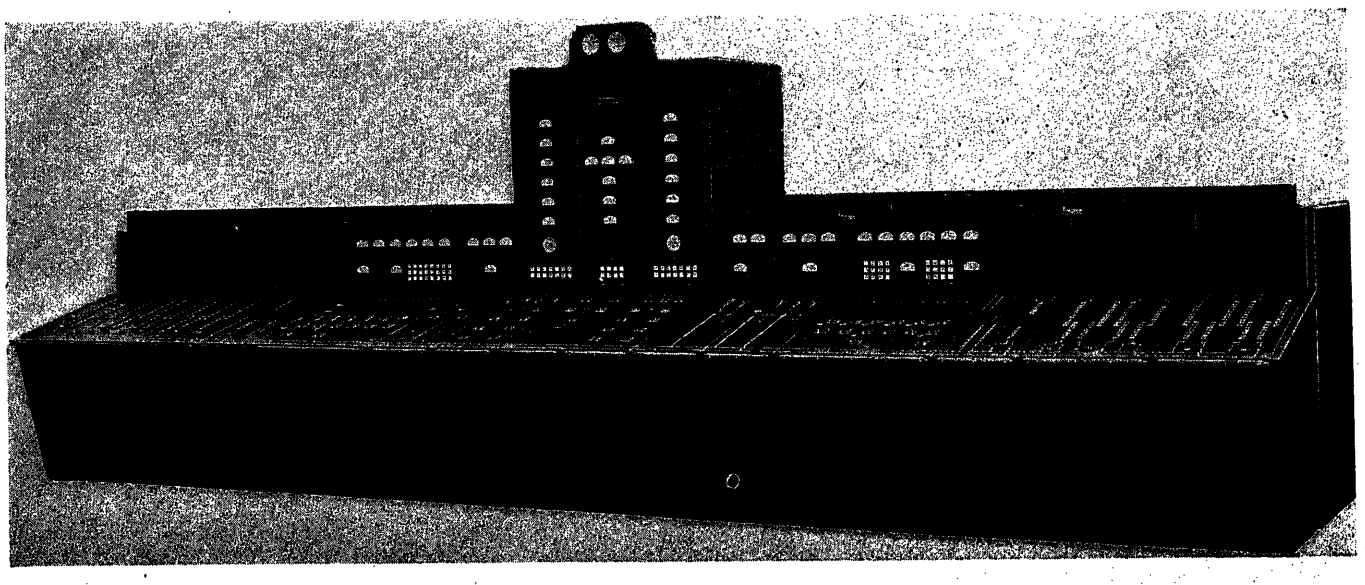
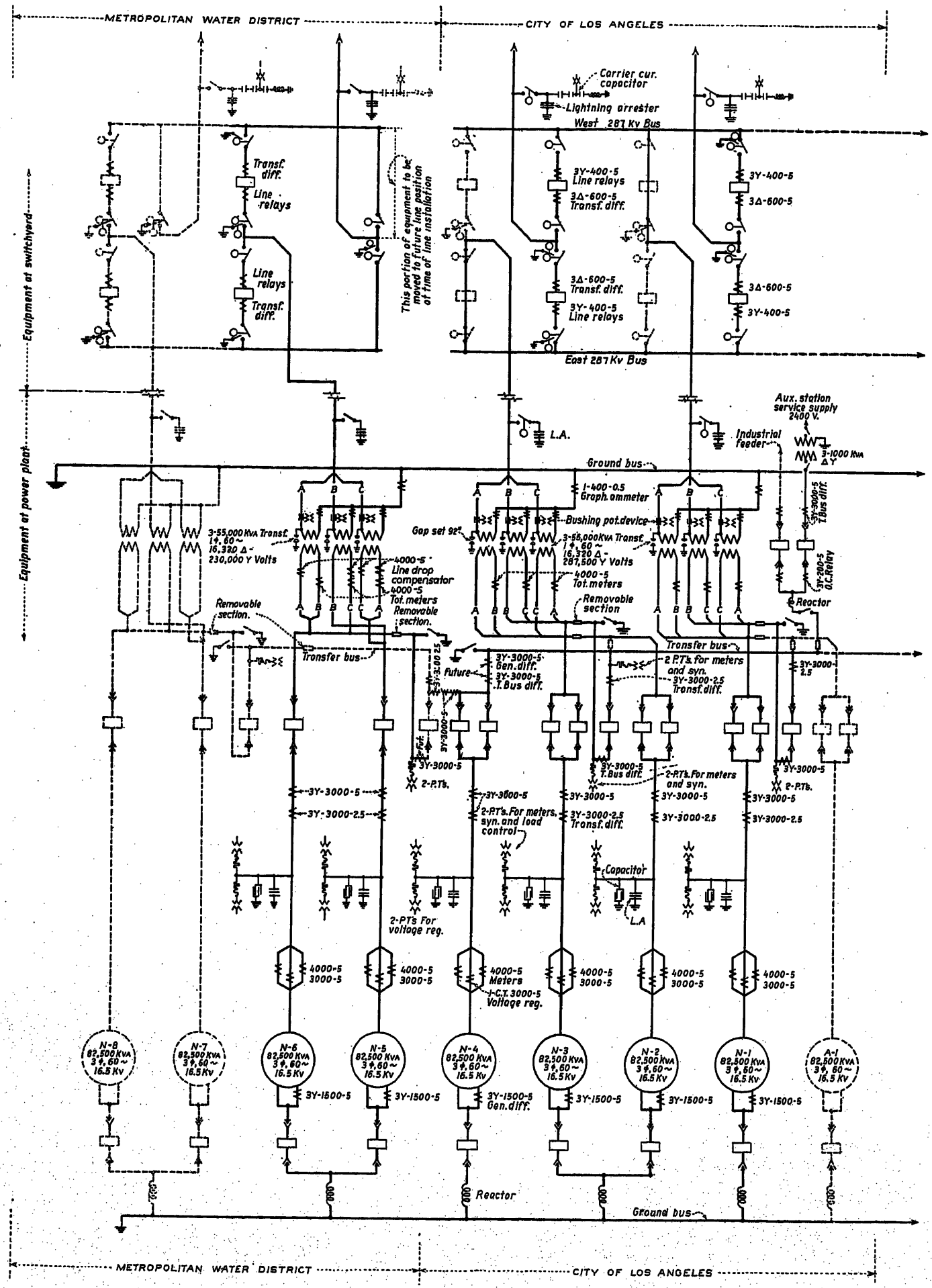


**Fig. 7. Front view of station service control desk**


METROPOLITAN WATER DISTRICT
CITY OF LOS ANGELES
Equipment at switchyard
Equipment at power plant
Carrier cur. capacitor
Lightning arrester
West 287 Kv Bus
East 287 Kv Bus
Transf. diff.
Line relays
This portion of equipment to be moved to future line position at time of line installation
3Y-400-5 Line relays
3Δ-600-5 Transf. diff.
3Δ-600-5
3Y-400-5
L.A.
Aux. station service supply 2400 V.
Industrial feeder
3-1000 Kva Δ Y
Ground bus
1-400-5 Graph. ammeter
Bushing pot. device
Gap set 92"
3-55,000 Kva Transf. 1 ϕ, 60 ~ 16,320 Δ - 230,000 Y Volts
3-55,000 Kva Transf. 1 ϕ, 60 ~ 16,320 Δ - 287,500 Y Volts
4000-5 Line drop compensator
4000-5 Tot. meters
Removable section.
Transfer bus
3Y-3000-5 Gen. diff.
3Y-3000-5 T. Bus diff.
2 P.T.s for meters and syn.
3Y-3000-2.5 Transf. diff.
Future
2-P.T.s.
2-P.T.s. For meters, syn. and load control
Capacitor
2-PTs For voltage reg.
4000-5 3000-5
4000-5 Meters
C.T. 3000-5 Voltage reg.
3Y-1500-5
3Y-1500-5 Gen. diff.
N-8 82,500 Kva 3 ϕ, 60 ~ 16.5 Kv
N-7 82,500 Kva 3 ϕ, 60 ~ 16.5 Kv
N-6 82,500 Kva 3 ϕ, 60 ~ 16.5 Kv
N-5 82,500 Kva 3 ϕ, 60 ~ 16.5 Kv
N-4 82,500 Kva 3 ϕ, 60 ~ 16.5 Kv
N-3 82,500 Kva 3 ϕ, 60 ~ 16.5 Kv
N-2 82,500 Kva 3 ϕ, 60 ~ 16.5 Kv
N-1 82,500 Kva 3 ϕ, 60 ~ 16.5 Kv
A-1 82,500 Kva 3 ϕ, 60 ~ 16.5 Kv
Reactor
Ground bus
METROPOLITAN WATER DISTRICT
CITY OF LOS ANGELES

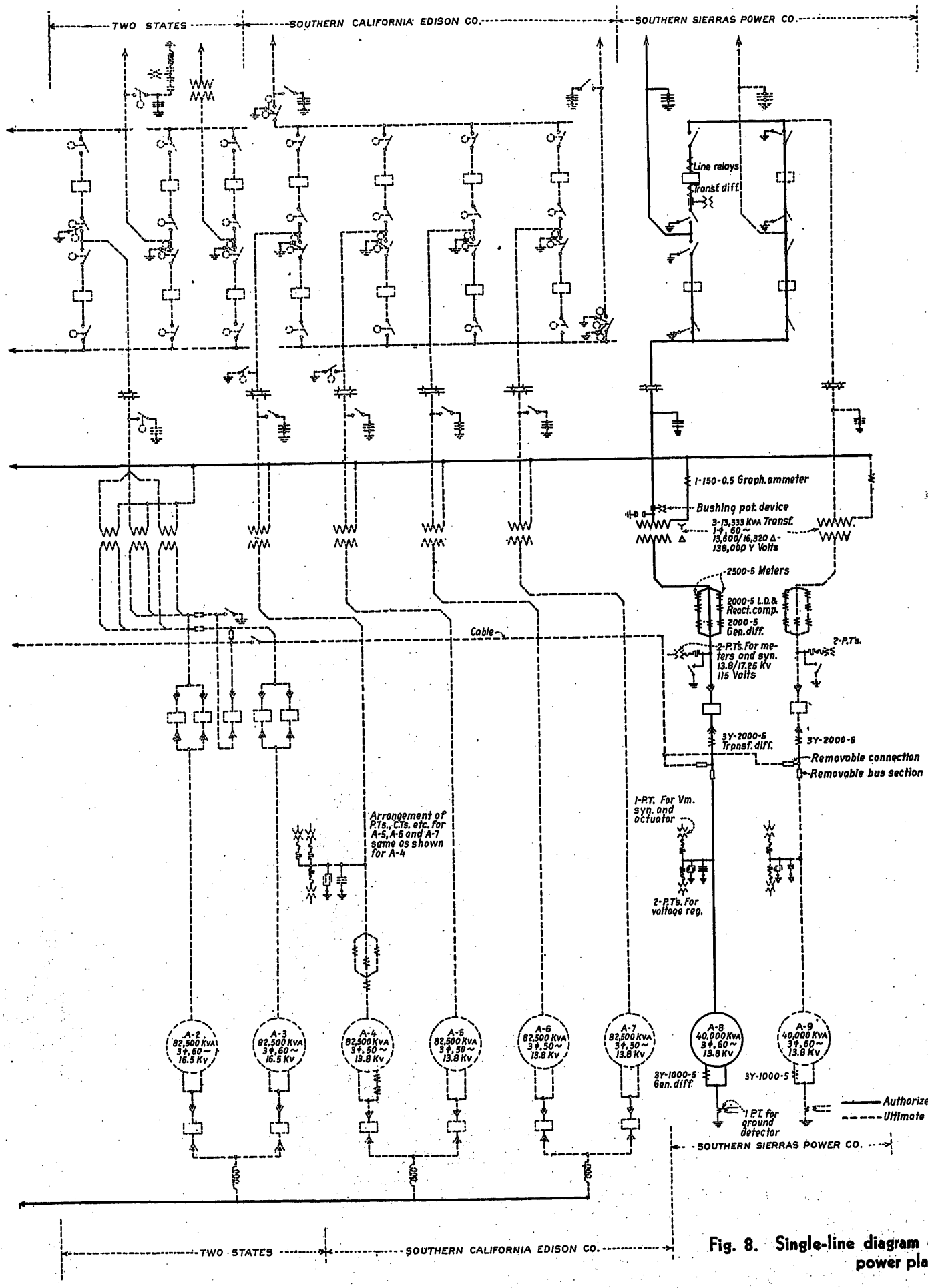



**Fig. 8. Single-line diagram of power plant.**

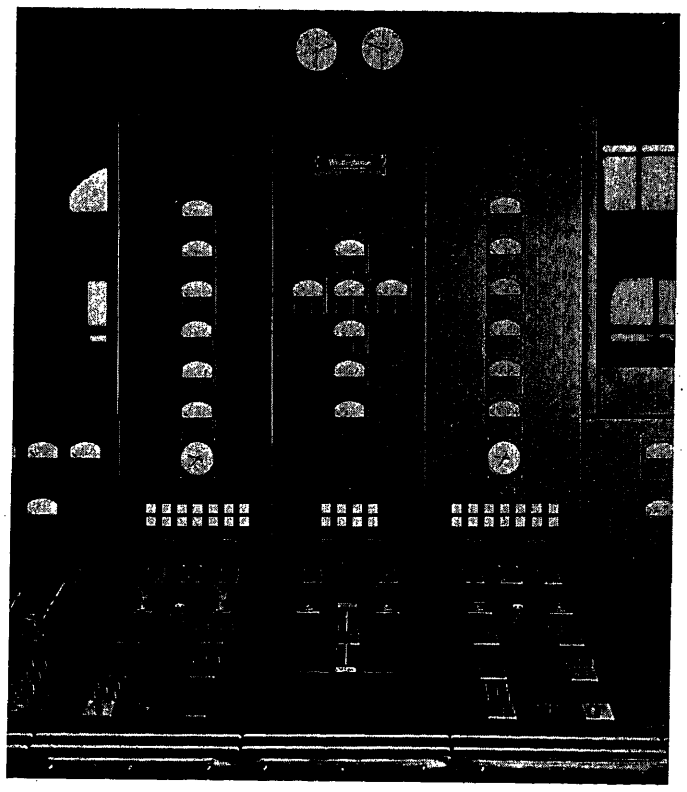


Fig. 9. Section of station service control desk

only for the individual generator or transformer units but also for the parts of the complete unit controlled. A combination of circuits is permitted only where multiple operation is required, as for the tripping of several circuit breakers from the operation of a single set of protective relays. Circuits from the 2 250-volt batteries are carried completely around the plant, so that control supply to the circuit breakers and other apparatus is always available.

Obviously, the control desk is of little value if either of the batteries is out of commission, so the usual circuit-breaker lamp indicators are connected so that a failure of either the 125-volt or the 250-volt storage battery source will put out the lights.

## High-Speed Differential Protection

High-speed clearance of internal transformer and generator faults is planned in order to maintain stability at the highest possible level and to limit the damaging effect of internal fault currents. Accordingly, the high-voltage oil circuit breakers on the 287-kv transformer bank will clear the fault in 3 cycles, and low-voltage breakers for the generators and the transfer bus will clear in 8 cycles. The differential relays for both the transformers and the generators will operate in approximately one cycle under fault conditions. These relays are of the balanced-beam type with low burden characteristics. The transformer relays are provided with self-contained voltage and timing interlocks so as to avoid operation and false tripping on the magnetizing-current rushes, either when the transformer banks are energized or as a result of recovery voltages following the clearance of an external fault, without introducing any delay in the event of a fault within the differential area.

The transformer differential relays will trip out all the circuit breakers feeding the transformer on both the high-voltage and low-voltage sides. The generator differential relays will trip not only the generator circuit breakers, but also the neutral and field breakers, shut down the water wheel, and release carbon dioxide into the generator housing. The low-voltage current transformers are located to provide overlapping protection zones, leaving no section unprotected.

Differential relay operation in one cycle introduces hazards of false tripping resulting from faults external to the protected zone. The balancing of dissimilar current transformers, unequal loading of transformers in parallel or divided power circuits, high ratio of fault to normal current, or slowly decaying d-c component of the external fault current may separately or jointly effect a saturation of the various current transformers, and thus unbalance the secondary currents to cause relay operation when no such operation should occur. The importance of these factors is evident when it is considered that the relays must determine whether the fault is within or beyond the transformer or generator and then operate in one cycle for an internal fault.

If the current transformers for the high-voltage side of the transformer are located in the circuit

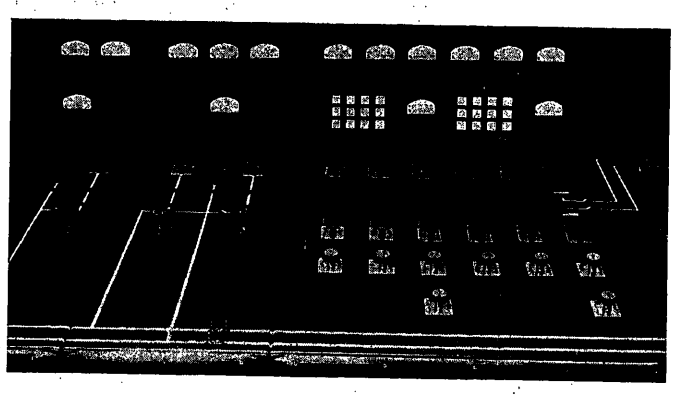


Fig. 10. Section of station service control desk

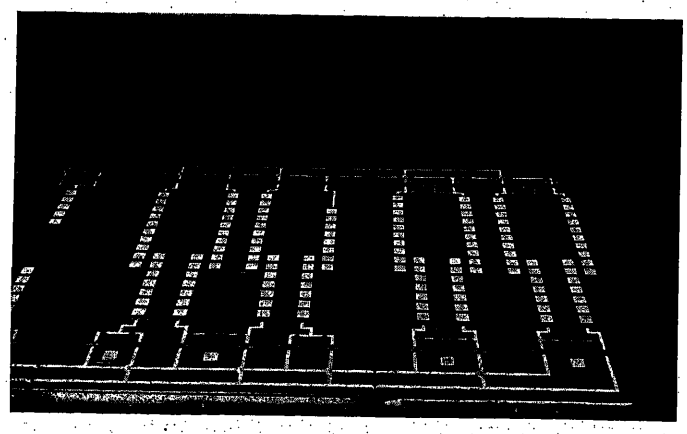


Fig. 11. Section of station service control desk

breakers of the double bus system, the current flowing in any given current transformer may be considerably larger or smaller than the current flowing through the transformer bank being protected because of current passing from one bus to the other. The restraint in the differential relay is very closely proportioned to the current flowing through the transformer bank, but the current tending to produce saturation in any given current transformer may be larger than this by the current flowing from one bus to the other through the transformer breakers. This would result in the current tending to produce saturation being much larger than the current to prevent the relay from operating.

The result of the d-c component of the short-circuit current and its low rate of change is to require a large total flux in the current transformer to transform this component from the primary to the secondary. If the flux required exceeds the saturation point for the current transformer, the latter will saturate during part of the short circuit, which in turn will cause the transformer to draw an excessive exciting current both for the d-c component

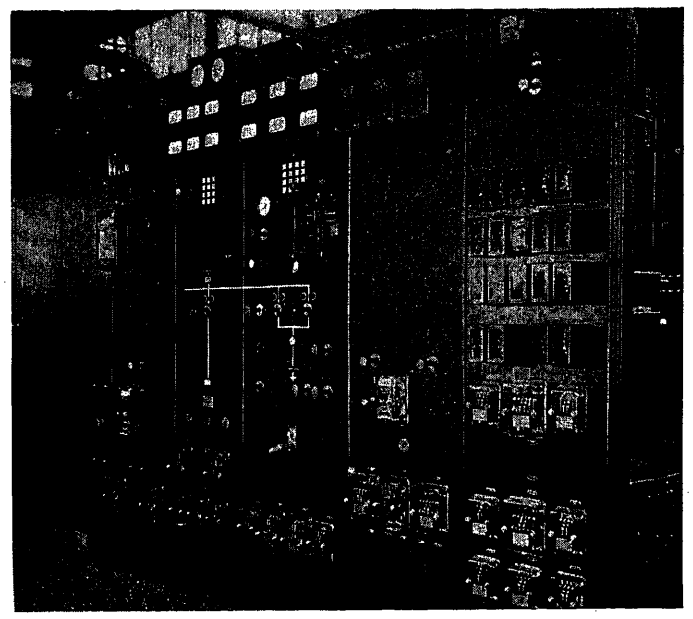


Fig. 13. Front view of cubicle of generator N–3

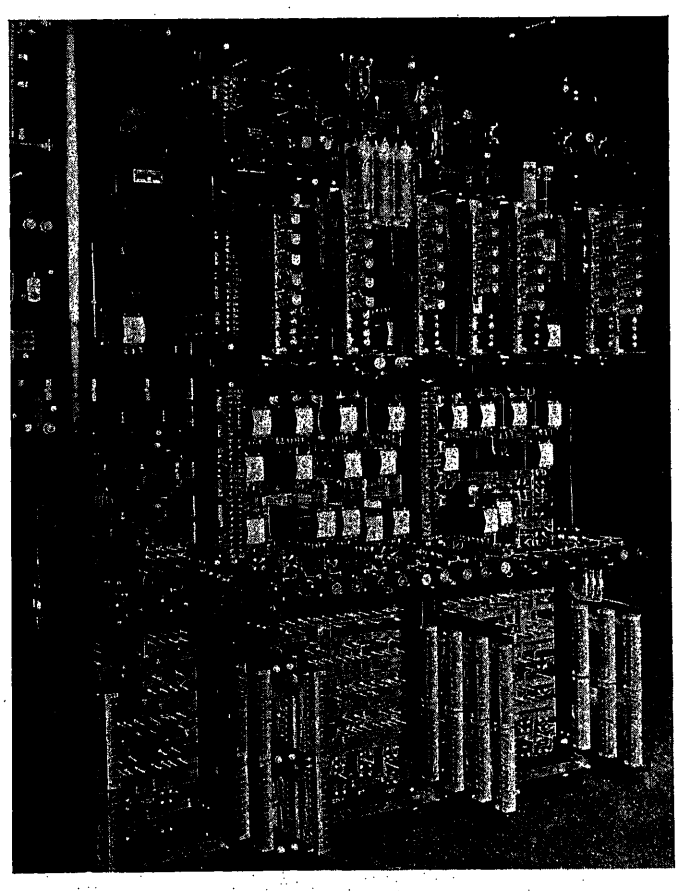


Fig. 12. Rear view of station service control desk

and for the a-c component being transformed at the same time. This results in a departure from ratio which can be very large in the most severe cases. Unless all the current transformers involved in the differential protection are affected in the same way and to proportionately the same extent, departure from ratio of one or more of the current transformers will result in current through the differential relay with some hazard of incorrect operation.

Referring particularly to the transformer protection, it is recognized that fully asymmetrical short circuits occur only infrequently, particularly on high-voltage faults, and likewise the worst short circuits occur only at rare intervals, and therefore the conditions which contribute to improper operation may be expected only at long intervals. However, the use of highly sensitive relays, and the presence of a slowly decaying d-c component emphasize the possibilities of such improper operation. Considering the relative importance to the City of Los Angeles of Boulder Dam power, it was desirable to eliminate this hazard as far as practically possible.

A complete theoretical analysis of the entire subject, supplemented by numerous oscillographic test data, indicated that the most practical solution would be obtained by 3 distinct steps. In the first place, the amount of iron in both the high-voltage and low-voltage current transformers was increased several times beyond normal. In the second place, the amount of copper in the current-transformer secondary windings, and in the connections from the transformers to the protective relays, was increased several times beyond normal in order to decrease the burdens. Lastly, the differential relays for the power transformers were located at the switch-yard rather than in the power plant, in order to shorten the runs and decrease the burden for high-voltage current transformers where the greatest unbalance might exist. All of these steps contribute to reduce the dangers of saturating, and thus tend to give proper current transformer performance within the limits of the differential relays under both steady-state and transient conditions.

In the case of the generator relays, the same type of problem exists, but the situation is more readily taken care of because of the similarity of design of

the current transformers co-operating in the differential protection scheme.

## Load and Frequency Control

Automatic load and frequency control of the most advanced and complete type will be provided for each of the initial power systems. Any of the City of Los Angeles generators can be placed on the following individual types of control regardless of the type of operation chosen for the remaining generators:

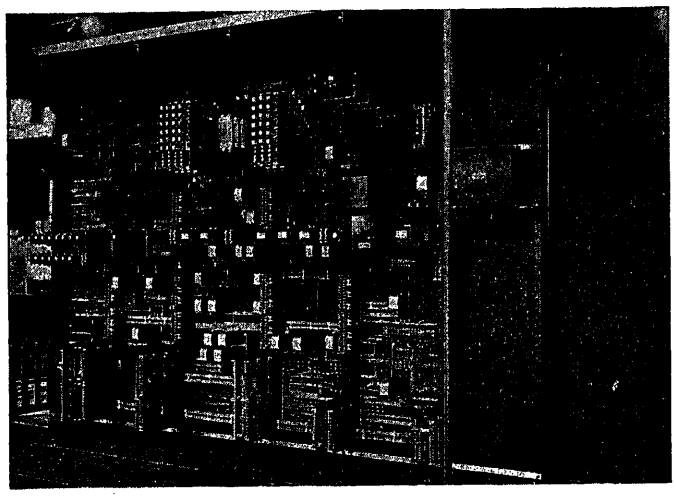


**Fig. 14. Rear view of cubicle of generator N–3**

1. Frequency control
2. Adjustable proportionate-load control
3. Independent base-load control

This equipment consists generally of a high-grade Warren Telechron type *E* master pendulum clock, a master frequency unit controller which can be switched to any generator unit at will, and a load controller for each unit. The master clock is separately mounted and the master frequency controller and the unit load controller together with their accessories, are mounted on the auxiliary control board. A combined system frequency and time error recorder is mounted on the auxiliary board, and a time-error indicator is mounted on the control desk. The unit load controllers are actuated by direct current obtained from "thermal converters" located at the generator cubicles.

While completely automatic load and frequency control is provided, manual control is also available, with suitable interlocking to prevent contradictory or conflicting operation and consequent "hunting" of control. In addition, the load and frequency control automatically trips off after an adjustable time delay on failure of the a-c or d-c supplies or when the frequency, unit load, or total load exceeds predetermined limits.

## Clock Supply Equipment

The complete plant will have approximately 300 synchronous motors operating various clocks, graphic instrument drives, etc. These clocks and graphic instruments should be kept operating regardless of the condition of the main power system, and particularly to obtain a graphic record under fault conditions and independent of the system under fault. Accordingly, a 115-volt 60-cycle frequency-regulated single-phase supply is obtained from 2 $7^1/_2$-kva generators, each driven by a d-c motor, energized from the main control storage battery. Either set can carry the entire load of clock supply.

The generators are regulated for voltage, which varies only under starting conditions, as the clock load is uniformly constant. Frequency is regulated by field control of the motors, taken from a standard frequency generator.

The standard frequency generator comprises an electrically maintained tuning fork, a vacuum-tube oscillator, duplicate amplifiers, etc. The tuning fork with its associated oscillator generates a small amount of constant-frequency current, which is amplified to operate standard clocks, used as monitors, and to energize the grids of hot-cathode mercury-vapor rectifier tubes, which serve in the field control of the motors to maintain constant speed.

While there is only a single master tuning fork and standard frequency supply, all tubes used therein are in parallel so as to insure continuity of operation and the field controls of the motors are independent.

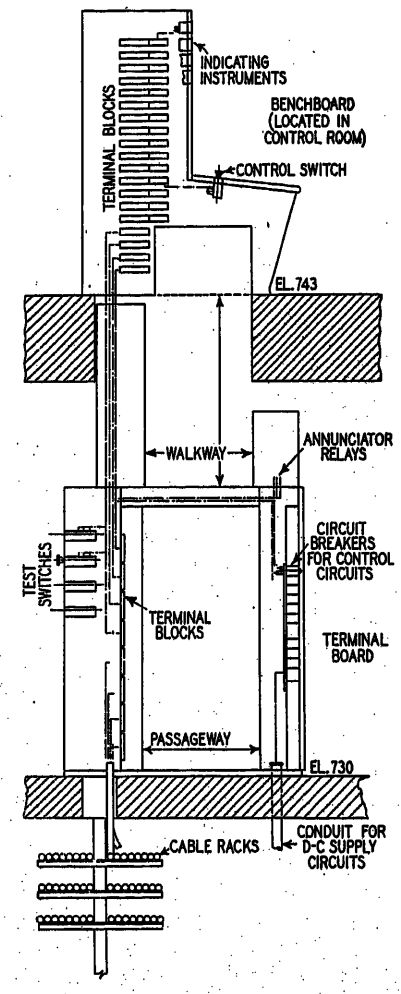



**Fig. 15. Cross section showing relation of terminal boards to control desk with their interconnections**

Suitable clocks are provided to check directly the output of the standard-frequency tuning-fork control, as well as the output of the motor generator set.

The equipment is expected to maintain a constant supply frequency with an error from standard time signals of less than one second per day. By checking with radio time signals, it should be possible to adjust so as to maintain the integrated time error very close to zero.

## Annunciator System

A very complete annunciator and signal system is required because of the large number of generating units, distances from each other and from the main control room, different operating floors, and the possibilities of operating the generators either from the main control desk or from the generator cubicles. The principal purposes are to provide communication between the main control room and the generator and governor floors, to call the operator's attention when a unit is being started or shut down, and likewise to call attention at the various points to any so-called "trouble" operation.

Dual telephone systems provide for the usual vocal communication.

For trouble indication, each of the generators and the transformers, including those for station service,

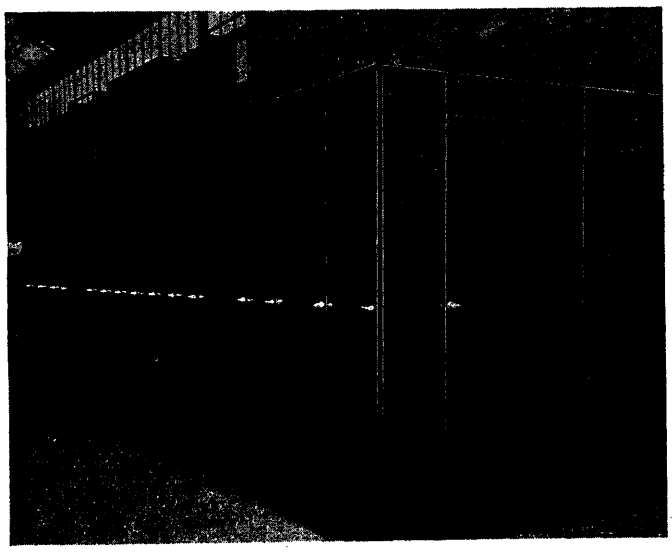


**Fig. 16. Terminal boards with doors closed**

is provided with an annunciator group at each of its control points. For instance, for generator $N$–1 there are provided an annunciator group on the main control desk, one on its generator cubicle, and one on the unit auxiliary control board in the governor gallery. In each of these groups is provided a lamp indicator to show

1. Low governor-oil pressure
2. Hot bearings
3. Generator-cooler failure
4. Hot generator windings
5. Generator cooling-water failure
6. Differential-relay operation
7. Overspeed
8. Overvoltage; direct current and several others

For each generator or transformer unit, the annunciator groups are identical, but the groups for the transformers and for the station service generators will differ slightly from those for the main generators, according to their respective needs.

Likewise on the feeder panels of the station service

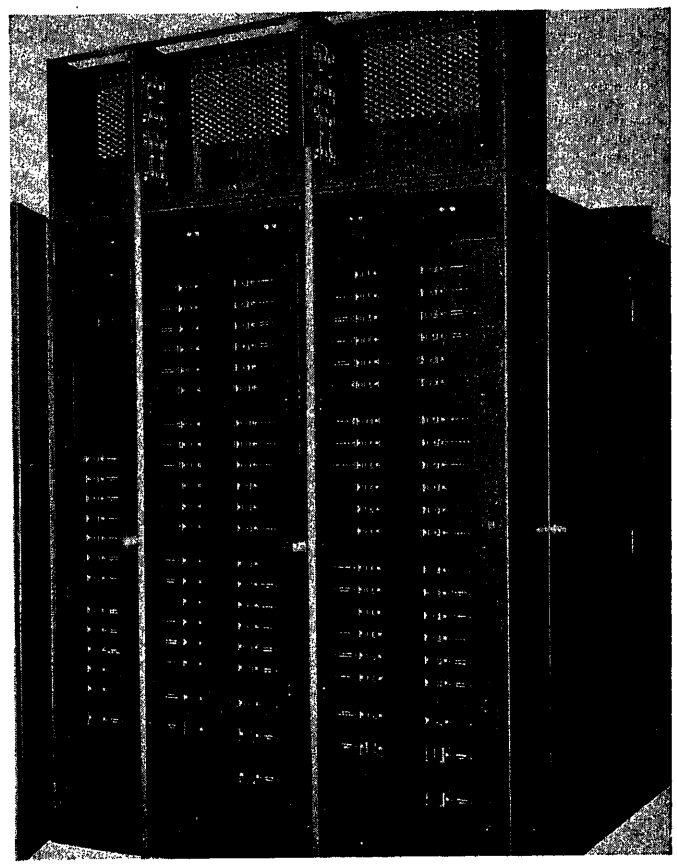


**Fig. 17. Front view of terminal boards with doors open, showing control distribution circuit breakers**

benchboard, there are similar annunciator groups to indicate, for instance, among others,

1. Ground on 250-volt battery number 1
2. Charger number 1 a-c supply circuit tripped
3. Nevada wing 250-volt feeder breaker tripped
4. Nevada canyon wall feeder trip
5. Feeder $A$ to switchyard tripped
6. Feeder to $N$–0 to $N$–6 600-kva transformer tripped

In each of the generator rooms there are provided large visual indicators on the generator balcony and on the governor gallery with numerals on 3 sides and visible at a distance of 300 feet to indicate at which unit the operator is required. Attention is called to these visual indicators by suitable audible signals, one to call the operator for standby service when starting up the unit, and the other in case of trouble.

Appropriate audible signals are also provided in the main control room, with bright lamp indicators to show the unit on which trouble occurs.

The annunciator system is operated by the protective relay which functions in cases of trouble; for instance, differential relays, low oil-pressure relays, high-temperature relays, etc. The trouble relays will usually maintain their contacts until the trouble has been corrected. When trouble occurs, the audible alarms will sound in the main control room and in the generator balcony and the governor gallery. These alarms will sound for approximately 10 seconds and then will reset automatically so as to be ready for the next trouble indication. At the same time, the large visual

indicators in the galleries will show the number of the unit on which trouble has occurred. One lamp indicator in each of the corresponding groups on the generator control board panel, the generator cubicle, and the unit auxiliary control panel in the governor galleries will be illuminated. After the trouble has been cleared, the annunciator indicator lamp can be extinguished by a reset push button at each group, but any attempt to do this before the trouble contacts have opened is futile. In addition, the operation or resetting of the annunciator indicator is not permitted to interfere with the automatic release of the audible alarms and their preparedness for further signals. The resetting of the annunciator indicator is done independently in each group, without affecting the indicator at another group. Likewise, resetting the alarm and annunciator indicators for one fault does not interfere in any way with the reception of signals and indication for subsequent faults.

On the end panels of the station service control desk are provided vertical rows of signal windows, to indicate the condition of the auxiliary control necessary for the generator units. For instance, for each main generator there are provided 10 lamp indicators for the a-c auxiliaries, including among others:

Transformer cooling water
Transformer-oil circulation
Fan indication
Generator cooling-water indication
Auxiliary control transformer
Governor oil-pump indication

and 7 signal windows for the d-c auxiliaries, including among others:

Generator bearing oil-pump indications
Generator field breakers
Generator differential-relay pilot lamp

Each signal window is about one inch square and is covered with a white translucent front on which designation of the equipment it represents is lettered in black, with a low-brilliancy lamp in back to indicate a normal condition.

It is obviously impossible to go into the detail of switchboard circuits and methods for a plant of this size. The foregoing description of a few of the problems gives a measure of the complexity of the over-all switchboard problem and some clue as to the completeness of the plans adopted.

Some further illustration of the problems may be obtained by considering that the electrical equipment in a plant of this size naturally represents many manufacturers. The main purpose of the switchboard is to control all of these electrical equipments, and to do so with a uniformity of methods that will facilitate operation and subsequent maintenance. For instance, the switchboards control oil circuit breakers of 3 manufacturers and air circuit breakers of 2 manufacturers. Each oil circuit breaker had originally its own control scheme, and while the distinctive features of each manufacturer have been retained, those different control schemes have been molded into an over-all uniform scheme.

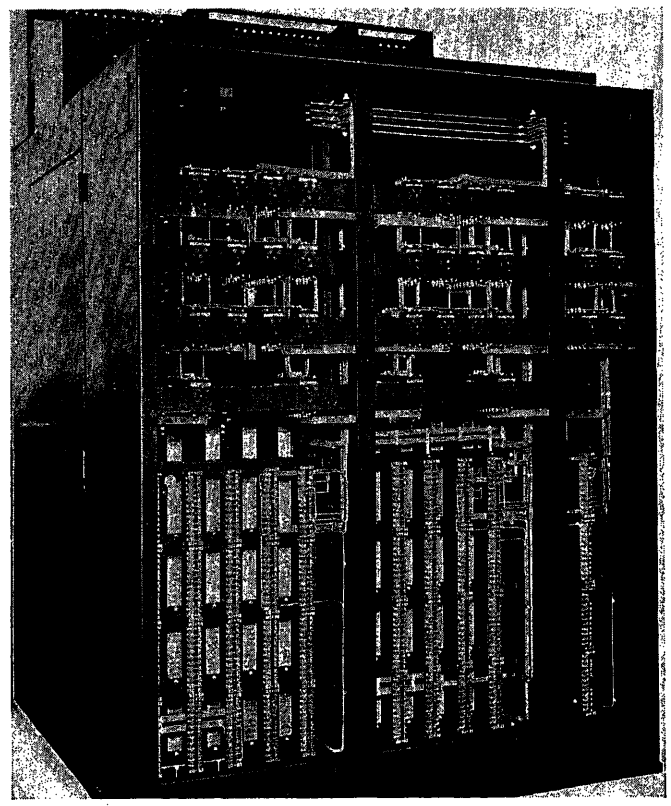


**Fig. 18. Rear view of terminal board with doors removed, showing terminal blocks and test switches**

Voltage regulators, load and frequency regulators, and automatic speed matcher and synchronizers are supplied by 3 different manufacturers. The switchboards provide mounting for graphic instruments from at least 2 manufacturers. All of these must be co-ordinated into a uniform and operating system.

While considerable emphasis has been given to the switchboards for the City of Los Angeles, because their 4 generating units are being controlled by the initial installation, the same features of design apply to the switchboards for the Southern Sierras Power Company.

It has been part of the fundamental plan to provide switchboards which will be complete in every detail, for every operating requirement of the best type of station, yet there is a simplicity, directness, and uniformity of design that will make operation and its attendant maintenance problems as simple as possible. The Boulder Dam switchboards are entirely modern and up to date, without departing from sound practice. They prove the feasibility of conventional switchboard design for a generating plant of this size and character.

## References

[Editor's Note: The following list of papers published in ELECTRICAL ENGINEERING on subjects related to the Boulder Canyon project is given for the convenience of those desiring further information.]

1. POWER LIMITS OF 220-KV TRANSMISSION LINES, A. A. Kroneberg and Mabel Macferran. ELECTRICAL ENGINEERING, volume 52, November 1933, pages 758–66.

2. CORONA LOSSES FROM CONDUCTORS OF 1.4-INCH DIAMETER, J. S. Carroll,

(*Concluded on page 244*)

# Electrical Water-Level Control and Recording Equipment for Model of Cape Cod Canal

By H. L. HAZEN
ASSOCIATE AIEE

**Control of water level according to a predetermined cycle and its automatic recording in a model of the Cape Cod Canal have been accomplished by electrical means which depend for operation upon the capacitances between the surface of the water and metal plates suspended above the water. The theory of operation and the apparatus are described in this paper.**

CAPE COD, which extends southeastward approximately 40 miles from the general coast line of Massachusetts, was cut by a canal some years ago to shorten coastwise shipping routes. In connection with the enlargement of this canal to facilitate the passage of large ocean vessels, certain problems arose that made it desirable to study the flow of water in the canal and in the adjoining portions of Cape Cod Bay and Buzzards Bay, using a hydraulic model. These model studies were undertaken as a co-operative project by the department of civil and sanitary engineering of the Massachusetts Institute of Technology, Prof. C. B. Breed in charge, and the Corps of Engineers, U.S. Army, Col. John J. Kingman, district engineer. The experimental work is being done at the River Hydraulic Laboratory at Massachusetts Institute of Technology under the direction of Prof. K. C. Reynolds.

Relatively high velocities of flow occur in the Cape Cod Canal, caused by the fact that the tidal range in Cape Cod Bay is somewhat more than twice that in Buzzards Bay, that is, the tides are more than twice as high, while the relative time phases are such that high water occurs in Buzzards Bay about 3 hours or a quarter-period before it occurs in Cape Cod Bay. In order to study by means of a hydraulic model the effect of enlarging the canal on these velocities, it is evidently necessary to reproduce in miniature the tidal water-level variations in the basins at the ends of the model canal. This requires automatic water-level control equipment. It is also necessary to obtain accurate water-level records at numerous stations along the canal and the adjoining waters of the model, as these readings constitute the useful data.

Both the automatic water-level controllers and the water-level recorders require a means of measuring the average water level over an area of a few square inches. Floats of any sort have proved unsatisfactory for this purpose because of the rather large and uncertain errors introduced by surface tension and by dynamic hydraulic forces. Floats also introduce an uncertain effect on flow in the model. Staff gauge water-level readings are subject to error because of surface waves which are unavoidable in this model. Because of these difficulties the electrical methods described in this paper were developed.

The model, built on a horizontal scale of 1 to 600 and a vertical scale of 1 to 60, represents the 8-mile canal together with $11\frac{1}{2}$ square miles of Buzzards Bay at its southern end and one square mile of Cape Cod Bay at its northern end. These areas of bay at either end are sufficient to extend to deep water where the tidal water levels can be assumed to be unaffected by any flow from the canal. By causing the water levels at these 2 deep-water ends of the model to follow any desired tidal cycle, the water levels and flows throughout the model are made to reproduce in miniature and to scale those occurring in nature. In this way the effects that any dredging will have on navigation, or the dredging profiles that are necessary to secure given depths of water, can be predetermined.

The water-level control problem is essentially that of making the water levels at the deep-water ends of the model bay areas rise and fall in accordance with the tides previously observed in nature. This water-level control is accomplished by 2 simultaneous adjustments. The first, or coarse, adjustment is obtained by a time-controlled flow of water into the deep-water end of each basin such that the tidal cycle would be reproduced to a first approximation without additional control. The second, or accurate, water-level adjustment is accomplished by automatically controlling the height of a discharge weir located at the deep-water end of each basin in accordance with the observed instantaneous error in water level near the weir.

In a basin covering a few hundred square feet, the rate of rise or fall of water level can be changed only slowly without causing serious waves. Therefore, a sensitive control device is required which will detect and correct an error in water level before it has become large enough to require a large change in weir discharge. Conversely, a sensitive control is subject to oscillation or hunting unless special care is taken to avoid it. Thus, the problem requires a compromise design based on a quantitative analysis of the dynamics of the entire system involved.

Attention is confined in this paper to the electrical control and recording equipment. The hydraulic aspects of the study are presented in an unpublished report by Prof. K. C. Reynolds.

A paper recommended for publication by the AIEE committee on automatic stations. Manuscript submitted June 15, 1936; released for publication September 3, 1936.

H. L. HAZEN is associate professor of electrical engineering at Massachusetts Institute of Technology, Cambridge.

The author acknowledges the aid others have given in this development; in particular, the enthusiastic co-operation of Prof. K. C. Reynolds, in charge of the River Hydraulic Laboratory at Massachusetts Institute of Technology, and of Prof. R. D. Bennett of the electrical engineering department.

## Layout of Water-Level Control System

As stated in the preceding section, the water levels in the 2 basins at the ends of the canal must be continuously adjusted so that the tidal levels observed in nature are correctly reproduced to scale in the model. This is done as follows:

A master "time" unit is used to control the sequence of all model tidal phenomena. This consists of an adjustable-speed d-c motor which is geared to a so-called Selsyn transmitter, and also to a valve-control shaft. The Selsyn transmitter drives 2 Selsyn synchronous motors, one near the weir of each basin. Each of these Selsyn motors is geared to a disk cam. The gearing and Selsyn units are so designed that the valve-control shaft and the 2 disk cams revolve synchronously at a speed of one revolution per tidal cycle. In nature the period of this cycle is about 12.42 hours, which is reduced to 9.63 minutes in the model. Each of the disk cams is essentially a polar plot of the tide-level curve for its basin. The problem then is to make the water level reproduce the tidal data given on the cam.

This is done by means of the apparatus shown schematically in figure 1. The cam continually adjusts the height of the "level unit" through the lever $L_1$. On this level unit is a plate $P$. Through the amplifier, weir motor, and rack and pinion, the weir is so controlled by the level unit that the water level tends to remain at a constant distance $D$ from plate $P$. As the cam is driven by the master time unit, the water level is made to reproduce the tidal curve. Lever $L_2$ provides damping in a manner explained in detail subsequently.

Evidently if this scheme alone were used to control the water level, enough water would have to be continuously supplied to the basin to raise the level at the most rapid rate called for by the tidal curve and to provide an excess for control by adjustable spillage over the weir. Also the weir would have to have a relatively large maximum spillage to lower the water at the maximum rate and discharge the inflow at the same time. To reduce the inflow of water required, and also to reduce the amount of controlling action imposed upon the weir, the simple expedient of controlling the water input to each basin by valves is used. Adjustable cranks on the valve-control shaft mentioned above operate ordinary gate valves through a lever system. Each gate valve controls the water supplied by gravity to one basin from a central constant-head tank. By suitably adjusting both the stroke and phase angle of these cranks, the amount of water-pump and weir capacity can be greatly reduced and the final level control made much more accurate. A separate valve-controlled water supply and weir-control unit is of course necessary for each of the 2 basins.

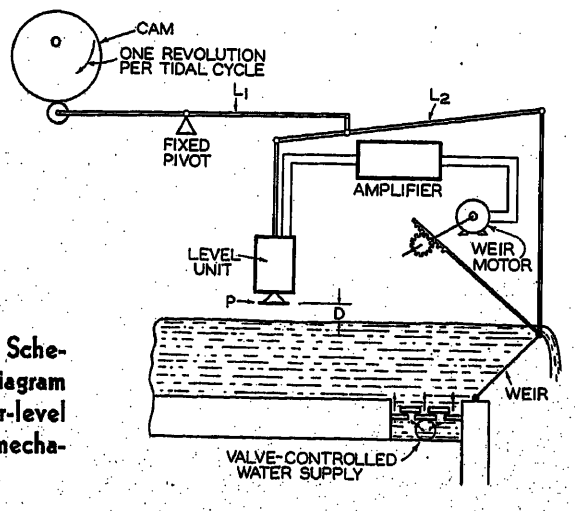



**Fig. 1. Schematic diagram of water-level control mechanism**

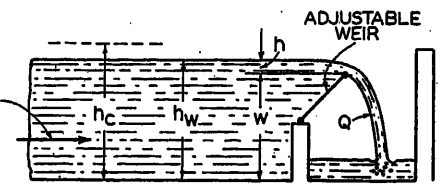



**Fig. 2. Diagram of a portion of a basin showing dimensions used in the analysis**

In the following section an analysis of the dynamic behavior of this water-level control system developed for the purpose of designing a stable and sufficiently accurate system is given.

## Analysis of Control System

Figure 2 shows schematically a portion of a basin representing the bay at one end of the canal for the purpose of indicating some of the hydraulic dimensions used in the control analysis. Three components of water flow affect the water level in this basin: first, the flow in and out from the canal; second, the flow in from the constant-head tank, controlled by the crank-operated gate valve; and third, the flow out over the weir. When the algebraic sum of these 3 components is correctly adjusted the water level in the basin will follow the prescribed tide-level curve. The first component is not subject to arbitrary control. The second component is an adjustable periodic function of time. Preliminary analysis showed that it should be such a function of time that the third component or weir discharge is approximately constant. This third component is then adjusted from instant to instant by the automatic control of the weir height to reduce the residual error in water level to a negligible value.

The analysis that follows applies to the action of the automatic weir-height control device. Let

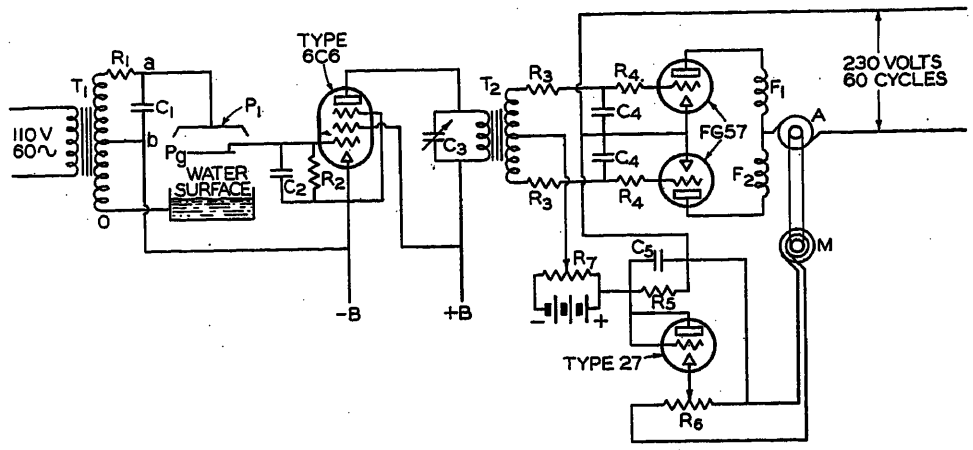
$h_c$ = desired height of water at any instant (feet)
$h_w$ = actual height of water at any instant (feet)
$w$ = height of weir crest (feet)
$t$ = time (seconds)
$Q_o$ = net inflow to basin including flow from pump and canal (cubic feet per second)
$Q$ = weir discharge under head $h$ (cubic feet per second)
$h$ = head on weir (feet) = $h_w - w$
$h_o$ = average value of $h$ (a constant)
$l$ = length of weir (feet)
$A$ = area of basin (square feet)

All heights are measured from an arbitrary datum plane.

Two equations describe the motion of the system.

**Fig. 3. Water-level controller circuit**

$C_1$ = 0.01 microfarad
$R_1$ = 4,000 ohms
$C_2$ = 0.0001 microfarad
$R_2$ = 30 megohms
$C_3$ = 0.17 microfarad
$R_3$ = 1.0 megohm
$C_4$ = 0.003 microfarad
$R_4$ = 50,000 ohms
$C_5$ = 1.05 microfarad
$R_5$ = 50,000 ohms
$R_6$ = 1,500 ohms
$T_2$ = Audio transformer (Sampson type Y)




The first is the water-level equation

$$\frac{dh_w}{dt} = \frac{Q_o - Q}{A} \tag{1}$$

The second equation describes the control action exerted on the weir, which can be arbitrarily specified. Preliminary analysis indicated that this control system would operate properly if the weir speed were made to depend linearly on the sum of 2 quantities, the error in water level, and the departure of the head on the weir from its average value. The weir-height equation is then

$$\frac{dw}{dt} = g(h_c - h_w) + m(h_w - w - h_o) \tag{2}$$

in which $g$ and $m$ are constants. The right-hand term in equation 2 introduces required damping, as shown subsequently. The coefficients $g$ and $m$ are to be fixed by the given allowable error and the necessity for aperiodic operation.

Before combining equations 1 and 2, $Q$ must be expressed in terms of the head on the weir. The law assumed for the weir discharge was

$$Q = 3.33\, l h^{3/2} \tag{3}$$

which can be put into an approximate linear form in $(h - h_o)$ for heads near an average head $h_o$ by using the first 2 terms of a Taylor's expansion about $h_o$. Thus

$$Q = 3.33\, l h_o^{3/2} + 5.00\, l h_o^{1/2} (h - h_o)$$

within about 5 per cent for $0.7\, h_o < h < 1.5\, h_o$. Substituting this approximation in the right-hand term of equation 1 gives

$$\frac{Q_o - Q}{A} \approx q_o - q_1(h_w - w - h_o) \tag{4}$$

in which

$$q_o = \frac{Q_o - 3.33\, l h_o^{3/2}}{A} \tag{5}$$

and

$$q_1 = 5.00 \frac{l}{A} \sqrt{h_o}$$

$$= 5.00 \frac{l}{A} \sqrt[3]{\frac{Q_{ave}}{3.33\, l}} = \text{constant} \tag{6}$$

From equation 6 it may be seen that the average weir discharge $Q_{ave}$ fixes the constants $h_o$ and $q_1$. It also fixes the constant term of $q_o$.

Putting equation 4 in equation 1,

$$\frac{dh_w}{dt} = q_o - q_1(h_w - w - h_o) \tag{7}$$

Differentiating equation 7 with respect to time, substituting equation 2 in the result, writing $p$ for $\frac{d}{dt}$, and rearranging gives

$$p^2 h_w + q_1 p h_w + m p h_w + q_1 g h_w - q_1 g h_c - p\, q_o - m q_o = 0 \tag{8}$$

Since the error in water level is desired rather than the actual height of water, equation 8 is rewritten using a change of variable

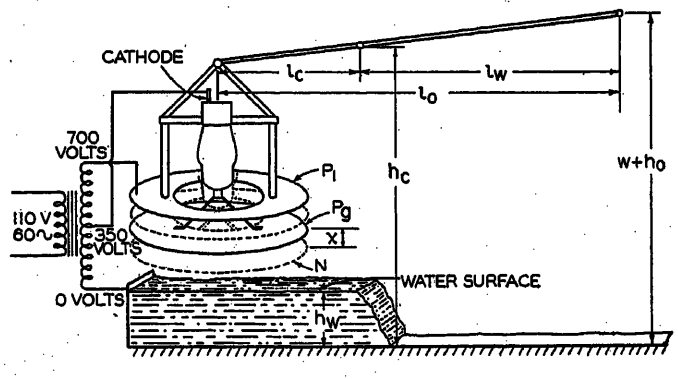



**Fig. 4. Diagram of damping lever**

*N* indicates position of $P_g$ for zero alternating potential on grid of tube

$$\delta = h_c - h_w \tag{9}$$

in which $\delta$ = error in water level in feet. Putting equation 9 in equation 8 and solving for $\delta$ gives

$$\delta = \frac{(p + q_1 + m)p h_c - (q + m)q_o}{p^2 + (q_1 + m)p + q_1 g} \tag{10}$$

In equation 10, $h_c$ and $q_o$ are time functions that can be determined from the tidal-level data, the valve-crank

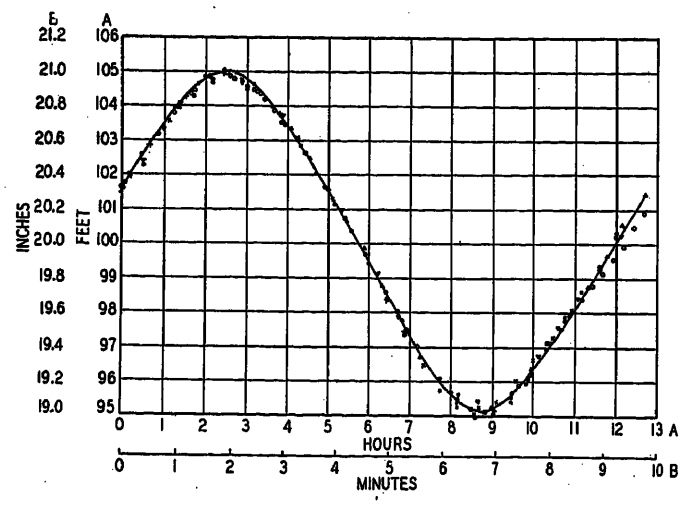



**Fig. 5. Typical level-controller performance**

Scales *A* for nature; scales *B* for model

Circles are actual tidal data obtained at Cape Cod Bay approach to canal. Solid curve is idealization of these data for model tide cycle. Other plotted points are typical water-level records taken in course of model studies

adjustments, and the dimensions of the basins; $q_1$ is a constant fixed by the constant component of weir spillage due to the average weir head $h_o$.

In order to determine $m$ and $g$, 2 additional conditions need to be imposed. The conditions selected are, first, that the operation must be aperiodic, and second, that the maximum value of the error $\delta$ shall not exceed a prescribed amount. For critical aperiodic operation, the denominator of equation 10 must have equal real roots, which imposes the condition

$$(q_1 + m)^2 = 4q_1g \tag{11}$$

The error condition is next imposed. A consideration of various features of the model study led to the selection of 0.0010 foot (equivalent to 0.06 foot in nature) as the maximum permissible value of $\delta$ which, preliminary calculations indicated, could be attained with reasonable apparatus.

It is subsequently shown that $q_1 << m$ and that therefore the numerator of equation 10 can be written with sufficient accuracy as

$$(p + m)(ph_c - q_o) \tag{12}$$

But $ph_c - q_o$ is the residual flow per unit of basin area which the automatic control must correct by adjustment of the weir, and can therefore be approximately described as a known function of time for either basin.

Thus far the analysis has been general, that is, it applies to any system of the type described. At this point it is desirable to insert actual numerical values, which necessitates considering a specific case. The end representing Buzzards Bay is arbitrarily chosen for the numerical work that follows.

Examination of the expected flow relations in the model of Buzzards Bay shows that this residual flow will impose on the automatic control a condition no more severe than that imposed by a sine-wave flow having an amplitude of 0.20 cubic foot per second and a period one-third that of the main tidal cycle. The main tidal period in the model is approximately 9.6 minutes. Therefore, for the basin of 900 square feet area the residual level variation to be corrected can be assumed for the purpose of design to have the form

$$ph_c - q_o = \Delta \sin 3 \frac{2\pi}{T} t \tag{13}$$

in which

$T$ = the period of the tidal cycle in model (seconds)
$\Delta$ = amplitude of assumed residual level error to be corrected by automatic control (feet)

Putting in the above numerical values,

$$ph_c - q_o = \frac{0.20}{900} \sin 3 \frac{2\pi}{9.6 \times 60} t$$

$$= 2.22 \times 10^{-4} \sin 0.0327t.$$

Replacing $p$ in equation 10 by $j\omega_3$ where $\omega_3$ is the angular velocity of the assumed residual level variation and $j = \sqrt{-1}$, and remembering that $q_1 << m$, gives

$$\frac{\delta}{\Delta} = \frac{m + j\omega_3}{-\omega_3^2 + mj\omega_3 + q_1g} \tag{14}$$

Using the simplified condition for critical damping

$$q_1g = \frac{m^2}{4} \tag{15}$$

in equation 14 gives

$$\frac{\delta}{\Delta} = \frac{m + j\omega_3}{\left(\frac{m}{2} + j\omega_3\right)^2} \tag{16}$$

Trial shows that $\omega_3 << m$, when equation 16 becomes

$$\frac{\delta}{\Delta} = \frac{4}{m}$$

Putting in numerical values gives

$$m = \frac{4 \times 2.22 \times 10^{-4}}{0.0010} = 0.89 \text{ foot of weir height per second for one foot departure of the weir head from } h_o$$

The quantity $q_1$ must now be evaluated. The average weir discharge for the conditions under which the auto-

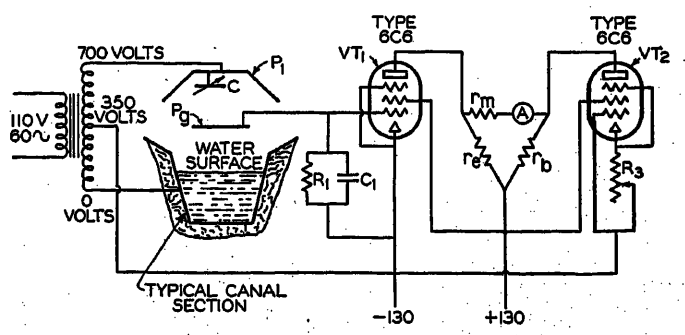



**Fig. 6. Circuit diagram of water-level recorder**

$R_1$ = 30 megohms $C_1$ = 0.0001 microfarad
$R_3$, $r_m$, $r_t$, and $r_b$ vary from unit to unit

matic control is to work is 0.7 cubic foot per second, which gives a value for the weir 12 feet long of

$$q_1 = \frac{5 \times 12}{900} \sqrt[3]{\frac{0.7}{3.33 \times 12}} = 0.0174 \text{ (dimensions same as for } m)$$

The assumptions $\omega_3 << m$ and $q_1 << m$ can now be checked. Thus

$\omega_3 = 0.0327$
$q_1 = 0.0174$
$m = 0.89$

which shows them to be justified within the accuracy justified by other data.

The constant $g$ can now be calculated from equation 15.

$$g = \frac{m^2}{4q_1} = \frac{0.89^2}{4 \times 0.0174} = 11.4 \text{ feet of weir height per second for one foot error in water level}$$

This completes the dynamic analysis, as all parameters are fixed.

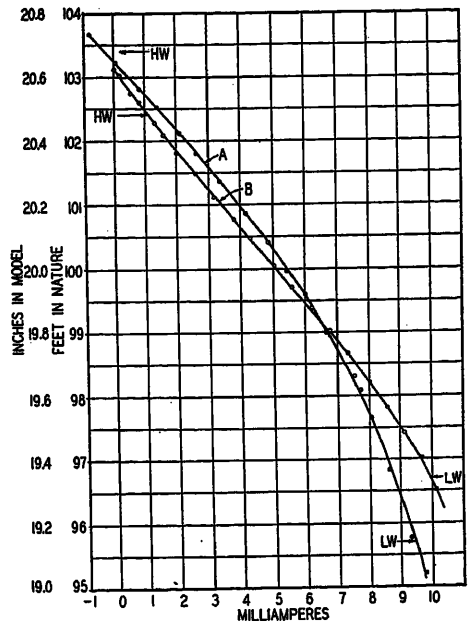



**Fig. 7. Typical calibration curves for water-level recorder**

*LW*—Low water

*HW*—High water

*A*—Recorder at narrow channel section adjacent to bridge piers

*B*—Recorder away from disturbing structures extending above water

## Design of Apparatus

Having determined the necessary numerical values of the damping coefficient $m$ and the level-restoring coefficient $g$, which are the 2 important dynamic parameters, the problem shifts to the design of apparatus that will be characterized by these values. This apparatus includes 3 essential parts: first, a level-measuring device; second, an amplifying device and motor to furnish power to operate the weir in accordance with the indications of the level indicator; and third, a suitable mechanism for inserting the damping described by the coefficient $m$. These parts will be described in order.

Figure 3 shows schematically the electrical features of the level indicator, amplifier, and weir-driving motor. The level indicator is essentially an electrostatic potential divider consisting of the water surface and the plate $P_1$ as its terminals between which the plate $P_g$ picks up electrostatically a potential intermediate between that of $P_1$ and the water. Plate $P_1$ is maintained at a 60-cycle alternating potential of 700 volts, effective value, above the potential of the water by the transformer $T_1$. The grid-to-cathode voltage of a type 6*C*6 pentode is the difference between the potential of plate $P_g$ and the midpoint of the 700-volt winding of $T_1$. The plates $P_1$ and $P_g$ are fixed mechanically with respect to each other and are moved as a unit by the water-level cam previously described. At some water level, $P_g$ and the midtap of $T_1$ will be at the same potential, and hence the grid-to-cathode voltage will be zero. If the water level is above this balance level, the grid will have impressed on it a 60-cycle voltage of a certain phase. If the level is below, the phase of the grid voltage will be displaced 180 degrees. Parts $R_1$ and $C_1$ constitute a phase-correcting circuit for making the voltage between $a$ and $b$ precisely in phase with the voltage between $b$ and $o$. This is required because the 2 secondary halves of $T_1$ are differently loaded.

Although the capacitance between $P_g$ and $P_1$ or $P_g$ and the water is only about 20 micromicrofarads, the circuit is very stable and requires practically no shielding. This is due in part to the excellent insulation of $P_g$, obtained by mounting it directly on the grid cap of the tube.

The amplifier consists of a type 6*C*6 pentode and 2 type *FG*57 thyratrons. The thyratrons are so biased by means of the resistance drop in $R_7$ that they fail to fire when no alternating current is present in the plate current of the pentode. Both have the same plate voltage but the a-c components of their grid voltages differ in phase by 180 degrees. The circuits are so adjusted by $C_3$, $R_3$, and $C_4$ that their grid and plate voltages are either in phase or 180 degrees out of phase. Consequently when the water level is above or below balance level, one or the other of the thyratrons fires, taking current from the 230-volt 60-cycle supply through the d-c motor armature $A$ and one motor field $F_1$ or $F_2$, thus driving the motor in one direction. To maintain correct phase relations this 230-volt supply must necessarily come from the same feeders as the 110-volt supply for $T_1$. If the other thyratron is fired, current flows through the motor armature and the other field, driving the motor in the opposite direction. The motor drives the hinged weir through a reduction gear and rack and pinion, as indicated in figure 1. Of course connections must be so made that a low water level raises the weir, and vice versa.

One other feature of the circuit will be mentioned. The motor (and weir) speed should be proportional to the indicated error in water level. The alternating voltage on the thyratron grids is proportional to this error. But the thyratrons are "on" and "off," that is, not smooth-control devices when used in this way. However, by driving an a-c magneto $M$ by the motor, rectifying its output, and charging capacitor $C_5$, which is shunted by a leak $R_5$, an additional d-c bias can be applied to the thyratrons. If this additional bias exceeds the peak value of the a-c grid voltage, it will cause the previously-firing tube to cease firing until the motor speed has de-

creased. Thus the average motor speed is kept very nearly proportional to the indicated error in water level.

Thus far no mention has been made of introducing damping. This important aspect will now be considered. Equation 2 can be written

$$\frac{dw}{dt} = (g - m)\left[\frac{g}{g - m} h_c - h_w - \frac{m}{g - m}(w + h_o)\right] \qquad (17)$$

in which the weir speed $(dw)/(dt)$ is a linear function of 3 heights—the desired water height $h_c$, the actual water height $h_w$, and the weir-crest height $w$, $h_o$ being a constant. This suggests the linkage shown in figure 4. The weir speed is proportional to the distance $x$, if $x$ is small, by which the plate system $P_1P_g$ is removed from its zero indication position, that is

$$\frac{dw}{dt} = kx$$

Since the water height is a directly additive (with negative sign) component in $x$, evidently $k = g - m$ and

$$x = \frac{g}{g - m} h_c - h_w - \frac{m}{g - m}(w + h_o) \qquad (18)$$

or

$$x + h_w = \frac{g}{g - m} h_c - \frac{m}{g - m}(w + h_o) \qquad (18a)$$

The linkage of figure 4 will produce this result if

$$\frac{l_o}{l_w} = \frac{g}{g - m}$$

Putting in the numerical values for the design for Buzzards Bay gives

$$\frac{l_o}{l_w} = \frac{11.4}{11.4 - 0.89} = 1.085$$

or

$$l_w = \frac{l_o}{1.085} = 0.92\, l_o$$

As mentioned earlier in the paper, all heights are measured from any common datum plane.

Final experimental adjustments of the constant $g$ were made by gear ratios and the values of $R_5$ and $C_5$ (see figure 3).

A similar calculation was made for the Cape Cod Bay basin controller which need not be repeated here, since it merely involves different numerical values.

## Practical Considerations

In the theoretical design given above, certain idealizations were made that are not realized in practice. One of the most serious of these is the tacit assumption that the water level changes at the same rate over the entire basin, following an adjustment of the weir height. Actually this is not so for 2 reasons. The first is that the weir displaces water when it is moved. This sets up a wave of higher or lower level, depending on whether the weir is raised or lowered, that propagates away from the weir over the basin at a finite rate. The second reason is that a lowering or raising of the weir also produces a local lowering or raising of the water level due to a changed discharge rate. This level change also propagates at a finite velocity.

If the water-level indicator for the controller is not very close to the weir, there is an appreciable time lag between the change in water level at the weir and the change of level at the level indicator. Such time delays in general

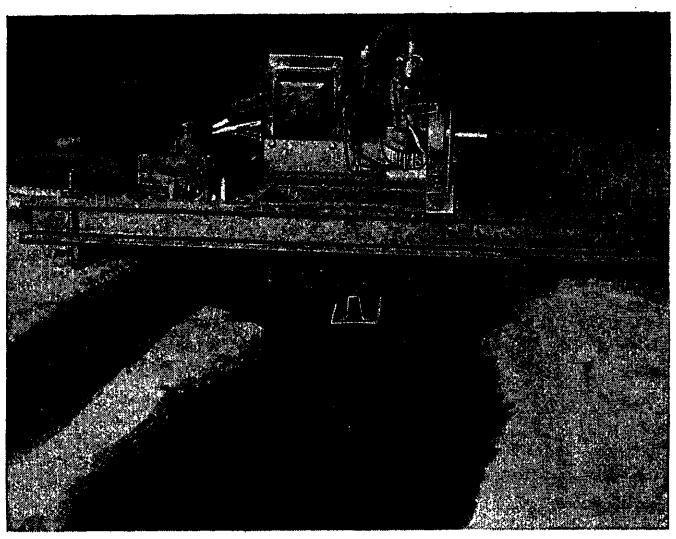


**Fig. 8. Level-recorder unit in place over canal**

Plate $P_g$ (figure 6) appears immediately above "bridge piers" in canal. Plate $P_1$ is the hood immediately above $P_g$. Tube $VT_3$ and resistor $R_8$ appear above framework

have the effect of introducing negative damping into any control system, that is, they tend to set up oscillation. In this installation this time lag was appreciable, which necessitated introducing somewhat more damping than that called for by the analysis. Final adjustment of the damping was made experimentally under actual operating conditions.

In the analysis it was assumed that the residual flow to be controlled by the automatic controller was made small by carefully adjusting the gate-valve cranks. In actual operation it proved more expedient to adjust these cranks only approximately and to make final adjustment of the tidal cycle by filing the control cams to a shape slightly different from the actual tidal curve. Since each tidal cycle is given a considerable amount of study, the time required to adjust the cams for each new cycle by filing is relatively unimportant. The advantage of making final adjustment by filing the cams is that there is a much more direct and easily-visualized relation between the residual water-level error and the change in the cam necessary to correct it than there is between this error and the corresponding corrective change in valve-crank setting. Once the cams are corrected, the tidal cycle repeats accurately thereafter, independent of any minor changes in the canal flow caused by trial modifications of the model.

## Controller Performance

After the adjustments described, together with certain minor circuit adjustments, were made, the controllers were put into operation in November 1935, and they have operated consistently since then with little attention. Errors in the water level of the 2 basins have been within the limits established as satisfactory for the studies to be made. Rough tests were made of the dynamic performance of the controller which showed that the device was operating in substantial accord with the design calculations. The significant test, however, is the performance of the controllers in accurately controlling the water levels under actual operating conditions. Typical performance data are shown in figure 5. In this figure the circles represent actual tidal data recorded at the Cape Cod Bay approach to the canal. The solid line is the slightly-idealized tidal cycle derived from these data to be reproduced in the model. The remaining plotted points are those obtained on the model during a series of typical runs.

## Water-Level Recorder

Attention is now turned to the other apparatus used on the canal model which is of interest to electrical engineers, namely, the water-level recorders.

As in the case of the water-level indicator for the water-level controller, floats were barred for level recorders because of the serious and uncertain errors introduced by surface tension and by dynamic forces caused by water currents. The general scheme adopted for the water-level recorder is similar to that described hereinbefore, that is, the water surface is used as one electrode of an electrostatic potential divider from which the grid potential of a pentode is derived. In the recorder, however, the variation in the d-c component of plate current rather than in the a-c component is used to indicate the water level. This d-c component is indicated by a d-c milliammeter. The simultaneous recording of the indications for the 9 water-level stations in the model is done photographically.

In figure 6 is shown the circuit of a recorder. The chief difference between this circuit and that of the first tube in figure 3 is the method of utilizing the output. In the recorder circuit, the fixed plates $P_1$ and $P_g$ are so placed, and the adjustable plate $C$ so set, that at the lowest water level the capacitance between the water and $P_g$ is slightly greater than that between $P_g$ and $P_1$, thus impressing sufficient alternating voltage on the grid to reduce the plate direct current slightly (about 10 per cent) below its value for equal capacitances. As the water level is raised, the capacitance unbalance and hence the grid alternating voltage become greater, decreasing the plate direct current. Thus the plate direct current is a measure of the water level. This is the general scheme of operation.

A number of refinements are necessary to reduce the errors. The goal for error was set at 0.5 millimeter probable error for level ranges up to about 4.5 centimeters. Plate $P_g$ is 2.5 centimeters or more from the high-water level to avoid difficulties resulting from splashing, while the canal section in some cases is only about 13 centimeters wide at the top. These conditions made it difficult to reach the desired accuracy with simple equipment.

Proper shaping and placing of plates $P_1$ and $P_g$ are important in order to obtain adequate sensitivity at low water when the capacitance of $P_g$ to the canal walls is much larger than its capacitance to the water surface, and when the rate of change of the latter capacitance with respect to water level is small. Conversely, at high water the rate of change of this capacitance with water level is relatively high. A reasonably linear calibration curve was obtained by using the steepest part of the curve for grid alternating voltage versus plate direct current at low water, and the flatter part at high water. Typical calibration curves are shown in figure 7. Because some grid alternating voltage is necessary even at low water, no phase-correcting circuit was required on the 350–700-volt half of the a-c high-voltage supply for a level-recorder unit.

Another aspect that must be given careful attention is the error resulting from variations in screen voltage. Unless some form of compensation is used, this error can easily become as much as 2 or 3 millimeters of water level per volt change in screen voltage at 130 volts for the 6*C*6 tubes used. By using a second 6*C*6 tube $VT_2$ with fixed grid voltage (see figure 6), this sensitivity to changes in screen voltage is considerably reduced and at the same time a convenient means is provided for suppressing the zero of the d-c plate milliammeter $A$. The screens and heaters of both tubes are supplied from the same sources. By suitably adjusting the values of the resistances $r_m$, $r_l$, and $r_b$ in the milliammeter mesh, the milliammeter reading can be made to range over any desired fraction of

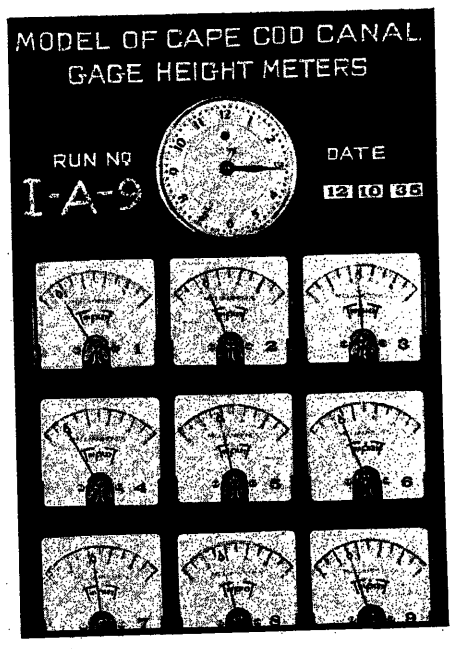



**Fig. 9. Instrument panel for water-level recorder**

The 9 milliammeters indicate water levels at 9 stations in model. Water levels are obtained from calibration curves

full scale for any given range of water-level variation. By adjusting the resistance $R_s$, these readings can be centered on the meter scale. The resistance $r_m$ is made large enough so that the temperature error due to copper in the milliammeter is made negligible. This feature is pertinent because of the rather wide fluctuations in temperature occurring in the building in which the model is located.

The best shape of calibration curve for water level versus milliammeter reading is obtained by properly shaping and placing the $P_1$ and $P_g$ plates, and finally by adjusting the low-water grid alternating voltage with the small auxiliary capacitor plate $C$.

Both alternating and continuous voltage regulators are used in the power-supply circuits because of the high degree of consistency required of the tubes and circuits. By this means the cathode temperature, the grid alternating voltage, and the screen voltages are maintained within the necessary close limits.

Figure 8 is a view of an assembled level-recorder unit in place over a section of the model canal. The instrument panel containing the 9 milliammeters, a clock, and a place for data pertaining to a run is shown in figure 9. This is photographed at intervals of 20 seconds throughout a tidal cycle lasting 9.63 minutes by means of a 35-millimeter motion-picture camera. After the film is developed the meters and clock are read from the projected image of the negative. Figure 9, in fact, is reproduced from one of the photographs taken in routine recording.

## Performance of Water-Level Recorder

The recorders have been in operation practically continuously since November 1935. With them level measurements have been consistently obtained that utilize the full hydraulic accuracy of the model.

In general the uncertainty of a current reading has been found to be of the order of 0.005 milliampere in a recorder-current range of about 0.8 milliampere. In terms of water level this represents an uncertainty of from 0.12 to 0.25 millimeter. Using the vertical scale factor of 1 to 60 between model and nature, this uncertainty is seen to represent from about 0.025 to 0.05 foot in nature, the larger figure being associated with the larger tidal ranges.

To achieve this precision requires careful calibration at intervals of 2 or 3 weeks. Other operating precautions are also necessary, such as careful control of all voltages, and allowing a warming-up period of about half an hour previous to taking readings. As stated hereinbefore, both alternating and continuous voltages are automatically controlled by voltage regulators whose settings are checked by manual adjustment. Good-grade portable voltmeters have sufficient accuracy for use in this checking and adjustment.

The principal cause for frequent calibration is the gradual change in the mutual conductance of tubes with use. Because of this change it is occasionally necessary to readjust the resistance $r_m$, shown in figure 6, in order to maintain a working range of 0.8 to 0.9 of full scale on the meter for the working range of water level. This is done before a calibration and occasions little inconvenience.

## Summary

The electrical equipment described in this paper has made possible the successful reproduction of tidal cycles and accurate recording of water levels in a hydraulic model. The equipment is relatively simple and inexpensive. Although requiring some care in operation, it has proved entirely serviceable and has been in practically continuous use since the installation was completed in November 1935. Ordinary adjustments are made by engineers with little electrical training. The results obtained with this electrical equipment are sufficiently accurate to make the hydraulic errors the controlling factor in the over-all accuracy of the model studies.

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# Lightning Currents in 132-Kv Lines

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**Data pertaining to lightning currents actually measured in tower structures, counterpoises, and ground wires on 132-kv lines during 1933–36 are presented in this paper. It is concluded that stroke currents rarely exceed 150,000 amperes, although 220,000 amperes has been indicated, and that currents as high as 60,000 amperes measured in the overhead ground wires indicate the necessity of adequate shielding of the line at station entrances.**

THE organized field and laboratory investigations on the effects of lightning on electric systems and apparatus, started some 10 years ago, have uncovered many of the mysteries of lightning affecting line performance and equipment protection. Voltage magnitudes and polarity have been measured, wave shapes determined with some degree of completeness and certainty, and frequency and severity of lightning disturbances observed.

As various theories of the mechanism by which lightning produced its disturbing effect on electric systems were put forth, discussed, and checked against the field operating experience, it became apparent that a fuller knowledge of the currents in the lightning stroke itself, and their distribution in the various parts of the electric system subject to its influence, were urgently needed to help solve the problems of lightning protection to lines and equipment.

Having actively entered into the very early investigation work mentioned above, and having recognized the value of this work in bringing about better service to electricity consumers and greater protection to apparatus, the authors have continued without interruption the field investigation work first started some 10 years ago. However, during the past 4 years their research has centered about the problem of determining lightning currents in strokes themselves, and in various parts of the transmission network. This investigation has been conducted on the properties of the American Gas and Electric Company and in co-operation with the General Electric Company.

In this paper there will be presented in a summarized form the high points of the field data obtained during the period 1933 to 1936, inclusive. Particular emphasis will be laid on the lightning currents actually measured in lightning strokes, tower structures, counterpoise wires, and ground wires. Correlation of line performance with these data will be given to the extent warranted by the data. However, the authors believe that, in view of the large volume of field data secured in this investigation of the past 4 years, it will be best to use available space to present the maximum amount of pertinent data, interpreting and correlating only the most important parts of those data.

The investigation was carried out on 2 132-kv lines forming part of the American Gas and Electric Company network, and on one line constructed for 132-kv but operated at 66-kv. These lines are the Glenlyn-Roanoke in Virginia, Philo-Canton in Ohio, and Deepwater-Pleasantville in New Jersey, respectively. Their general design characteristics and past performance record have been previously presented.[1] The major part of the field measurements was obtained on the Glenlyn-Roanoke line where instruments were located to record lightning currents in tower structures, tower arms, counterpoise wires, ground wires, and tower-top lightning rods. The impulse flashover characteristics of insulator assemblies on this line are approximately 910 and 750 kv on the 1x5 and $1^1/_2$x40 impulse waves, respectively. On the Philo-Canton and Deepwater-Pleasantville lines, measurements were recorded in tower-top lightning rods only.

To make most effective use of the available equipment, measuring instruments were concentrated at line locations which from past experience appeared to be the most heavily lightning-infested sections of the line. The degree of instrument coverage in per cent of total line length on which investigation was carried out throughout the 4 years (1933 to 1936) was 7.3 per cent of the Philo-Canton line, 5.3 per cent of the Deepwater-Pleasantville line, and 100 per cent of the Glenlyn-Roanoke line in 1933–34 and 1935, and 23 per cent in 1936. Summarizing this on the basis that would have existed if the entire work had been carried out in one year, the field setup to record lightning currents appears as follows:

| | Length of Line Investigated (Miles) |
|---|---|
| Tower-top lightning rods | 70 |
| Counterpoises | 28 |
| Tower arms | 88 |
| Tower legs | 218 |
| Ground wires | 29 |

In evaluating the extent of line covered as shown by the above tabulation, it must be remembered the 4-years' work gave a diversity of lightning severity not possible with a single-year's investigation.

## Determination of Lightning Currents

All lightning currents reported here were determined by the surge-crest ammeter in the field. The surge-crest

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1. For all numbered references see list at end of paper.

ammeter[2] consists essentially of small laminated cobalt-iron magnets approximately $1^1/_2$ inches long by 0.1 square inch in cross section placed in a definite position in the magnetic field of the conductor in which the current is to be measured. By measuring the residual magnetism left in the magnet after the passage of current the crest value of the current is determined and in some cases its oscillatory characteristics as well.

The field setup of these magnetic links on a typical tower as installed in 1936 is shown in figure 1. Similar installations were in service during 1933, 1934, and 1935, although all towers at which field setups were made did not provide for measurements at all points of the tower structure shown in figure 1.

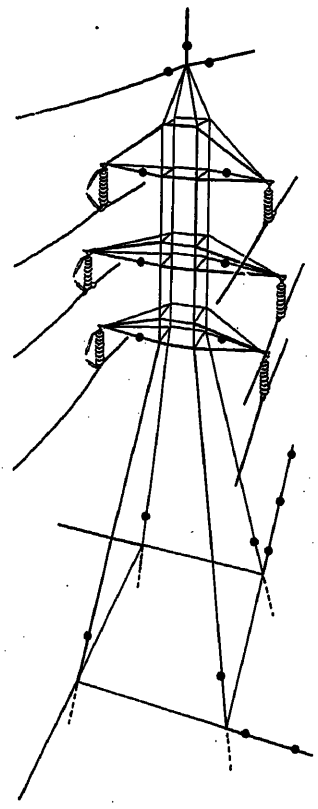


**Fig. 1. Arrangement of magnetic links of surge-crest ammeter on a typical tower in 1936**

The number of surge link installations and their locations for the 4 years herewith reported are shown in table I. Previous to 1936 currents were measured in quite a few towers by the use of one surge link installation on one leg only of the tower, the total tower current being subsequently obtained by multiplying the reading recorded in one leg by 4. Although this method of measurement seemed to give reasonably accurate results, the more precise method of using separate link installations on each tower leg was followed in 1936 when the investigation was concentrated on particularly heavy lightning infested line sections.

In the attempt to determine the flow of lightning current in the tower structure, several cases were encountered in the past where the absence of any current indication in certain locations caused some doubt as to the interpretation to be placed on the results. In such cases it is necessary to consider both the maximum and minimum currents the surge-crest ammeter, as set up, is capable of measuring. The range of measurements for the different types of field installations is shown in table II, these values being for unidirectional surges. Currents of the oscillatory type can be measured in a slightly higher range by suitable calibration of the surge-crest ammeter. This was done in some cases.

## Field Measurements of Current

Although the field records are too numerous to present completely here, some of the outstanding data and a summary will be given for currents measured in tower legs, tower-top lightning rods, tower arms, counterpoises, and ground wires, and the 4-years' data condensed and correlated so far as space permits.

A knowledge of lightning currents, both in the stroke itself and in the tower structures, was early recognized as most valuable as an aid to the study of lightning performance of lines. Therefore, the field setup was planned to obtain current readings in the lightning stroke by various means and in the tower structures by measurements in the tower legs close to the ground line.

### Currents in Tower Legs and Lightning Stroke

A summary of currents obtained in legs on single towers for the 4 years is given in table III. It may be observed that over 150 observations of currents in excess of 10,000 amperes, 14 in excess of 50,000 amperes, and 2 between 90,000 and 100,000 amperes were made. Such data have been used in the past in combination with individual tower-footing resistances to indicate the maximum potential of the tower, and from that the possibility of flashover under lightning conditions has been predicted and in many cases verified.

In determining the lightning current in the stroke itself, 3 different methods of attack have been used. The first consisted of a summation of lightning currents in

**Table I—Number and Location of Surge-Crest Ammeters**

| Location | 1933 | 1934 | 1935 | 1936 | Total |
|---|---|---|---|---|---|
| **Glenlyn-Roanoke Line** | | | | | |
| All 4 tower legs | 240 | 560 | 560 | 368 | 1,728 |
| One tower leg only | 212 | 132 | 132 | 3 | 479 |
| One per crossarm | 270 | 270 | 450 | 450 | 1,440 |
| One per counterpoise | 0 | 80 | 40 | 0 | 120 |
| Two per counterpoise | 0 | 0 | 0 | 40 | 40 |
| Three per counterpoise | 0 | 0 | 40 | 40 | 80 |
| Two per ground wire* | 0 | 0 | 80 | 120 | 200 |
| Tower-top lightning rod† | 20 | 20 | 20 | 0 | 60 |
| Tower-top lightning rod‡ | 20 | 20 | 20 | 20 | 80 |
| **Philo-Canton Line** | | | | | |
| Tower-top lightning rod | 30 | 30 | 30 | 30 | 120 |
| **Deepwater-Pleasantville Line** | | | | | |
| Tower-top lightning rod | 30 | 30 | 30 | 30 | 120 |
| Totals | 822 | 1,142 | 1,402 | 1,101 | 4,467 |

* One on each side of tower.
† Lightning stroke recorder across resistor.
‡ Surge-crest ammeters; at same location as lightning stroke recorders 1933–34–35.

**Table II—Application and Range of Measuring Instruments**

| Location | Magnet Spacing From Conductor Centers—Inches | | Unidirectional Current Range—Amperes | |
|---|---|---|---|---|
| | Inner | Outer | Minimum | Maximum |
| Tower arms | 2.6 | 2.6 | 1,600* | 16,000* |
| Counterpoises | 1.25 | 4.0 | 800 | 25,000 |
| Ground wires | 3.5 | 12.0 | 2,000 | 73,000 |
| Tower legs, 6-inch | 3.35 | 9.35 | 2,000† | 57,000† |
| Tower legs, 8-inch | 4.1 | 10.1 | 2,500† | 61,000† |
| Lightning rods | 4.0 | 4.0 | 2,500 | 25,000 |
| Lightning rods | 3.5 | 12.0 | 2,000 | 73,000 |

* One arm member only; multiply by 2 for total arm current.
† Measurements on one leg.

adjacent towers which appeared to be affected by one lightning disturbance. A summary of these data for the 4 years is shown in table IV. Here 31 stroke currents in excess of 50,000 amperes, 12 in excess of 100,000 amperes, and a maximum of 220,000 amperes for the stroke are indicated. The second method of determining current in the lightning stroke was by direct measurement in the tower-top lightning rod mounted at the tower top with suitable measuring instruments. Here the current in the stroke is measured directly. Data for the 4 years obtained in this way are shown in table V. The currents by this method of determination run much lower, the maximum current recorded being 50,000 amperes. The third and partially direct method, although not carrying with it the certainty of the direct measurement in the lightning rod but still probably having more justification than the addition of currents in the adjacent tower legs, is the method of adding current readings in a ground wire section as recorded at adjacent towers under conditions where the lightning stroke appears to have hit the ground wire in mid-span and has flowed in both directions to adjacent towers. Adding these currents at each end of the affected spans gives a value of the total lightning-stroke current. These data are given in table VI. These in a single year's observation on one line show 7 records in excess of 50,000 amperes and 1 in excess of 100,000 amperes, the maximum being 110,000 amperes. The stroke currents obtained by each of these 3 methods have been plotted in curve form in figure 2. A curve representing the average of these 3 methods of determining stroke current has been plotted here also and another showing the single tower currents tabulated in table III. It is particularly interesting to compare the last curve with the curve of average total stroke current.

**Table III—Tower Currents Above 5,000 Amperes per Tower**

Number of Tower Years 911

| Amperes | 1933 | 1934 | 1935 | 1936 | Total |
|---|---|---|---|---|---|
| 5,000– 10,000 | 12 | 15 | 16 | 18 | 61 |
| 10,000– 20,000 | 12 | 24 | 11 | 15 | 62 |
| 20,000– 30,000 | 4 | 16 | 8 | 14 | 42 |
| 30,000– 40,000 | 1 | 26 | 11 | 7 | 45 |
| 40,000– 50,000 | 0 | 7 | 2 | 2 | 11 |
| 50,000– 60,000 | 1 | 2 | 1 | 2 | 6 |
| 60,000– 70,000 | 1 | 3 | 0 | 0 | 4 |
| 70,000– 80,000 | 0 | 0 | 1 | 1 | 2 |
| 80,000– 90,000 | 0 | 0 | 0 | 0 | 0 |
| 90,000–100,000 | 0 | 2 | 0 | 0 | 2 |
| Total | 31 | 95 | 50 | 59 | 235 |

**Table IV—Lightning-Stroke Currents Indicated by Summation of Tower-Leg Currents**

Number of Tower Years 911

| Kiloamperes | 1933 | 1934 | 1935 | 1936 | Total |
|---|---|---|---|---|---|
| 10– 20 | 12 | 3 | 3 | 6 | 24 |
| 20– 30 | 2 | 10 | 4 | 10 | 26 |
| 30– 40 | 1 | 11 | 2 | 4 | 18 |
| 40– 50 | 1 | 7 | 4 | 2 | 14 |
| 50– 60 | 0 | 1 | 1 | 3 | 5 |
| 60– 70 | 1 | 0 | 2 | 0 | 3 |
| 70– 80 | 0 | 3 | 0 | 3 | 6 |
| 80– 90 | 0 | 2 | 1 | 0 | 3 |
| 90–100 | 0 | 1 | 0 | 1 | 2 |
| 100–120 | 1 | 2 | 2 | 1 | 6 |
| 120–140 | 0 | 3 | 1 | 0 | 4 |
| 140–160 | 0 | 0 | 0 | 0 | 0 |
| 160–180 | 0 | 0 | 0 | 1 | 1 |
| 180–200 | 0 | 0 | 0 | 0 | 0 |
| 200–220 | 0 | 1 | 0 | 0 | 1 |
| Total | 18 | 44 | 20 | 31 | 113 |

**Table V—Lightning-Stroke Currents by Direct Measurement in Tower-Top Lightning Rods**

Number of Tower Years 380

| Kiloamperes | 1933 | 1934 | 1935 | 1936 | Total |
|---|---|---|---|---|---|
| 5–10 | | 0 | 0 | 0 | 0 |
| 10–20 | | 8 | 11 | 6 | 25 |
| 20–30 | | 1 | 0 | 2 | 3 |
| 30–40 | | 0 | 0 | 2 | 2 |
| 40–50 | | 0 | 0 | 4 | 4 |
| Total | | 9 | 11 | 14 | 34 |

**Table VI—Lightning-Stroke Currents by Addition of Ground-Wire Currents; Glenlyn-Roanoke Line, 1936**

| Amperes | Number of Records |
|---|---|
| 10,000– 20,000 | 2 |
| 20,000– 40,000 | 11 |
| 40,000– 50,000 | 5 |
| 50,000– 60,000 | 1 |
| 60,000– 70,000 | 4 |
| 70,000– 80,000 | 1 |
| 100,000–110,000 | 1 |
| 110,000 maximum | |

## Lightning Currents in Counterpoises

The indicated benefits of counterpoises both by theory and, to some extent, by practice has led to a search for actual field data to show what was taking place in these buried conductors under lightning conditions. Field setups were therefore made to measure currents at various points along the counterpoise length. The particular counterpoises used on the Glenlyn-Roanoke line consisted of 2 long (150 feet) buried wires parallel to the line and 2 40-foot buried wires at right angles to the line. Current measurements on the long counterpoise were made on both ends and in the middle, and on the short counterpoise at both ends (see figure 1). The current distribution in these counterpoises is shown in figure 3, in percentage of the current measured in the long counterpoise at the point close to where connected to the tower. Figure 3 shows that the long counterpoise carries on the average approximately 4 times as much current as the short counterpoise as measured at the tower leg. At a distance of 40 feet which, in this case, is the end of the short counterpoise, the long counterpoise is carrying 6 times the current measured in the short counterpoise. It will also be noted that the current on the end of the short counterpoise is approximately the same, on the average, as that at the end of the long 150-foot counter-

poise, although in 3 cases the current at the far end of the long counterpoise is in excess of that entering the short counterpoise at the tower. The greater effectiveness of the long counterpoise in discharging current to ground is indicated clearly by the data.

It was expected in the initial field instrument setup that a relation would be found between the currents measured in the tower legs and those measured in counterpoises. Currents measured in counterpoises and the tower leg to which they were attached have been plotted as frequency-magnitude curves in figure 4. The surprising features shown by these data, are, first, that the current in the long counterpoise is apparently greater than that in its tower leg; the current in the short counterpoise is more along the expected lines, being less than that in its tower leg. This may be partially explained by the fact that measurements in tower legs were made in the main legs of the tower and the cross lattice bracing may have shunted some appreciable part of the tower current past the measuring instrument. If this explanation for the larger current in the counterpoise than in the tower leg is correct then the individual tower leg currents shown in figure 2 would be considerably greater than indicated, which would bring that curve even closer to the curve of average lightning stroke currents in figure 2.

Typical data on current values in tower legs and counterpoises are given in table VII. These data show that although the ratio of currents in tower legs and counterpoises is remarkably constant in some cases from year to year or between one observation and the next one, there

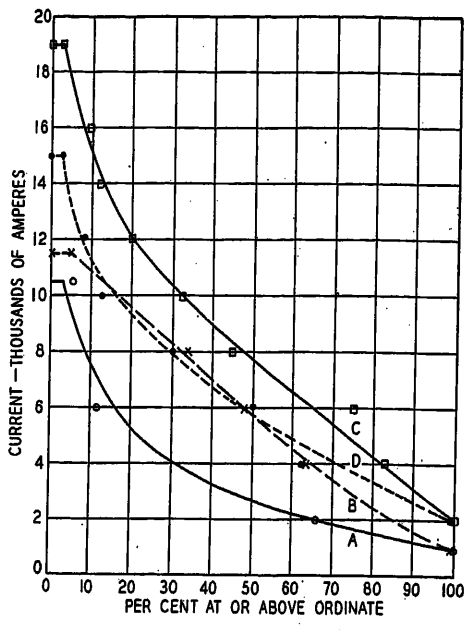



**Fig. 4. Relation between currents in tower leg and attached counterpoise on Glenlyn-Roanoke line, 1934–35–36**

*A*—Short counterpoise
*B*—Short - counterpoise tower leg
*C*—Long counterpoise
*D*—Long - counterpoise tower leg

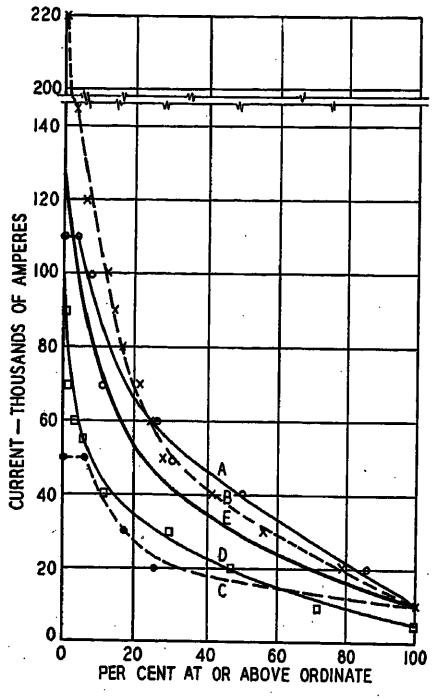



**Fig. 2. Magnitude and frequency of lightning stroke currents, 1933–36**

*A*—By ground-wire currents
*B*—Sum of adjacent tower currents
*C*—By tower - top lightning rods
*D*—Single tower currents
*E*—Average of *A*, *B*, and *C*

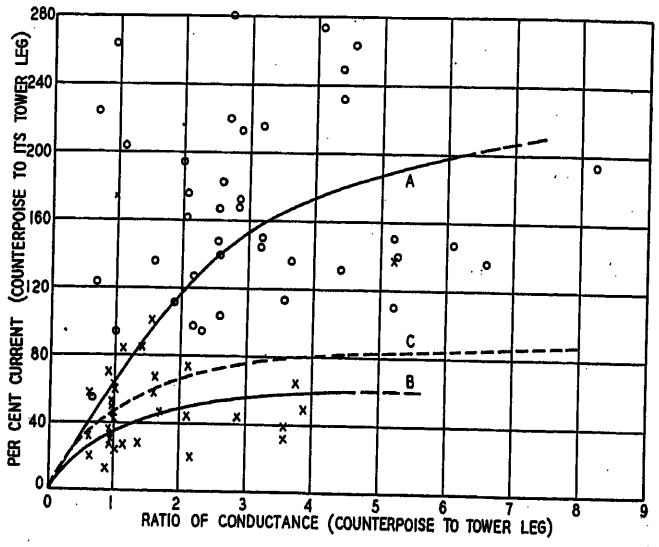



**Fig. 5. Current distribution in counterpoises and tower legs on Glenlyn-Roanoke line, 1934–35–36**

*A*—Result of test on long (150-foot) counterpoise; test points indicated by circles
*B*—Result of test on short (40-foot) counterpoise; test points indicated by crosses
*C*—Calculated on d-c basis

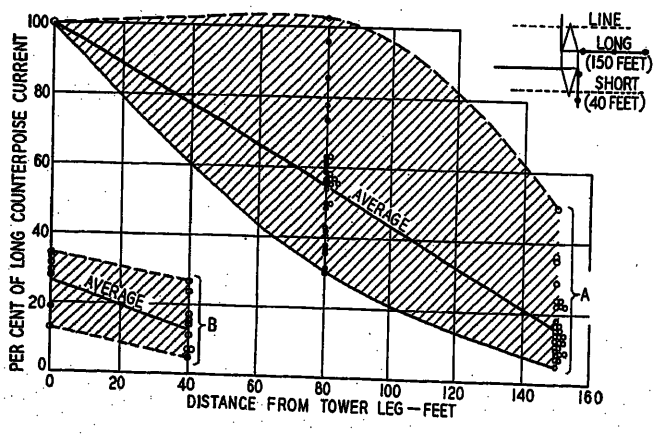



**Fig. 3. Attenuation of lightning currents in counterpoises on Glenlyn-Roanoke line, 1935–36**

*A*—Long counterpoise (30 records)
*B*—Short counterpoise (9 records)

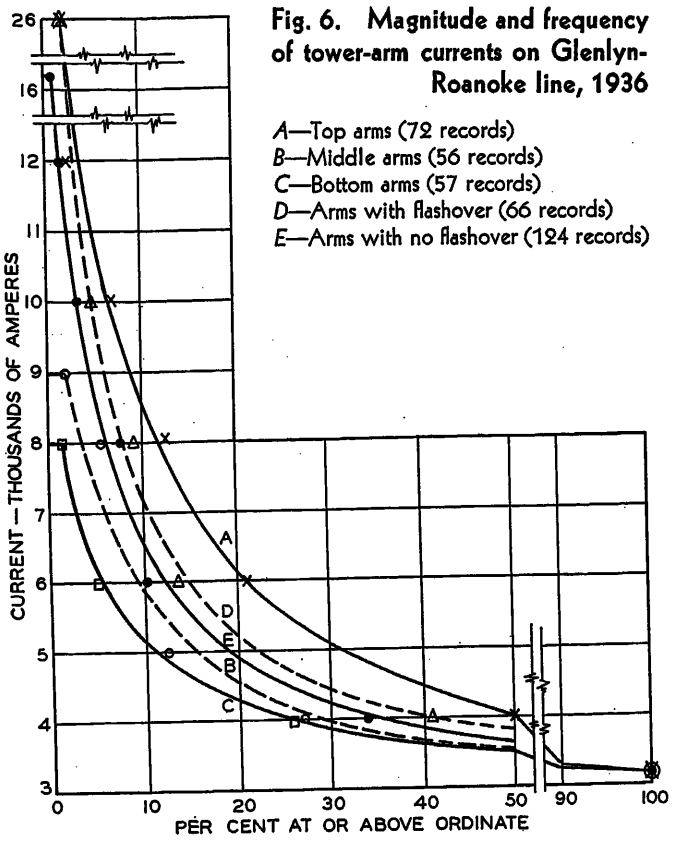



**Fig. 6. Magnitude and frequency of tower-arm currents on Glenlyn-Roanoke line, 1936**

*A*—Top arms (72 records)
*B*—Middle arms (56 records)
*C*—Bottom arms (57 records)
*D*—Arms with flashover (66 records)
*E*—Arms with no flashover (124 records)

are nevertheless many cases where a wide range of ratios exists. Thus, the table which gives the records at 9 towers which were subjected to a lightning disturbance from 2 to 4 times in the 3 years during which the observations were made, it will be seen that at tower 18*R*, for example, the ratio of current in long counterpoise to that in tower leg varied only from 1.65 to 1.47. At tower 21*G* the variation was from 1.09 to 1.39. Conversely, at tower 10*G* the variation ran from 0.55 to 2.28. Although it may be suggested that counterpoise and even tower leg resistances may have changed within a period of 2 years, it is, however, significant that ratios of from 2 to 1 for the long counterpoise current to tower leg currents, and from 3 to 1 for ratios of short counterpoise currents to tower leg currents have been obtained in the same year at the last mentioned tower, that is, 10*G*. It is suggested that these different ratios of current division between tower leg and counterpoise at a given location may be due to some extent to the difference of wave shape of the initiating lightning surge.

To aid further, an analysis of the current distribution in tower legs and counterpoises the data in figure 5 are presented. Here the ratio of current in the counterpoise to that in its tower leg has been plotted against the ratio of conductance of the same counterpoise to the same tower leg. The conductance of the tower leg has been calculated from the tower footing resistance measured before counterpoises were installed, (the tower, of course, being disconnected from the ground wire) on the assumption that the resistance of each tower leg footing was equal, that is, the resistance of one tower leg was 4 times the measured resistance of the 4 legs of the towers. The "shotgun" diagram of figure 5 does not permit drawing curves with any high degree of certainty. However, a characteristic trend is definitely indicated both for the long counterpoise and the short counterpoise.

If it is assumed that the current distribution in the ground at the foot of the tower is on the basis of measured resistance only, then the current division should be proportional to the conductance of tower leg and counterpoise. Such a distribution of current is shown by the dotted curve in figure 5. An examination of that curve

**Table VII—Lightning Currents in Counterpoises and Tower Legs, Glenlyn-Roanoke Line, 1934–35–36**

| Tower Number | Year | Resistances—Ohms | | | Currents—Amperes | | | | Current Ratios—Counterpoise to Tower Leg | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | Tower* | Long CP | Short CP | Tower Leg† | Long CP | Tower Leg‡ | Short CP | Long CP | Short CP |
| 20*G* | 1934 | 15 | 21 | 90 | 10,300 | 10,000 | 9,000 | 2,900 | 0.98 | 0.32 |
| 20*G* | 1935 | | 21 | 90 | 4,300 | 9,400 | 8,000 | 1,600 | 2.18 | 0.20 |
| 20*G* | 1936 | | 21 | 90 | 6,800 | 19,000 | 5,200 | 3,000 | 2.80 | 0.58 |
| 21*G* | 1934 | 140 | 107 | 196 | 9,200 | 10,000 | 9,600 | 3,900 | 1.09 | 0.41 |
| 21*G* | 1935 | | 107 | 196 | 7,700 | 10,700 | 7,700 | 2,400 | 1.39 | 0.31 |
| 21*G* | 1936 | | | | | | | | 2.48 | |
| 22*G* | 1934 | 96 | 86 | 237 | 2,500 | 6,200 | | | | |
| 22*G* | 1935 | | 86 | 237 | 13,300 | 17,500 | 11,500 | 6,800 | 1.32 | 0.59 |
| 22*G* | 1936 | | 86 | 237 | 2,400 | 5,600 | 2,400 | 1,600 | 2.33 | 0.67 |
| 26*G* | 1935 | 198 | 250 | 477 | 2,000 | 2,900 | | | 1.45 | |
| 26*G* | 1936 | | 250 | 477 | 3,600 | 7,700 | 2,800 | 1,300 | 2.14 | 0.47 |
| 26*G* | 1936 | | 250 | 477 | 2,400 | 3,600 | | | 1.50 | |
| 7*R* | 1935 | 43 | 65 | 168 | 2,500 | 3,500 | 2,000 | 1,200 | 1.40 | 0.60 |
| 7*R* | 1936 | | 65 | 168 | 7,200 | 7,500 | 8,000 | 3,600 | 1.04 | 0.45 |
| 7*R* | 1936 | | 65 | 168 | 9,000 | 7,300 | 3,000 | 1,300 | 0.81 | 0.43 |
| 18*R* | 1936 | 103 | 161 | 442 | 4,800 | 7,900 | 4,700 | 3,300 | 1.65 | 0.70 |
| 18*R* | 1936 | | 161 | 442 | 9,300 | 13,700 | 8,800 | 3,300 | 1.47 | 0.38 |
| 20*R* | 1936 | 92 | 127 | 347 | 10,000 | 17,000 | 4,200 | 2,200 | 1.70 | 0.53 |
| 20*R* | 1934 | | 127 | 347 | | | 2,300 | 1,400 | | 0.61 |
| 21*R* | 1934 | 61 | 118 | 223 | 3,500 | 5,600 | 3,000 | 2,600 | 1.60 | 0.87 |
| 21*R* | 1934 | | 118 | 223 | 4,300 | 7,500 | 3,600 | 3,000 | 1.75 | 0.83 |
| 21*R* | 1936 | | 118 | 223 | 8,000 | 7,800 | 7,700 | 2,200 | 0.98 | 0.29 |
| 21*R* | 1936 | | 118 | 223 | 2,000 | 2,500 | | | 1.25 | |
| 10*G* | 1935 | 60 | 347 | 107 | 2,500 | 5,700 | 2,000 | 900 | 2.28 | 0.45 |
| 10*G* | 1936 | | 347 | 107 | 12,500 | 6,800 | 4,500 | 3,300 | 0.55 | 0.73 |
| 10*G* | 1936 | | 347 | 107 | 7,000 | 8,600 | 7,500 | 1,600 | 1.23 | 0.21 |
| | | | | | | | | Average | 1.56 | 0.51 |

* Tower alone without counterpoise.
† Tower leg attached to long counterpoise only.
‡ Tower leg attached to short counterpoise only.
CP = counterpoise.

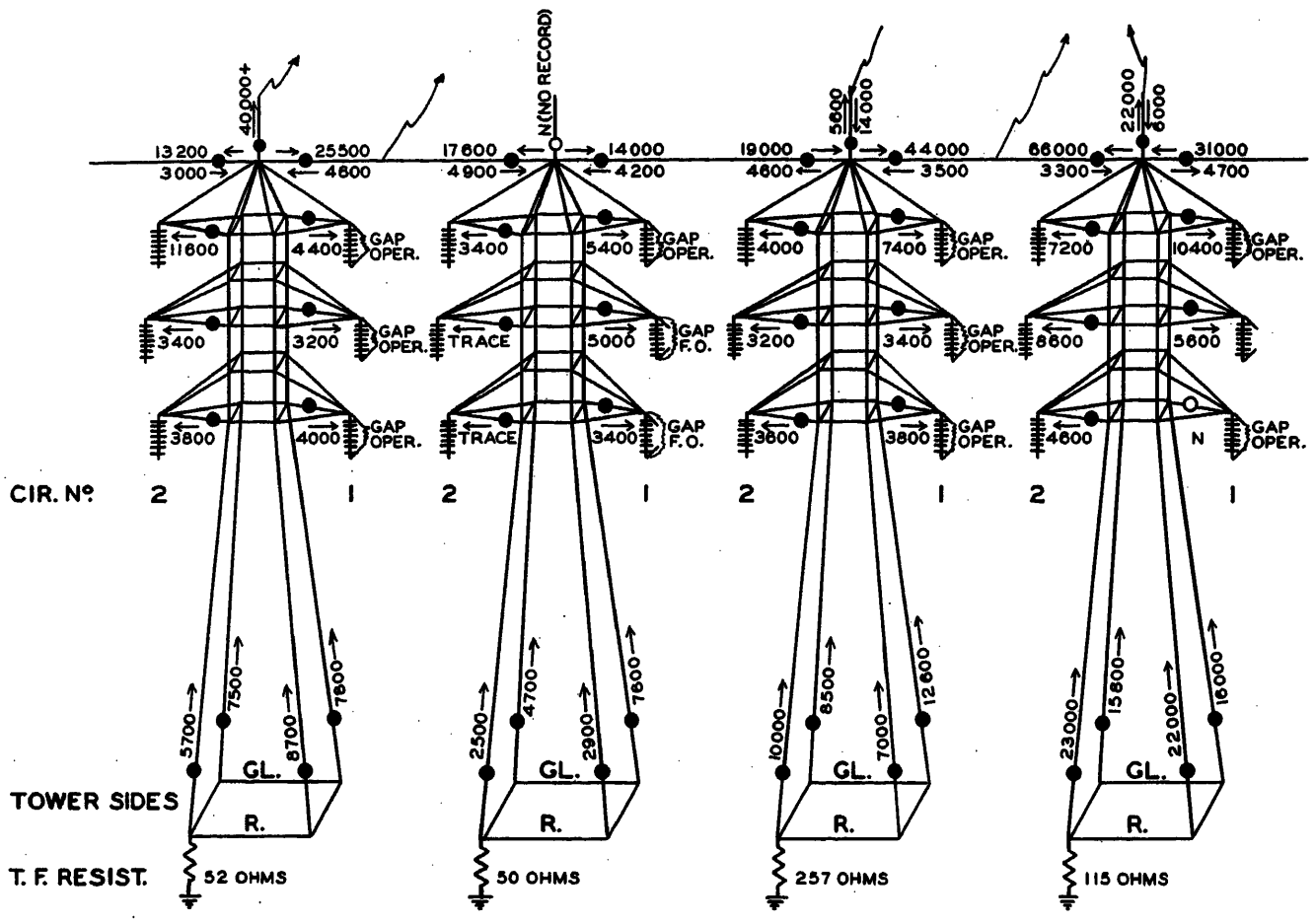



**Fig. 7. Lightning currents measured in towers of 132-kv Glenlyn-Roanoke line, May 4–15, 1936**

and of the 2 others in figure 5 seems to indicate that the short counterpoise apparently behaves very closely along the lines expected from a straight d-c characteristic, but that the long counterpoise carries considerably more current than can be explained from the standpoint of a d-c characteristic. It is recognized that the data shown in figure 5 are perhaps too erratic to permit definite conclusions, but the general trend seems to be indicated.

### Tower Potential

In the past in analyzing field records of currents in towers, a procedure of multiplying tower current by the tower resistance was frequently employed to indicate potentials which could be compared with line insulation flashover and thus determine whether or not insulator assemblies should have been expected to flashover under the conditions encountered. In the authors' investigation work, in general, high tower potentials obtained in this way have almost, without exception, correlated with flashovers at towers carrying these high potentials. There are on record, however, a few cases where flashover marks have been found on insulator assemblies and high tower potentials were not obtained by the method of calculated *IR* drop outlined here.

With the values of tower footing resistances and counterpoise resistances known, it is possible from the data obtained to make a comparison between the *IR* drop in the tower footing and the *IR* drop in long counterpoise and short counterpoise. This interesting comparison is given in table VIII. Columns 9, 10, and 11 give the voltage comparisons by these 3 methods of analysis. It may be noted that there is no regular consistency in the tower voltages indicated, although frequently there is very good agreement between the readings obtained by 2 methods, but the third method is distinctly out of line. There are, of course, a number of variables which cannot be evaluated readily and it seems that some of these will have to be investigated further before any general agreement can be reached as to the accuracy of determining tower potentials by any of these 3 methods.

### Tower Arm Currents

At the start of this work in 1933, in concentrating on the measurement of lightning currents, the surge-crest ammeter was recognized as a device which, when located on tower arms, had the possibility of indicating whether or not insulator assembly flashover had taken place.

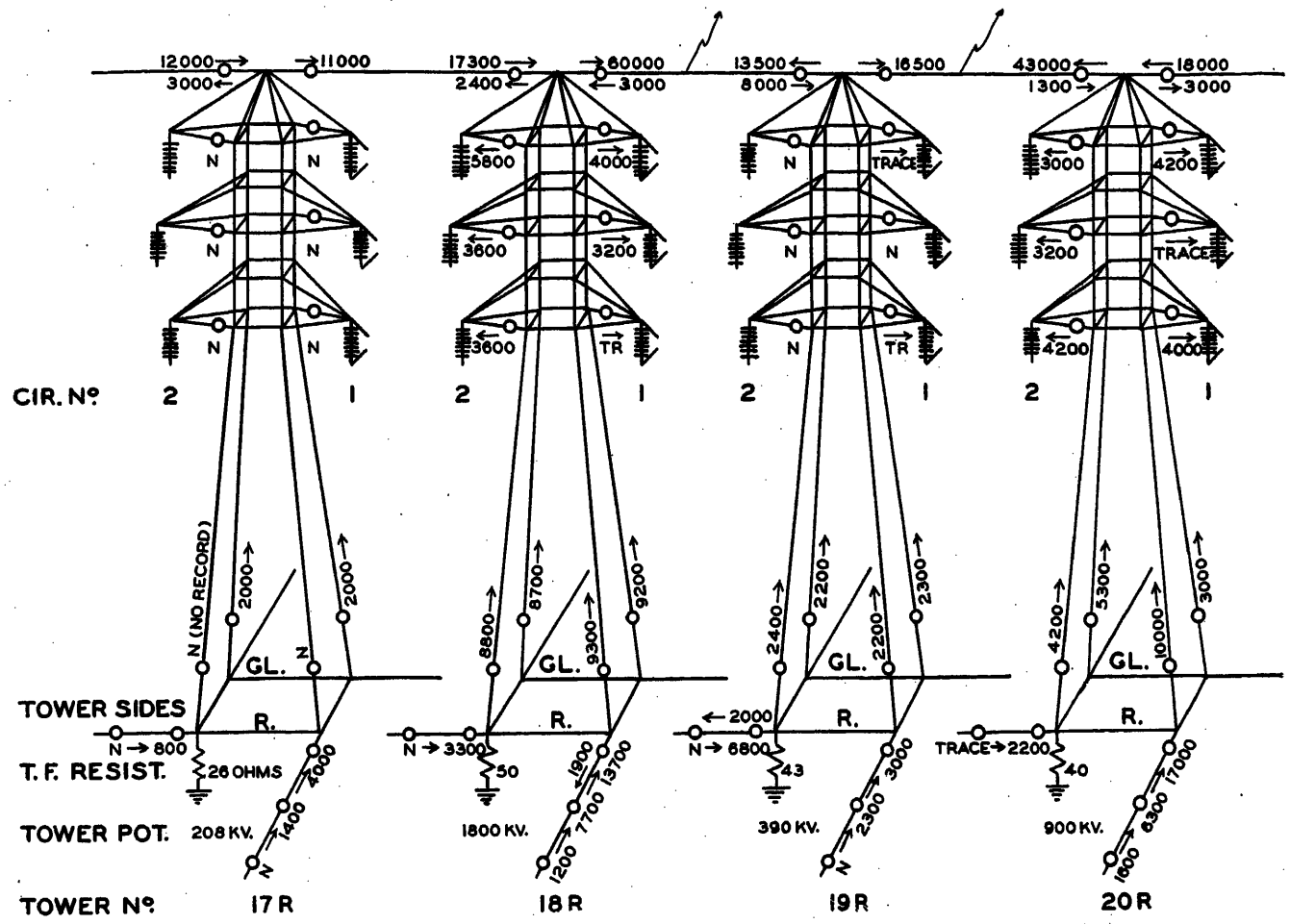



**Fig. 8. Lightning currents measured in towers of 132-kv Glenlyn-Roanoke line, August 31–September 16, 1936**

The original application was made primarily for this purpose. As the work progressed, however, it appeared that it was possible to obtain calibrated current readings, and the records have been gone over and correlated on this basis. The summarized data on current readings in tower arms are shown in figure 6. The outstanding point brought out by this group of curves is that the currents in the top tower arms were the highest, in the lower arms the lowest, and in the middle arms slightly greater than in the bottom arm but considerably less than

## Table VIII—Tower Potential Where Flashover Occurred, Glenlyn-Roanoke Line, 1936

Counterpoise Section Only

| Number | Tower Resistance‡ Ohms | Insulators Flashed Over | Tube Operated | Tower* Current— Amperes | Long Counterpoise† Current— Amperes | Long Counterpoise† Resistance— Ohms | Ground Wire Amperes at Tower | Kilovolts Tower IR | Kilovolts Long Counterpoise IR | Kilovolts Short Counterpoise $I_cR_c$ | Short Counterpoise† Current— Amperes | Short Counterpoise† Resistance— Ohms |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 6*R* | 66 | Yes | Yes | 59,000 | 16,700 | 237 | 17,800 | 3,894 | 3,957 | 7,600 | −17,000 | 447 |
| 6*AR* | 80 | | Yes | 24,300 | 13,300 | 197 | 20,000 | 1,944 | 2,620 | 3,320 | 10,500 | 317 |
| 7*R* | 19 | | Yes | 21,300 | 7,300 | 65 | 13,500 | 405 | 474 | 220 | 1,300 | 168 |
| 26*G* | 115 | | Yes | 10,600 | 7,000 | 250 | 28,000 | 1,219 | 1,925 | 620 | 1,300 | 477 |
| 27*G* | 96 | Yes | N | 3,400 | 168 | 15,000 | | 571 | 330 | | 1,100 | 300 |
| 28*G* | 41 | | Yes | 6,200 | 3,400 | 150 | 14,500 | 254 | 510 | 212 | 1,000 | 212 |
| 22*R* | 15 | | Yes | N | 2,500 | 31 | 12,200 | | 77 | 50 | 1,100 | 45 |
| 24*G* | 35 | | Yes | N | 1,200 | 86 | 11,800 | | 103 | | | |
| 21*G* | 85 | | Yes | N | 3,200 | 107 | 12,600 | | 342 | | | |
| 20*G* | 8 | | Yes | 23,400 | 19,000 | 21 | 3,700 | 187 | 399 | 270 | 3,000 | 90 |
| 19*G* | 14 | | Yes | 6,800 | 6,800 | 31 | 3,200 | 95 | 99 | 198 | 2,200 | 90 |
| 10*G* | 27 | | Yes | 28,600 | 12,500 | 347 | 33,000 | 772 | 4,337 | 350 | 3,300 | 107 |
| 7*R* | 19 | | Yes | 81,700 | 7,500 | 65 | 60,000 | 602 | 487 | 605 | 3,600 | 168 |
| 28*G* | 41 | | Yes | 29,000 | 11,800 | 150 | 26,000 | 1,189 | 1,770 | 805 | 3,800 | 212 |
| 18*R* | 50 | | Yes | 17,900 | 7,900 | 161 | 33,000+ | 895 | 1,272 | 1,460 | 3,300 | 442 |
| 11*G* | 28 | | Yes | 29,400 | 7,400 | 132 | 12,200 | 823 | 976 | 238 | 2,500 | 95 |
| 10*G* | 27 | | Yes | 26,000 | 8,600 | 394 | 11,800 | 702 | 2,984 | 171 | 1,600 | 107 |
| 27*G* | 96 | Yes | Yes | 33,400 | 13,500 | 168 | 46,000 | 3,206 | 2,234 | 1,170 | 3,900 | 300 |
| 23*G* | 87 | | Yes | N | N | 116 | 3,300 | | | | | |
| 18*R* | 50 | | Yes | 36,000 | 13,700 | 161 | 60,000 | 1,800 | 2,207 | 1,460 | 3,300 | 442 |
| 20*R* | 40 | | Yes | 22,500 | 17,000 | 127 | 43,000 | 900 | 2,159 | 760 | 2,200 | 347 |

* Sum of currents in all 4 legs. † Data on counterpoise wire only. ‡ Including counterpoises.

## Table IX—Lightning Currents‡ in Tower Structures for Ground-Wire Currents of 20,000 Amperes and More

Glenlyn-Roanoke Line, 1936

| Tower Number | Tower Resistance—Ohms§ | Tower Legs** | Counterpoises*** | Tower Arms† | Lightning Rods | Ground Wire Glenlyn Side | Ground Wire Roanoke Side |
|---|---|---|---|---|---|---|---|
| 55R | 75 | 34,100 | # | −21,800 | 14,500 | −45,000* | 27,000 |
| 56R | 47 | 42,900 | # | −29,200 | −12,300 | 6,700 | −60,000* |
| 59R | 118 | 23,700 | # | −20,800 | 2,000 | −30,000* | 15,700 |
| 60R | 172 | 25,200 | # | −16,600 | − 2,000 | 12,000 | −31,000* |
| 62R | 217 | 9,600 | # | − 2,400 | | 14,300 | −29,000* |
| 63R | 53 | 29,700 | # | −30,400 | −40,000 | −25,500* | −13,200 |
| 65R | 257 | 38,100 | # | −25,400 | 14,000 | −44,000* | 19,000 |
| 66R | 115 | 76,800 | # | −36,400 | −22,000 | 31,000 | −66,000* |
| 6AR | 80 | 24,300 | 47,600 | | | −22,000 | 20,000 |
| 13G | 11 | 20,500 | 16,400 | −12,600 | | −25,000* | 1,500 |
| 26G | 115 | 10,600 | 18,000 | − 3,000 | | −28,000* | 14,300 |
| 21R | 29 | 26,400 | 10,000 | −19,400 | | −26,000* | 9,700 |
| 22G | 51 | 11,100 | 14,400 | − 3,200 | | 2,400 | −35,000* |
| 10G | 27 | 28,600 | 31,600 | − 7,800 | | −33,000* | 12,000 |
| 7R | 19 | 31,700 | 22,200 | −15,100 | | −60,000* | 10,500 |
| 28G | 41 | −29,000 | −31,200 | 18,400 | | −16,700 | 26,000* |
| 14G | 12 | 9,300 | 26,600 | | | − 2,200 | −24,300* |
| 18R | 50 | 17,900 | 22,400 | −23,800 | | −33,000* | 12,000 |
| 60R | 172 | 17,100 | # | −13,400 | 2,000 | −25,000* | 6,800 |
| 68R | 187 | 10,100 | # | − 6,400 | | −21,500* | 9,800 |
| 69R | 37 | 11,800 | # | − 6,800 | − 2,000 | 7,000 | −27,300* |
| 28G | 41 | 16,600 | 4,200 | −19,400 | | −23,000* | 6,000 |
| 27G | 96 | 33,400 | 17,400 | −17,200 | | 9,700 | −46,000* |
| 18R | 50 | 36,000 | 17,000 | −20,200 | | −60,000* | 17,300 |
| 20R | 40 | 22,500 | 19,200 | −18,600 | | 18,000 | −43,000* |

* Probable lightning stroke in mid-span. ** Total of 4 legs. *** Two times current in 2 counterpoises. † Total current in all 6 arms. ‡ Currents toward tower top designated as positive. # No counterpoise installed. § Including counterpoise where counterpoise is installed.

in the top arm. It may also be noted that the solid curve of figure 6, which shows arm currents where flashovers of insulator assemblies were known to have occurred, accounts for currents as high as 26,000 amperes and as low as 4,000 amperes.

It is definitely known that tower-arm currents as low as from 3,000 to 5,000 amperes have been recorded in the field both with and without indication of insulator flashover. These can be accounted for even without line flashover, on the basis that the tower leg at the arm location is shunted by the arm and its hanger bar. This consideration leaves somewhat uncertain the interpretation of tower arm currents. High arm currents, in the order of from 10,000 to 26,000 amperes, were recorded in 1936 in only 5 cases, of which 2 instances were on flat-top towers without ground wires (of which there were 4 on the line). It is believed the remaining 3 cases were caused by direct strokes to the line conductors. This interpretation of tower-arm currents indicates a high degree of shielding afforded by the single conventional ground wire.

### Ground Wire Currents

Measurements in the ground wire itself at each side of a tower were first obtained this year. Typical readings of currents in the ground wire are shown in table VIII, column 8. Currents above 20,000 amperes and their distribution have been tabulated separately in table IX. The highest current measured in the ground wire, it may be seen, was 66,000 amperes but there are 25 records of currents above 20,000 amperes. If currents of this magnitude are to be expected in wires of a transmission system subject to lightning, serious consideration must be given to keeping currents of such magnitude out of stations if station apparatus is to be protected. Also, consideration must obviously be given to the ability of protective devices to handle lightning currents of this magnitude, since these are considerably in excess of what has ordinarily been considered possible to reach a station where pre-station voltage limitation is provided for by steel tower construction and limited insulation for a reasonable distance beyond the station. Again, currents of this order, if they are to be taken as traveling waves associated with line surge impedance, indicate voltages far in excess of values which could exist on the line without flashover. There is room, therefore, in this connection for further research.

### Typical Field Records

Typical field records showing currents obtained in tower legs, arms, ground wires, lightning rods, etc., have been charted in figures 7 and 8, and a close study of these, it is believed, will prove fruitful. It is from records of this type that the data summarized, presented, and discussed in this paper have been obtained. The double-reading indications on the ground wires in both figures are obtained from a proper calibration of the surge-crest-ammeter records; the reverse directions of current flow apparently indicate reflections of current. In general, such current oscillations are absent or of small magnitude in tower legs, arms, and in counterpoise readings except in the last where they are sometimes encountered in combination with high current values.

## Summary and Conclusions

Based on the field data obtained on lightning currents during the past 4 years, part of which has been presented in this paper, the following conclusions seem definitely warranted:

1. Although lightning stroke currents as high as 220,000 amperes have been indicated, it appears that the maximum stroke currents

(*Concluded on pages 259–60*)

# Tooth-Frequency Eddy-Current Loss

By PAUL NARBUTOVSKIH
ASSOCIATE AIEE

**A method of recording, by means of an oscillograph, the eddy currents in various parts of the cross section of a squirrel-cage-rotor bar is presented in this paper. From such records the magnitude of the power loss caused by eddy currents, and its variation with load, may be determined. A series of tests of this nature has been made; the results, which the author believes to be correct in general, show that the change of eddy-current loss with load is negligible, thus simplifying the determination of the composite stray-load loss of a squirrel-cage induction motor.**

THE eddy currents in a squirrel-cage rotor bar may be measured by a method that occurred to the author some time ago; the method permits recording by means of an oscillograph the current flowing at any particular point of a conductor cross section, if the cross section and the distribution of the current density in it remain substantially uniform throughout the portion of the conductor length along which the current flow is studied. A bar of a squirrel-cage rotor essentially satisfies these requirements, being of a uniform cross section, and having a uniform distribution of the current density, at least through the stacked-iron length of the bar.

At normal operating conditions the frequency of the fundamental working current in the bar is so low that the effect of the fundamental-frequency leakage flux upon the distribution of the current density throughout the bar cross section is negligible; that is, the main current is distributed almost uniformly throughout the cross section of the bar. This main current, however, is not by any means the only current flowing in the bars. Part of the fundamental air-gap flux passes through the slots, and hence through the conductors, and the pattern of this slot leakage flux pulsates at the frequency of the passing stator teeth.[1,2] As a result of this, tooth-frequency eddy currents are produced in the rotor bars, the amplitudes reaching a very substantial value in some parts of the bar cross section, as shown by observation. The method of recording such currents by means of an oscillograph, to be described later, provides a means of studying the current distribution in the bars and an experimental measurement of the attendant power loss. The determination of this power loss, its variation with load, and the study of factors causing its variation with load constitute the subject of this paper.

## Results and Conclusions

The machine used for the experiments was a squirrel-cage motor, rated at 10 horsepower, 220 volts, 60 cycles, 1,200 rpm. The number of teeth in the stator was 72; the number of teeth in the rotor, 37. The shape of the rotor and stator punchings is given in figure 1, together with the dimensions of the rotor-bar section.

As should have been expected on the basis of A. B. Field's[3] and J. J. Thomson's[4] theories, the amplitude of the eddy currents was found to be a maximum on the surface of the bar (nearest to the air gap), decreasing rapidly with distance from the surface in the interior bar. The maximum amplitude of the tooth-frequency eddy-current density on the surface was several times greater than the main working current density. In spite of this, the power loss caused by the tooth-frequency eddy currents was found to be considerably less than the copper loss caused by the fundamental working current, because the region of the high eddy-current density is limited to a comparatively thin surface layer of the conductor facing the air gap.

The actual magnitude of power loss caused by tooth-frequency eddy currents, based on oscillographic records, was 27 watts. The copper loss caused by the main current, using the amplitude obtained from the oscillographic records, was computed to be 87 watts; as obtained from slip measurement, it was 85 watts. The values of the fundamental current loss were computed as a check upon the correctness of results obtained from the oscillograms.

The magnitudes of the tooth-frequency power loss just given remained substantially unchanged as the load was applied. If any change with load was observed in the particular motor tested, it was a decrease instead of an increase. Considering that the total power input to the motor at full load was approximately 10 kw, the tooth-frequency eddy-current loss constituted about 0.3 per cent of the power input at full load. Though this quantity itself is not entirely negligible, any observed change of it with load was much too small to be of any practical importance. The significance of this conclusion is obvious, for no convenient method of testing a motor for the change of this item with load is available. A possibility of neglecting it simplifies the problem of testing for the stray-load loss.

Though no experimental data on other motors is

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1. For all numbered references, see list at end of paper.

available, this conclusion very likely applies to all motors in general. There is every reason to believe that the tooth-frequency eddy-current loss in other motors has a relatively lower value than in the motor tested, for the latter had very thin rotor-tooth shoulders, and shallow slots, with a consequent large area of bar surface facing the air gap, where the eddy current density is particularly large.

## Method of Measurement

The method of recording the current flowing at any point of the bar cross section, can be explained

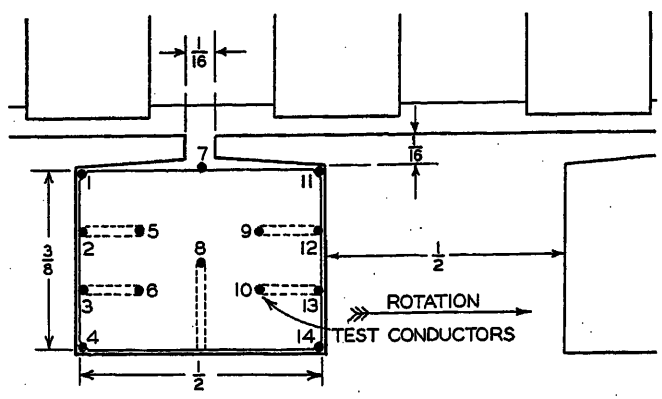



**Fig. 1. Diagram showing dimensions of stator and rotor teeth and location of test conductors**

Dimensions are in inches

with reference to figure 2. It requires placing an insulated test conductor $a$—$b$, within the bar material, and at that point of the bar cross section where the current to be recorded flows. One end of the test conductor $a$ is connected directly to the oscillograph, and the other end is connected to the rotor bar at point $c$. Point $d$ of the bar is the terminal of the other lead to the oscillograph. The instantaneous voltage appearing between leads $a$ and $d$ can be shown to represent correctly the density of the instantaneous bar current flowing along path $a$—$b$, that is,

$$e_{ad} = K\delta_{ab}$$

where $e_{ad}$ is the voltage between leads $a$ and $d$ and $\delta_{ab}$ is the instantaneous current density along path $a$—$b$. This follows from consideration of the equation giving the total electric potential between points $a$ and $d$

$$e_{ad} = \int_{abcd} \left[ K_\varphi \frac{\partial B}{\partial t} \sin \beta + \delta\rho \cos \gamma \right] dl$$

where

$B$ = magnetic flux density along the path of integration
$\beta$ = angle between the direction of the magnetic flux and the path of integration
$\delta$ = current density along the path of integration
$\gamma$ = angle between the direction of current flow and the path of integration
$\rho$ = resistivity of the material

The subscript below the integral sign indicates the path along which the integral is taken. This integral can be divided into 2 parts:

$$e_{ad} = \int_{abc} [X]dl + \int_{cd} [X]dl \tag{1}$$

in which $X$ denotes the quantity inside the brackets in the previous equation. The first term is taken along the test conductor and the second along some path within the bar. The path $c$—$d$, being arbitrary, can be taken along the surface of the conductor from $c$ to $b'$, then alongside the test conductor from $b'$ to $a'$, and on the surface from $a'$ to $d$. The end surfaces of the bar are outside any magnetic influence and the current density along them is zero; therefore, all points of these surfaces are at the same magnetic potential. Hence, the integral along these surfaces will disappear, and

$$\int_{cd} [X]dl = \int_{b'a'} [X]dl$$

taken in the immediate vicinity of the test conductor in the bar material.

Considering now equation 1 again

$$e_{ad} = \int_{abc} [X]dl + \int_{b'a'} [X]dl$$

$$= \int_{abc} K_\varphi \frac{\partial B}{\partial t} \sin \beta dl + \int_{abc} \rho\delta \cos \gamma dl +$$

$$\int_{b'a'} K_\varphi \frac{\partial B}{\partial t} \sin \beta dl + \int_{b'a'} \rho\delta \cos \gamma dl \tag{2}$$

Since the paths $a$—$b$ and $b'$—$a'$ are in the immediate vicinity, and neglecting the integral along $b$—$c$,

$$\int_{ab} K_\varphi \frac{\partial B}{\partial t} \sin \beta \cdot dl + \int_{b'a'} K_\varphi \frac{\partial B}{\partial t} \sin \beta dl = 0 \tag{3}$$

Also, if the circuit of the test conductor is linear, with impedance $Z$, and current $i$ taken by the oscillograph,

$$\int_{ab} \rho\delta \cos \gamma dl = -iZ \tag{4}$$

The use of equations 4 and 3 reduces equation 2 to

$$e_{ad} = -iZ + \int_{b'a'} \rho\delta \cos \gamma dl$$

When the distribution of current density is uniform along the bar, $\delta$ is constant, $\gamma = 0$, and this expression reduces to

$$e_{ad} = -iZ + \rho\, \delta_{b'a'} l \tag{5}$$

$\delta_{b'a'}$ being the current density in the bar along the test conductor. The condition of uniformity of the distribution of current density is fulfilled along the

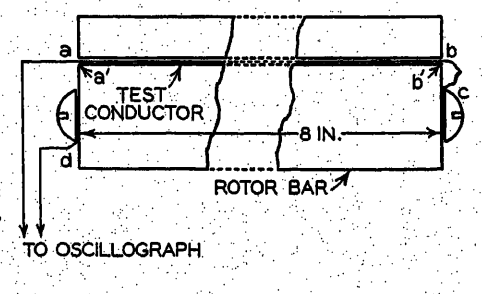



**Fig. 2. Sketch of the device used to detect eddy currents in various parts of the cross section of a rotor bar**

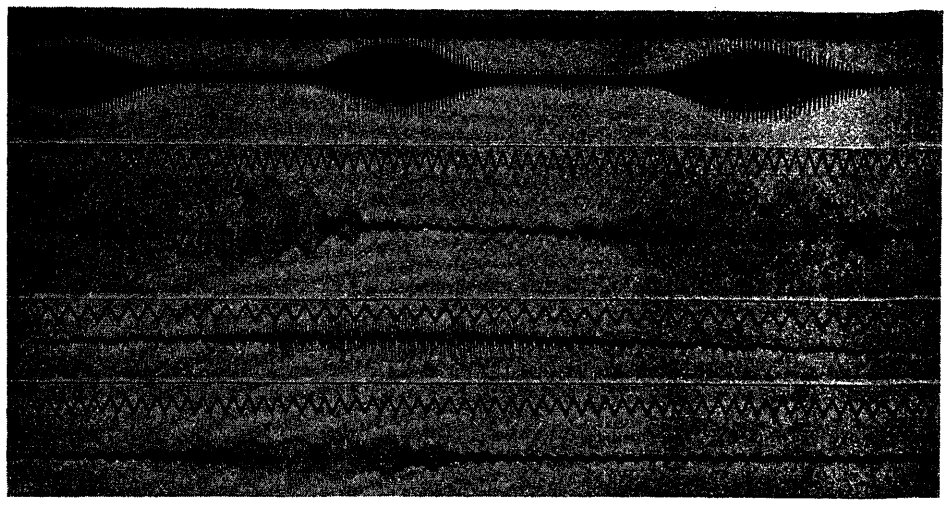


**Fig. 4. Oscillograms of tooth-frequency eddy currents in the trailing outer corner of a rotor bar for various conditions of operation**

*A*—No load
*B*—Motor load
*C*—Generator load
*D*—Motor load with bar disconnected

major part of the bar length. The ends of the bar near and beyond the length of stacked iron undoubtedly introduce a slight irregularity in the resultant voltage, but the effect of this irregularity cannot be important practically.

The use of a vacuum-tube amplifier was found to be necessary to record the voltage $a$—$d$ on the oscillograph. This further simplified equation 5, for $i = 0$ and

$$e_{ad} = \rho\delta b' a' l$$

This equation merely states that the voltage between points $a$ and $d$ is proportional to the current density in the bar along $a$—$b$.

For the purpose of the present study 14 conductors were placed in one rotor bar, 9 of which were located at different points on the surface, and 5 inside of the bar. The location of the test conductors is given on figure 1.

To place the conductors inside the bar, slots 25 mils wide were milled as indicated by the dotted lines on figure 1 to the depth at which the test conductors were to be placed. A steel piano wire of a diameter slightly larger than number 26 enamel-insulated copper wire, used for the test conductors, was then placed at the bottom of the slots, and the slots were filled with sheet copper, soldered to the walls of the slots. After pulling out the steel wire, very fine canals were formed parallel to the axis of the bar, just large enough to place the test conductors inside without injuring the insulation. This method of placing the test conductors inside of the bar impares somewhat the homogeneity of the bar material. It is doubtful, however, that the effect can be appreciable, for the layers of solder introduced were extremely thin.

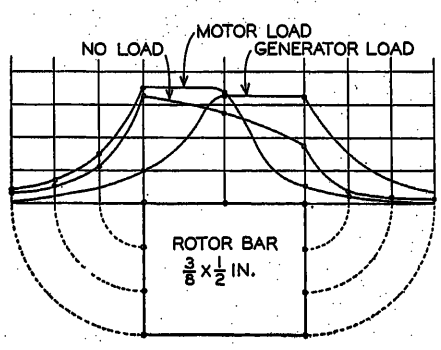



**Fig. 3. Diagram showing distribution of the amplitude of tooth-frequency eddy currents on the surface of a rotor bar**

The scale of amplitude is in hundredths of an inch

With the 14 test conductors a series of oscillograms was taken, one set of 3 different conditions of operation for each of the test conductors. These conditions of operation were:

1. No load, motor idling on a line at rated voltage.
2. Approximately full motor load at rated voltage.
3. Generator load at rated voltage, with the slip the same as for the second test.

The general character of the eddy current wave can be obtained from the reproductions of some of the oscillograms given in figure 4.

## Effect of Load

Before considering the power loss caused by the tooth-frequency eddy currents, it seems advisable to understand the factors producing a change in this loss as the motor is loaded. The only factor producing the tooth-frequency flux pulsation in the rotor slots at no load is the tooth-frequency component in the permeance distribution along the stator periphery. When the motor is loaded, the load currents produce an additional component of the tooth-frequency flux, because of the tooth-frequency component in the distribution of the magnetizing force along the stator periphery. As a result, the amplitude of the tooth-frequency pulsations may be expected to increase with load.

Actually the situation is considerably complicated by the effect of saturation of the rotor-tooth shoulders, produced by the combined effect of the rotor leakage flux and the main air-gap flux of the machine. The observed distribution of the eddy-current density for different load conditions can be seen from the oscillograms of figure 4 and also from figure 3, which gives the distribution of the eddy-current density on the surface of the bar, obtained from the oscillograms. An almost symmetrical distribution for no load becomes greatly distorted when the machine is loaded either as a motor or as a generator, but the character of distortion is different in the 2 cases. For motor operation, the amplitude of the tooth-frequency eddy current is increased in the region of the trailing

corner of the bar and greatly decreased in the leading corner. For generator operation, the effect is reversed: the amplitude is greatly decreased in the trailing corner of the bar, and increased in the leading corner. This difference between motor and generator operation immediately suggests the explanation of the phenomenon, which can be readily understood with reference to figure 5. This illustration shows the relative direction of the main flux and rotor-leakage flux in the rotor-tooth shoulders. As can be seen from figure 5*a*, when the machine is operated as a motor the leading (with respect to the center of the bar) tooth shoulder operates at a lower flux density than does the trailing tooth shoulder, for the main and rotor leakage fluxes here oppose each other. As a result of this low flux density, the leading tooth shoulder acts as an effective magnetic shield, reducing the influence of the tooth-harmonic flux in the leading

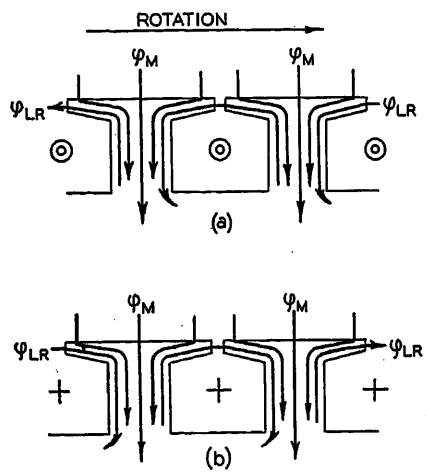



**Fig. 5. Diagrams illustrating the effect of rotor leakage flux and main flux upon the magnetic saturation in the rotor-tooth shoulders**

(*a*)—Machine operating as a motor
(*b*)—Machine operating as a generator
$\phi_M$—Main flux
$\phi_{LR}$—Rotor leakage flux

corner of the bar. The trailing tooth shoulder, on the contrary, operates at a high flux density and therefore produces little or no shielding effect. When the machine is operated as a generator the direction of the leakage flux reverses with the resultant reversal of the effect in the leading and the trailing corners of the bar. A conclusive proof of the origin of the redistribution of eddy-current density with load is obtained by operating the machine with the test bar disconnected from the short-circuiting ring at one end, thus preventing the main current from flowing. Under this condition the effect was found to disappear, because the leakage flux had been largely eliminated.

For the particular motor used the effect of saturation in the tooth shoulders was pronounced, as can be seen from figures 3 and 4. The net change of power loss produced by the effect may be either an increase or a decrease, depending upon the design of the punchings and the conditions of operation. Without attempting a rigorous analysis, the design of the punchings and the conditions of operation may be said to affect the eddy-current redistribution in the following way: When the shoulders are operated at a fairly high fundamental flux density, so that their shielding effect is small, the addition of the leakage flux may be expected to result in a decrease of the total eddy-current loss. This result may be expected because the increase of flux density in one of the shoulders will not reduce its shielding effect appreciably, being small already. On the contrary, a decrease in the flux density in the other tooth shoulder may bring it to a point of high permeability, and hence increase the shielding effect of the shoulder more than enough to offset the decreased shielding effect in the other shoulder in their common effect upon the eddy-current losses. The opposite result may be expected, if the main flux alone does not saturate the shoulders. The eddy current loss in the conductors remains low at all times, if the shoulders provide effective shielding at all loads, that is, when no saturation is caused even by the combined action of the main and the leakage fluxes.

## Method of Computation

For the purpose of computing the tooth-frequency eddy current loss in the rotor, using the observed current amplitude distribution, Field's equation, giving the distribution of the eddy current density inside of a solid piece of conducting material in terms of the current density on the surface, was employed:

$$\delta_x' = e^{-mx}\delta_s' \sin(\omega t - mx) \tag{6}$$

where

$\delta_x'$ = instantaneous current density at a distance $x$ from the surface along a normal
$\delta_s'$ = current density on the surface

$$m = 2\pi\, 10^{-4}\sqrt{\frac{\mu f}{10\rho}}$$

$\mu$ = permeability of the material
$f$ = frequency of the eddy currents
$\rho$ = resistivity of the material

This equation states that the eddy-current density distribution along distance $x$ normal to the surface has a character of an attenuated wave. For the purpose of this analysis, only the total amplitude variation with $x$, instead of the instantaneous value of $\delta_x'$ is of importance. This is obtained by dropping the function $\sin(\omega t - mx)$, which reduces equation 6 to

$$\delta_x = \delta_s\, e^{-mx} \tag{7}$$

where $\delta_x$ and $\delta_s$ denote the total amplitudes of the eddy currents at a depth $x$, and at the surface, respectively.

Equation 6 is developed for the following conditions: (1) uniform phase and amplitude of $\delta$ on a plane surface; and (2) a piece of material thick enough to allow the eddy-current wave to disappear largely before it reaches another boundary surface, that is, there is an absence of reflections of the wave within the conductor.

The first of these 2 conditions is not realized in the actual case observed. This fact is accounted for later in the application of equation 6. The second condition is sufficiently realized for the observed eddy current amplitude attenuates with sufficient rapidity to obviate any appreciable effect of reflections. In

(*Concluded on page 260*)

# Reactance of End Connections

By J. F. H. DOUGLAS
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**Use of image conductors in iron, of Rayleigh insulating partitions, and of images of conductors in these partitions is shown in this paper to afford one possible line of attack on the problem of the reactance of the end connections of electrical machinery. The use of 2 other methods to reduce the field in the end zone to a basis where Ampere's equation may be correctly applied is also suggested.**

THE PURPOSE of this paper is to suggest certain lines of attack upon the problem of end-connection reactance, which it is hoped will lead to more accurate formulas than are available at present. No completed solutions are given, because it is felt that the proposals should be discussed thoroughly before the details are filled in by calculation. In this way the path will be clearer for further research.

There are 2 methods of approach at present to the subject of end-connection reactance. The first consists in supposing the poles, armature, iron, and slot conductors removed, and the end-connections joined. On this basis, Ampere's equation may be applied and formulas for the specific permeance of self-induction per centimeter of end turn found. These expressions are of the type

$$P' = 0.2 \log_e \frac{D}{r} + C \qquad (1)$$

In this equation $D$ is the diameter of a circular or the side of a square end-connection, $r$ is the geometric mean radius of the coil, and $C$ is a constant depending on the form of the coil and may be approximately from $-0.05$ to $-0.10$.

A second line of approach is to assume a potential function over the surface of the end-connections of the form

$$V = M \sin (\pi x/A) \cos (\pi y/B) e^{-Cz} \qquad (2)$$

In this equation $A$ is the pole pitch, $B$ is the axial length of both end connections, and $C$ is chosen to satisfy Laplace's equation. The $x$ co-ordinate is measured parallel to the circumference, $y$ parallel to the shaft, and $z$ along a radial line. The origin is at the intersection of the armature surface, the point of reversal of magnetomotive force, and a plane perpendicular to the shaft and flush with the pole ends.[1]

It will appear from the discussion that both of these lines of approach are equivalent to an erroneous placement of a Rayleigh flux partition perpendicular to the shaft and flush with the pole ends. The second equation also implies a Rayleigh conducting partition placed perpendicular to the shaft and at the ends of the armature winding.

The assumptions made in this paper are as follows: Ampere's law may be applied to determine end-connection fields, provided image conductors are assumed in certain Rayleigh conducting and insulating partitions. When a plane iron surface is slotted, and there is a difference of magnetic potential across the gap thus formed, the gap may be closed with a fictitious conductor carrying current opposite to the currents establishing that difference of potential. The Schwarz - Christoffel theorem may be used to transform certain known fields into other new and useful fields with different boundary shapes. Rayleigh insulating partitions may be placed perpendicular to the shaft only so as to join the edges of the pole in the interpolar regions. Radial Rayleigh insulating partitions may be placed at the edges of the poles so as to divide the end zones into polar and interpolar regions.

## Inductance and D-C Machines

Figure 1 shows several examples of conductors near iron. The symbol $S$ is used to denote stator iron, $R$ rotor iron, $P$ polar iron, $Y$ yoke iron, and $A$ armature

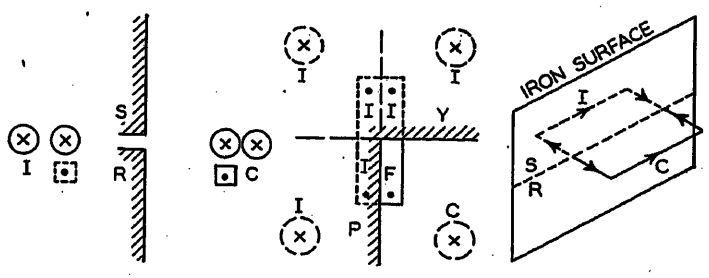



**Fig. 1. Image coils in iron**

iron. The symbol $C$ denotes an armature end conductor, and $F$ a field coil. By placing the image conductors $I$ as shown the iron surfaces may be eliminated because of the symmetry. The figure shows several important cases. At the left is shown a basis for the leakage inductance of an induction motor, in the center a basis for the inductance of a coil of a d-c machine undergoing commutation, and at the right the means in part for estimating open-circuit reactance of an induction motor. So far as these fields are 2-dimensional, reference may be made to

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1. For all numbered references see list at end of paper.

Hague,[2] who has developed the idea of image conductors in a number of cases.

Several examples of the use of a fictitious conductor *FC* to close an air gap and establish a required potential difference across the gap are shown in figure 2. The current must be equal and opposite to that in the other coil. There are image conductors in this case also, but for simplicity they are not shown. They are governed by the same rules as in figure 1. At the left in figure 2 is a basis, in part, for the estimation of the open circuit inductance of an induction motor; in the center is a basis for estimating pole-end leakage from a d-c machine; and at the right there is combined the left-hand picture of figure 2 with the right-hand picture of figure 1 as the complete picture of 2 coils co-operating to establish 2 iron surfaces at a definite difference of potential.

Figure 3 shows a conductor *C* in the corner between 2 perpendicular Rayleigh partitions. The plane *RI* is an insulating plane, while *RC* is a conducting plane. This gives rise to the image conductors as shown, and the inductance of this field may be found by Ampere's equation. The Schwarz-Christoffel[3] equation may be used to transform the field in the quadrant to that in the infinite half plane shown at the right. The equations applying to this case are

$$dz/dt = S\sqrt{t} \qquad t/a = (z/a)^2 \tag{3}$$

where $(z = x + jy)$ is the co-ordinates of any point in the $Z$ plane or left-hand figure, and $(t = q + js)$ is the co-ordinates of the corresponding point in the $T$ plane or right-hand figure. The inductances of the 2 fields are the same. The radius of the conductor is doubled, and the angle $\theta$ doubled in the right-hand figure. This boundary condition is useful in estimating inductance of end connections in one of the zones into which the field may be divided.

Figure 4 shows 2 current elements symmetrically located on either side of a plane surface. The figure shows the elements, a point $P$ on the plane of symmetry, the radii vectors from the elements to the point $P$, and the angle between the elements and the radii vectors, all in orthographic projection. Two cases are shown establishing conditions for the plane of symmetry being respectively a Rayleigh insulating and a Rayleigh conducting plane. It is the basis for establishing image conductors for the 3-dimensional case.

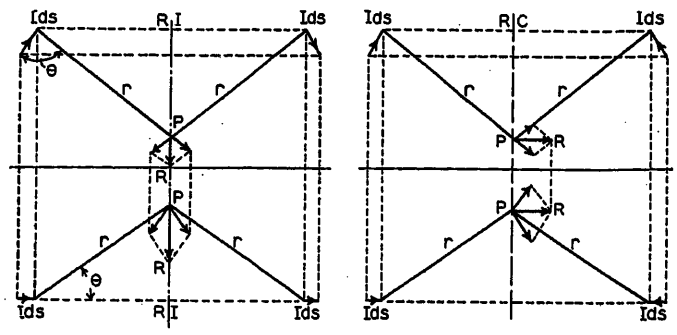



**Fig. 4. Ampere's law and Rayleigh planes**

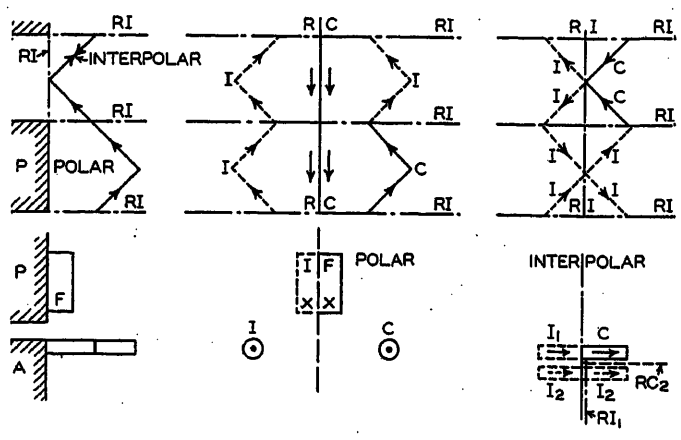



**Fig. 5. Image conductors, direct reaction**

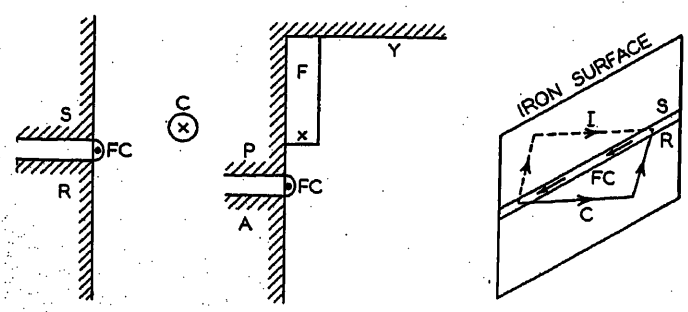



**Fig. 2. Fictitious conductor closing gap**

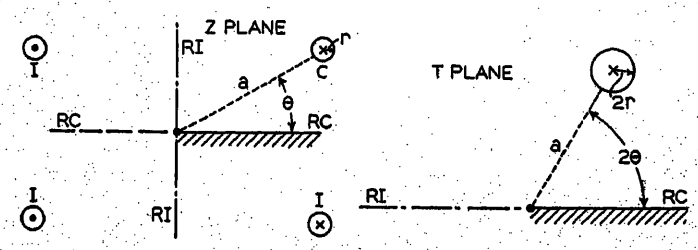



**Fig. 3. Rayleigh planes and conformally transformed field**

## Synchronous Machines

In figures 5 and 6 the end connection field of a synchronous machine is analyzed and methods of computing inductance are established. In figure 5 directly magnetizing conditions are shown, and in figure 6 transversely magnetizing conditions are shown. At the left of both figures the poles, the interpolar spaces, and the armature iron, as well as the field and armature coils, are shown in orthographic projection. Also shown are assumed insulating Rayleigh partitions, dividing the end connection zone from the zone over the armature surface, and dividing the end-zone into 2 regions, namely a polar zone, opposite the polar iron, and an interpolar zone opposite the interpolar regions. Although these assumed planes cramp the flux, it is believed that less error results from them than from those used as the basis of present formulas. The insulating Rayleigh planes are designated by the symbol *RI*. The iron surfaces constitute Rayleigh conducting planes.

In the center and right-hand parts of figure 5 the Rayleigh partitions, the coils of the armature and

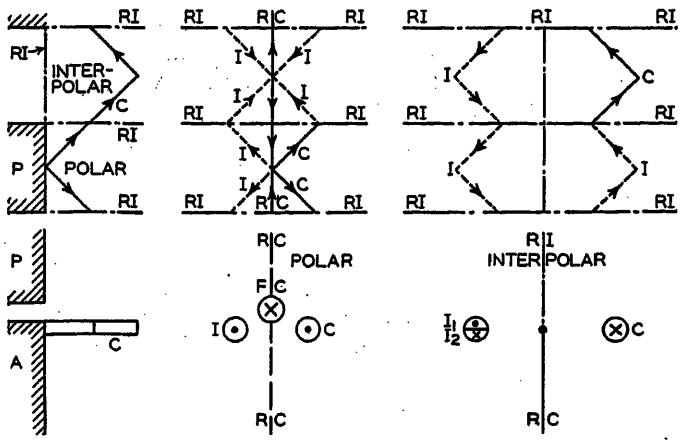



**Fig. 6. Image conductors, transverse reaction**

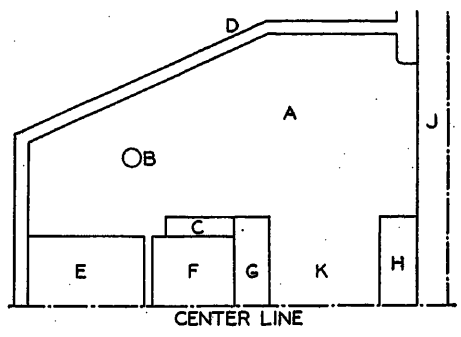



**Fig. 7. Experimental analogue for testing end-connection reactance**

A—Water trough
B—Brass rod at trace of armature coil
C—Muller brush electrode at trace of field coil; 128 wires lead in
D—Housing iron
E—Armature iron
F—Field iron
G—Yoke iron
H—Spider iron
J—Shaft iron
K—Rayleigh insulating plane; made of copper in model

All iron surfaces are made of insulation in model

field designated by $C$ and $F$, and their images are shown. In the center figure the image system for the polar zone is shown, and in the right-hand figure the image system for the interpolar zone. In the elevation view of the interpolar zone an inconsistency may be noted, caused by the vertical plane being in part an insulating, and in part a conducting plane. This may be resolved in 2 ways. If the line $RI$ is assumed to be drawn adjacent to the armature too small an inductance is obtained, but there is the image system $I_1$ which can be calculated. On the contrary, if a Rayleigh conducting plane $RC_2$ is placed just under the armature conductors, the image system $I_1$ and $I_2$ is obtained which gives an inductance approximately twice as great as the former, and which is too large. A compromise value will therefore be subject to an uncertainty of 33 per cent. It is hoped that discussion may show the way to a better solution of this particular zone.

In figure 6 there is at the left the orthographic projection of the machine structure, together with assumed Rayleigh insulating partitions. In the center is the image system in the polar zone and in the right hand part is the image system in the interpolar zone. In this case, in the polar zone, it is necessary to introduce the artifice of the fictitious conductor for closing the gap and establishing the needed difference of potential across the gap, between the polar and armature iron. In the elevation at the right it may be noticed that the image of $C$ is either $I_1$ or $I_2$ according to whether the line $RI$ or $RC$ is taken for forming the image. This case is really the Rieman surface which was resolved in the discussion of figure 3.

If the basic assumptions indicated here should prove valid, a program of research would include the evaluation of the inductance of single coils, groups of coils, and the effect of mutual inductance. This would be built up into combined coefficients for the 3 symmetrical components of current and for both the steady and the transient states.

The effect of variations in the boundary conditions such as those caused by the proximity of iron of the frame, housing, and shaft may in some cases be resolved by the Schwarz-Christoffel transformation, but the greatest promise is offered by the use of an experimental method devised by Mullner.[4] In figure 7 is shown a diagram of a water tank in which the conjugate field of end connections may be set up, in the form of an electrokinetic analogue. The experimental arrangements include a brush electrode for a field coil, a circular rod for the armature coil, and the use of copper on the boundary for Rayleigh insulating partitions and of insulation on the boundary for Rayleigh conducting partitions.

A solution of the problem of end connection inductance is to be desired not only for its own sake, but also as an aid in estimating of losses caused by such fields in nearby metal.

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## Lightning Currents in 132-Kv Lines

(*Continued from page 252*)

rarely exceed about 150,000 amperes. Only 10 per cent of the measured currents were in the range above 70,000 to 100,000 amperes.

2. Single-tower currents showed 100,000 amperes as a maximum, with 10 per cent of them above 45,000 amperes. Apparently fairly definite relationships between current magnitude and frequency of occurrence exist. Such data used in combination with tower-footing resistances are helpful in predicting the lightning performance of transmission lines.

3. Counterpoises in the order of 40 feet long are far less effective in discharging lightning currents to ground than longer counterpoises of say 150-foot length, the ratio of currents being in the order of 1 to 4 respectively at the point of attachment to the tower.

4. The short counterpoise not coupled with the line discharges

lightning currents in a manner closely following its expected performance from the standpoint of its ohmic conductance to ground. The long counterpoise, coupled with the line (underlying it), discharges currents of the order of twice this value, on the average.

5. Currents recorded in tower arms have yielded no conclusive data. It would appear that in view of the fact that only 3 records of currents were obtained in 1936 in excess of 10,000 amperes, under conditions attributable to direct strokes to line wires, that the present typical construction with one ground wire of the Glenlyn-Roanoke line is giving a high degree of shielding of the line wires. Two similar records were obtained at one point on the line, where for structural reasons the ground wire was absent.

6. The high currents measured in the ground wires (66,000 amperes maximum) indicate the necessity of adequate shielding of the line at station entrances. They also clearly show the need of knowing more definitely the characteristics of lightning-protective devices, in view of the possibility of much higher currents through these devices than have been considered in the past.

7. Previous field investigation work on lightning effects on electrical lines and equipment has yielded many valuable data which are useful in evaluating the factors affecting the operating performance of such equipment under lightning conditions.

The breaking down of the over-all picture of lightning on a line into its component parts, to determine the currents in the various parts of the electric circuit as covered by the planned investigation work presented in this paper, is beginning to give a clearer understanding of what is actually taking place in the various parts of the entire lightning circuit. The situation is steadily being approached where lightning currents in the electric system can be predetermined with some degree of assurance, which should be of paramount value in providing protection to lines and equipment and determining the duty on protective equipment. However, a great deal of the unknown remains to be explored.

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## Tooth-Frequency Eddy-Current Loss

(*Continued from page 256*)

fact, it decays faster than is predicted by equation 6, which is probably a result of the phase difference between eddy currents at different points of the bar surface. It follows from this observation that the eddy-current loss computed on the basis of equation 6 will not be less than the actual value.

Using equation 7, the power loss per unit area of the conductor surface is

$$\frac{P}{bl} = \int_0^\infty \rho \left(\frac{\delta_x}{2\sqrt{2}}\right)^2 dx = \frac{1}{8}\rho\delta_s^2 \int_0^\infty e^{-2mx} dx = \frac{\rho\delta_s^2}{16m} \qquad (8)$$

where $b$ and $l$ are the width and length, respectively, of the conductor surface at which power loss $P$ takes place, and $\delta_s/(2\sqrt{2})$ is the effective value of the current density at distance $x$ from the surface. This equation requires 2 modifications before it can be applied to this analysis: (1) to account for the variation of the eddy-current amplitude that takes place at the frequency of the fundamental rotor current and its multiples; and (2) to account for the nonuniformity of the eddy-current amplitude on the surface of the conductor as given by figure 3.

The first of these conditions can be met approximately by assuming that the shape of the eddy-current wave is a pure sine wave, 100 per cent modulated by a fundamental-frequency sine wave given by a function

$$\delta = \delta_m \sin \omega_t t \cdot (1 - \sin \omega_r t)$$

$\omega_t$ being the angular velocity of the tooth ripple, and $\omega_r$ being that of the fundamental rotor current. This assumption introduces a factor into equation 8 equal to a ratio of power loss with modulated and unmodulated waves. The value of this factor is then

$$K = \frac{\frac{\omega_r}{2\pi}\int_0^{\frac{2\pi}{\omega_r}} \rho\delta_m^2 \sin^2 \omega_t t\,(1 - \sin \omega_r t)^2 dt}{\frac{\omega_t}{2\pi}\int_0^{\frac{2\pi}{\omega_t}} \rho\delta_m^2 \sin \omega_t t dt}$$

On the assumptions that the value of the ratio $\omega_t/\omega_r$ is large and is an integer, both of which are reasonable since the value of $\omega_t/\omega_r$ is of the order of 1,000 or greater, the value of $K$ reduces to

$$K = 0.113/0.5$$

To overcome the difficulty caused by nonuniformity of the distribution of current density on the surface, as an approximation the distribution of the eddy-current amplitude along any normal to the bar surface may be assumed to comply with equation 7. Measurements show that the amplitude within the bar is less than that given by equation 7; hence, the actual power loss is less than that computed on the basis of equation 7. Equation 8 therefore may be written in the form

$$\frac{d\left(\frac{P}{l}\right)}{db} = K\frac{\rho\delta_s^2}{16m}$$

The power loss per unit length of the bar will be

$$\frac{P}{l} = \int_0^b \frac{0.113\rho\delta_{sm}^2}{0.5 \times 16m}\, db$$

This integral was evaluated by numerical integration, using values of $\delta_{sm}$ obtained from figure 3. The result obtained, 27 watts for all the bars in the rotor at no load, probably is greater than the true value.

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# First Report of Power System Stability

**The AIEE subcommittee on interconnection and stability factors* presents herein the first comprehensive review by an AIEE committee of the subject of stability, or successful parallel operation of a-c machines transmitting large blocks of power without loss of synchronism. A summary of principal installations made during the past 10 years which gives data on the various stability measures employed and a comprehensive bibliography are included.**

STABILITY, in the sense employed in this report, is concerned with the successful parallel operation of a-c machines as affected by the magnitude of power transmitted. While this problem has existed since the beginning of parallel operation, it is only within the past 10 to 15 years that it has assumed a position of major concern. During this period stability has received a great deal of attention in papers before the AIEE and in the technical press. The development of analytical methods for predicting power system performance has been followed by methods for improving stability. However, during this period the general subject of stability has not been comprehensively reviewed by any AIEE committee. Hence, this "First Report on Power System Stability" has been prepared for the purpose of reviewing the developments and of summarizing in so far as appears practicable the present status of the art in this field.

## Historical Review

The early problems of parallel operation were concerned principally with the phenomenon known as hunting. Prior to 1890 parallel operation of synchronous machines was accomplished in isolated instances. The problem did not assume importance until after the change from belted machines to engine-driven machines and from smooth to slotted armature construction. At about this time the necessity for parallel operation became general and the hunting problem approached serious magnitude. The cause was not well understood. It was variously ascribed to the presence of harmonic circulating currents, to the pulsating torque of the prime-movers, to the correspondence of the electro-mechanical period of the power system and the periodicity of the impulses of the prime-movers and to the improper design or functioning of prime-mover governors. Considering the complexity of these problems, particularly during the transient conditions involved in the hunting phenomena, it is not surprising that the state of the art at the time made exceedingly difficult the determination of the true cause of hunting. Probably the most successful method for minimizing hunting was the introduction of the damper winding proposed by LeBlanc in France in connection with alternators and independently by Lamme in the United States in connection with synchronous converters. Gradually the essential factors of the problem were understood and the question of harmonic circulating currents eliminated. In the first decade of the present century the problem ceased to be one of serious importance. The principal reason for this change in the situation was the introduction on a large scale of constant-torque type prime-movers in hydro-electric and steam turbines. The great increase in the size of the power systems made them inherently more stable and less subject to disturbances arising from the peculiar characteristics of an individual machine or application. However, the problem still existed in connection with special applications, such as those involving gas engine prime-movers or synchronous motor-driven compressors. It was also found that hunting was likely to be encountered with synchronous converters if the supply lines had a resistance drop of more than 15 per cent. During the last 20 years hunting has not been a serious problem considering the operation of power systems as a whole.

Another type of the general problem of parallel operation is one involving the ability to maintain synchronism both during steady-state or normal circuit conditions and during transient conditions, such as those arising from sudden increase in load, change in circuit condition, or occurrence of a short circuit with its subsequent clearing. This problem, commonly called the stability problem, is concerned with power limits and is distinct from the hunting problem which is characterized by periodic phenomena. In the early days it was recognized that synchronous and induction motors had very definite power limits. However, this was viewed as a machine problem; the corresponding system problem did not at this time receive consideration.

The methods for controlling voltage regulation were not well developed; the automatic tap changer under load, the feeder voltage regulator, the automatic generator voltage regulator, the use of synchronous condensers for voltage control were either not employed at all or not to the degree to which they are today. Consequently, the effort was directed to provide systems of good inherent regulation which was obtained generally by making lines and apparatus of low impedance. This practice to achieve good voltage regulation and the use of multiple circuits to minimize interruptions of service resulted in systems capable of transmitting relatively large amounts

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of synchronizing power with corresponding high power limits under normal operating conditions.

With the advent of the automatic voltage regulator and its application to condensers at the receiving end of long transmission lines it became possible to obtain good local regulation from a system which had high reactance and low synchronizing power. Thus it became practical to operate systems much closer to their steady-state stability limits. While this combination solved the voltage regulation problem, its exploitation in the course of time led to the transmission of large blocks of power per circuit and consequently to the stability problem.

Parallel with this development of long-distance straight-away transmission, interconnections of large power systems for economic and emergency purposes led to a different form of the stability problem. The character of the operation in this case depended very largely upon the properties of the tie line. Frequently these lines operated quite satisfactorily for steady-state conditions but in the event of a disturbance on either system, if the tie line were incapable of transmitting sufficient synchronizing power, instability would be inevitable. However, it was found that no difficulty was encountered except during severe faults if the systems were tied solidly together through tie lines designed to carry a large amount of load. Troubles were for the most part encountered on systems which were connected through fringes or through so-called "shoe string" lines. Interconnection to reduce cost and improve service reliability thus became a factor in the problem.

Concurrently, consideration was being given to the use of generator and bus reactors for the purpose of limiting the interrupting capacity required of circuit breakers. These layouts also affect system stability by decreasing the synchronizing power under conditions before and after the fault is cleared and by reducing the severity of the disturbances themselves during the fault condition.

About 1920 the work on the power circle diagram in connection with long distance power transmission focused attention to the margin of power between the operating point and the theoretical stability limit. This led to exhaustive tests, both in the laboratory and in the field, for establishing the characteristics of power systems under steady-state conditions and during transient disturbances. In 1925 a case of instability occurred on a long-distance high-capacity transmission system in which the system was operating under steady-state conditions while portions of the paralleling line were out of service for maintenance and repair. While the possibility of pull-out had been recognized before this experience, its occurrence nevertheless did stimulate further careful investigation of stability limits of long transmission systems. As a result of the interest in the subject and the development in the methods of calculating electrical systems, it was found that system oscillations during disturbances could be predicted with satisfactory accuracy by step-by-step methods. This has been substantiated by the data on power system oscillations obtained during (1) scheduled tests and (2) normal operation by means of automatic transient recording apparatus.

Attention was then directed toward methods for improving system stability including consideration of the power system layout and operation as well as features of the apparatus. As a result of this work a number of important changes in practice came about, concerning particularly the reactance of synchronous machines, the speed of response of excitation systems, and characteristics of automatic voltage regulators. The most successful modification of practice in order to improve stability has been the recent developments of high-speed circuit breakers and relays. Consideration has also been given to the control of all factors in the problem with a view to co-ordinating them to give the maximum improvement in stability at a minimum cost.

## Methods of Analysis

Parallel with the recognition of the importance of the stability problem the necessity arose for the development of methods for calculation. Thus about 1922 engineers seriously undertook to determine the stability limits of power systems; they set about the task of predicting the time variation of angle, power, and voltage quantities for all types of transient disturbances. Prior to this time the basic ideas relating the power, angle, and voltages of simple systems were understood but it was necessary to extend these basic concepts for the more complicated problems under consideration. An example of these extensions is the power circle diagram which was developed to include distributed capacity and general networks. The analytical work back of the circle diagram was extended, covering not only the case of 2 machines but 4 or more machine cases for which the circle diagram is not applicable.

The power circle diagram was early found to be of considerable value in pointing out maximum power limits and requirements in reactive kilovolt-amperes to maintain system voltages. It was also helpful in obtaining power-angle relations between 2 ends of a long line, particularly between points of maintained voltage.

Since the stability problem is so closely related to the characteristics of machines the next development was the extension of the Blondel 2-reaction method to include the transient performance of machines with salient-pole rotor construction.

Undoubtedly the most important analytical development in the general field of unbalanced polyphase problems is that of "symmetrical components." Applied to the stability problem, it became possible to calculate the distribution of current and voltage throughout the system during periods of unbalanced faults and also to determine the equivalent balanced positive-sequence impedance that should be placed at the point of fault to completely simulate in its action upon machine performance the particular unbalanced fault. In this connection it was necessary to develop methods of calculation and of test for the phase-sequence constants of lines and apparatus.

An interesting development of this period was the mechanical analogue, a mechanical equivalent of the actual electro-mechanical system, in which the principal generating units are replaced by small flywheels and the

system reactances by springs. By properly proportioning the elements of this system the angle-time variation of this equivalent will exactly duplicate the system performance quantitatively as well as qualitatively, thus indicating stability or instability for different kinds of faults. While the mechanical analogue has been used to some extent for the purpose of calculating system performance, its principal value has been its unique facility for visualizing the essential factors in the stability problem.

A very tedious and irksome part of the early stability calculations was the reduction of the actual system into an approximately equivalent network of a more manageable form, such as 2- or 3-machine problem. The construction and use of the network analyzer or a-c calculating board has eliminated much of this labor. By means of the a-c calculating board the entire system impedance diagram including the generating sources can be set up, thus representing in miniature the equivalent of the actual system. From this duplicate system the necessary constants may be obtained which will reduce a given system to the simplest number of impedance branches. The problem may be solved by a step-by-step method, either analytically or by the calculating board, using small intervals of time and adjusting by steps the phase position and magnitudes of the machine voltages as dictated by the simultaneous solution, considering the acceleration and inertia of all the machines. Mention should also be made of the integraph which has been employed in the production of general curves which have been used in the solution of specific stability problems.

The development of automatic recording equipment has provided an important source of information on power system performance. This equipment, which is of the oscillographic type, is capable of recording instantaneous variations in voltage, current, power, and phase angle quantities—including both phase quantities and their sequence components. The data obtained in this manner are useful in determining the margins in stability under operating conditions. These records are valuable in checking relay and circuit-breaker performance, and also in determining the character and location of the fault.

The most recent development affecting methods of analysis has to do with the determination of the machine constants to be used. It has been shown that saturation affects transient reactance and also certain other reactances used in transient stability calculations. Recently, work has also been done toward the determination of the appropriate values of reactance to use in steady-state stability calculations. The results of this work are being reviewed by a subcommittee of the AIEE electrical machinery committee.

In summarizing this review of the methods of analysis, it can be stated that the available methods are now considered to be satisfactory for determining the stability of a system under any assumed set of conditions. It is recognized, however, that for certain types of systems the present methods require analysis by a relatively large number of independent machines and this requires a considerable amount of work to cover a reasonable range of operating conditions.

## General Discussion of Factors Affecting Stability

In this report the stability terms are used in accordance with the following definitions:*

"Stability, when used with reference to a power system, is that quality of the system or part of the system which enables it to develop restoring forces between these elements equal to or greater than the disturbing forces so as to restore a state of equilibrium between the elements.

"Steady-state stability exists in a power system if it operates with stability when there is no aperiodic disturbance on the system.

"Transient stability exists in a power system if, after an aperiodic disturbance has taken place, the system regains steady-state stability.

"If automatic devices are used to aid stability their use should be indicated by the following phrases:

Steady-state stability with automatic devices.
Transient stability with automatic devices.

"The term, automatic devices, includes only those devices which are operating to increase stability during the period preceding and following a disturbance as well as during the disturbance. Thus relays and circuit breakers are excluded from this classification and all forms of voltage regulators included. Devices for inserting and removing shunt or series impedance may or may not come within this classification depending upon whether or not they are operating during the periods preceding and following the disturbance."

These definitions of stability terms recognize a distinction between stability with automatic devices, and stability by inherent action. While the general term includes both effects, it is the intention that mention should be made of automatic devices when used.

It is recognized that the definitions of stability are based upon viewing the problem as essentially one of equilibrium. In each synchronous machine there is a problem of equilibrium between the mechanical forces acting on machine shafts and the electrical forces acting on the machine windings. Thus in the synchronous generator there are the mechanical forces due to the prime-mover tending to accelerate the rotor and the electrical forces due to electrical output and losses tending to decelerate the rotor. In the synchronous motor there is the corresponding problem of equilibrium between the electrical input and the mechanical output and losses. If, in the process of maintaining equilibrium, synchronism is not lost, stability results.

The factors affecting the stability problem, therefore, include any which will affect the mechanical input (or output) and the electrical output (or input). Among the mechanical factors are the prime-mover input, the governor characteristics and inertia of rotating parts, and among the electrical factors are the characteristics of circuits including switching operations and apparatus including excitation systems and their voltage regulators, and load circuits including induction motors as well as static apparatus.

The above discussion indicates that there are many factors entering into the stability problem. Also, there are many ways in which these factors may be controlled to secure stability. The extent to which any of these

* These definitions are taken from the report of the subject committee on definitions of terms used in power system studies, presented at the AIEE winter convention, New York, N. Y., January 22, 1932.

factors are beneficial in improving stability is dependent upon the particular system under consideration.

This report is principally concerned with stability as affecting the operation of synchronous machines, such as a combination of a generator and a motor or 2 groups of synchronous generators with an intervening transmission line. The report is also principally concerned with the usual type of power system where parallel circuits are employed and a relatively high standard of service is required.

In general, the transient stability limit of a system is considerably lower than the steady-state stability limit. Hence, the transient stability limit is more important for the service and layout conditions normally encountered. In general, the basis of system design from the stability standpoint is predicated on the successful clearing of a particular type of fault in any line section. The type of fault considered is usually the double line-to-ground fault on transmission systems. However, single line-to-ground faults are sometimes considered for transmission systems and 3-phase faults for metropolitan systems. In a few situations single-circuit lines may be employed because service conditions permit the interruption of supply to the load or because the system layout is such as to permit the loss of an entire station output. In these situations the steady-state stability limit, of course, becomes of greater importance. However, even in such cases secondary circuit faults or abrupt load changes are likely to make the controlling stability limit a transient limit.

## Discussion of Specific Factors in the Stability Problem

A discussion will now be made of the effect of various specific factors in the stability problem. For convenience these will be arranged under 2 principal headings of (1) power system layout and operation and (2) characteristics of apparatus.

### Power System Layout and Operation

The stability characteristics of power system layouts should be analyzed for the 3 circuit conditions associated with the fault, *viz.*:

1. **Before the fault.**
2. **During the fault.**
3. **After the fault.**

Some features of layout are beneficial to stability for all 3 circuit conditions while other features are beneficial for one condition and detrimental for another; hence, the many features of power system layout must be weighed individually in connection with each circuit condition.

#### *Series Reactance*

The most obvious method of increasing the stability limit of a system is to reduce the transfer reactance or "through reactance" between synchronous machines as this directly increases the synchronizing power that may be interchanged between them. The reactance of a transmission line may be reduced by reducing the conductor spacing. Usually, however, the spacing is controlled by other features, such as lightning protection and minimum clearance to prevent an arc from one phase involving another phase. Another method of reducing line reactance is to increase the conductor diameter by using material of low conductivity or by hollow cores. Usually, however, the characteristics of the conductors are fixed by economic conditions quite apart from stability. The split-conductor has been considered for a number of cases as a measure for decreasing line reactance but objections from a mechanical point of view have prevented its use on any major project.

The transformer reactance should be kept as low as practical. While some variation from normal reactance is permissible, economic considerations usually prevent much departure from the normal value.

The series capacitor provides another means for decreasing the "series" reactance of transmission systems. However, at times of system faults the current through the capacitor raises the voltage across it to a value much in excess of its normal value. Hence, to protect the capacitor against puncture the usual practice is to use a normal voltage capacitor with means to short circuit it during excess current conditions. The series capacitor as proposed is thus rendered ineffective at just the time when it is most desired. The alternative is to use capacitors capable of withstanding the high voltages arising under fault conditions. In no major project in America has the series capacitor received serious consideration.

The usual ways of reducing transmission circuit reactance drops are to use additional parallel lines or circuits of higher voltage. Comparisons at times are made

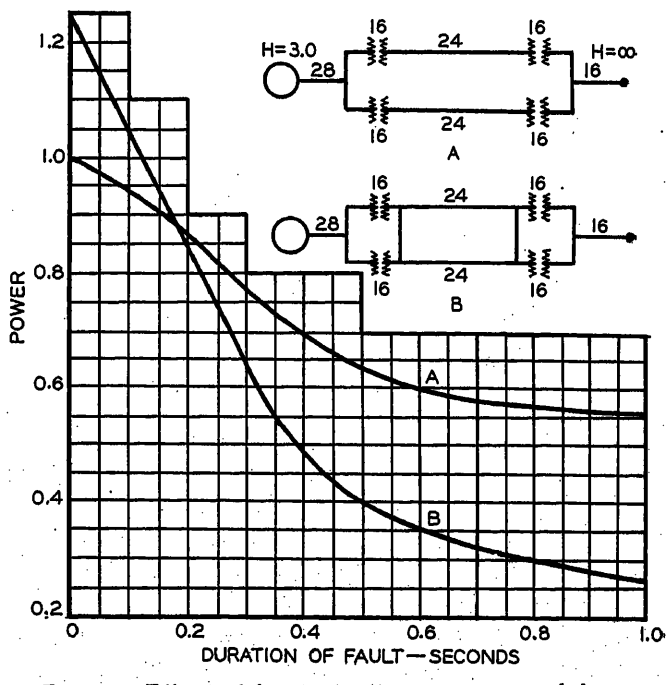



**Fig. 1. Effect of bussing arrangement on stability limits; double line-to-ground fault at sending end**

*A*—Low-voltage bussing *B*—High-voltage bussing
System reactance shown in per cent; inertia constant $H$ = kilowatt-seconds/kilovolt-ampere

between a larger number of low voltage circuits and a small number of high voltage circuits. In these cases it must be borne in mind that the switching out of a circuit produces a relatively greater reduction in the power limit of the layout with the smaller number of circuits than with the larger number.

*Bussing Arrangements*

The method of paralleling lines or apparatus, or the bussing arrangements, may have an important bearing on system stability. The use of high-voltage busses at the ends of transmission lines or at intermediate points results in smaller reduction in the "through reactance" at the time of the isolation of a faulted transmission line section than for the case with low-voltage bussing, since the latter involves the loss not only of the line but also of the associated transformers. During the faulted condition the shock to the system is greater with the high-voltage bus than with a low-voltage bus. It is impossible to generalize on the relative merits of high- and low-voltage bussing arrangements as the result in any particular case is dependent upon the relative reactance proportions of the system, the type and duration of the fault, and the character of system grounding. The results of calculations on a particular system with alternative bussing arrangements are illustrated in figure 1. It will be observed that for the faults of short duration the change in the "through impedance" of the system after the fault is cleared is more important than the shock to the system during the fault, and, therefore, the high-voltage bussing arrangement gives higher stability limits; while for faults of longer duration, the shock to the system is more important and the converse regarding layout is true. By using reactors between the high-voltage busses, it is possible to obtain characteristics intermediate between those for high- and low-voltage bussing, approaching either to any degree desired. Figure 2 shows the results of the study in a particular case of the effect of varying the number of intermediate switching stations on a long transmission line.

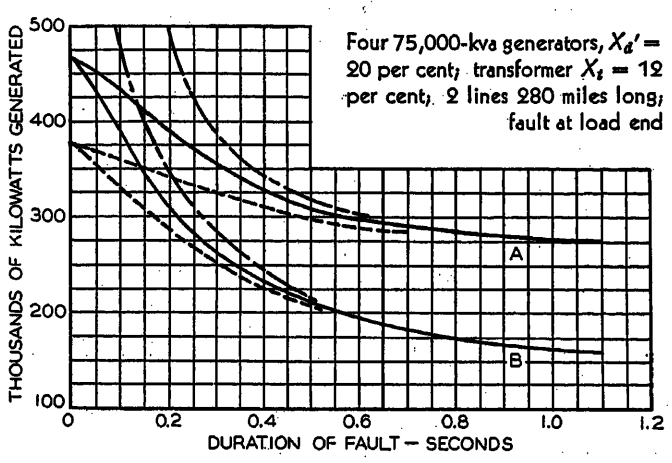



**Fig. 2. Effect of number of switching stations on stability limit**

*A*—Single line-to-ground fault
*B*—Double line-to-ground fault
- - - - - One intermediate station
——— Two intermediate stations
— - — Bus fault cleared with no loss of line

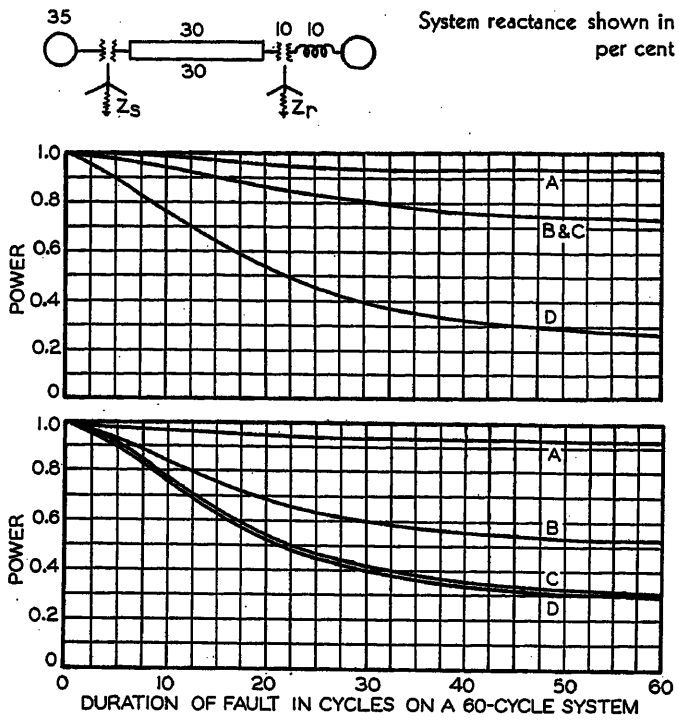



**Fig. 3. Effect of grounding methods upon system stability**

| Curve | Kind of Fault | $Z_s$, Per Cent | $Z_r$, Per Cent |
|---|---|---|---|
| *A* | Single line-to-ground | 13 | +110 |
| *B* | Double line-to-ground | 13 | +110 |
| *C* | Double line-to-ground | 13 | 0 |
| *D* | Double line-to-ground | 0 | 0 |

Upper set of curves for fault on high-voltage bus at sending end
Lower set of curves for fault on high-voltage bus at receiving end

Another method of bussing is incorporated in the scheme known as "synchronizing at the load" as applied to metropolitan type power systems. By metropolitan system is meant the type of system that exists in large cities and is characterized by large turbogenerating units located close together with short transmission distances. With this scheme there are no direct ties between synchronous machine busses but only indirect ties through a multiplicity of connections at secondary or utilization voltages. With this layout secondary faults will not have a severe effect upon the system and can be "burned clear." Faults on a particular generator bus will require disconnection of that unit but the remaining units while subjected to a substantially greater shock, will accelerate or decelerate as a unit. Of course, the shock to the connected load will be decreased as the speed of circuit breakers and relays is increased.

While "synchronizing at the load" was developed for supplying power to metropolitan areas, the underlying general principle has been considered in connection with long-distance transmission projects. The modification of the scheme for this application is characterized by the

bussing of the system only on the low-voltage side at the receiving end. On such a system transmission-line faults result in the disconnection of an entire unit consisting of a generator, sending transformer, transmission line, and receiving transformer. Since the plan of operation contemplates the disconnection of a unit for every fault on

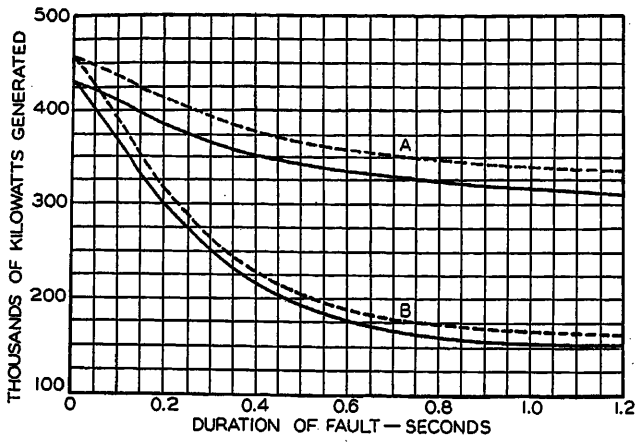



**Fig. 4. Effect of generator reactance upon stability**

*A*—Single line-to-ground fault
*B*—Double line-to-ground fault

Solid curves for generator transient reactance $X_d'$ = 30 per cent; broken curves for $X_d'$ = 21 per cent

Fault at load end; 2 lines, 280 miles, 3 sections; transformer $X_t$ = 10 per cent; 4 70,000-kva generators

the transmission line or its associated apparatus, each circuit may be operated relatively close to its steady-state power limit. Faults on the low-voltage bus at the receiving end will probably be controlling in determining the transient power limits. These connections are similar to those employed on early systems where transmission lines from separate hydroelectric plants were paralleled only at the receiver.

The same general principles of system connection have also been employed in circuits employing 2-winding generators and 4-winding transformers. These schemes improve stability by limiting the severity of short circuit and by distributing the stress among the remaining units. An important advantage of the double-winding generator arises from the fact that in the event of a fault on one winding the sound winding can carry load and thus minimize the disturbance to the system which would result from the disconnection of the faulted machine and the readjustment of load on the remaining units.

Another method of bussing is the "loose-linked" system which consists of a number of power areas normally operated in parallel, being loosely connected for purposes of synchronizing and interchange of power. The plan of operation is such that in any power area the largest generator or the interlinking ties may be lost without leaving a load in an area in excess of the ability to carry it. In the event of a serious disturbance within a power area, that area including its load and sources of power is isolated from other power areas by opening of the ties at appropriate points.

*Grounding*

In America it is common practice on high voltage systems to ground the neutral solidly and on moderate-voltage systems to ground the neutral solidly or through a resistance. For certain types of high-voltage systems there has been recently an increase in the tendency to provide transformers with sufficient insulation in the neutral to permit grounding through a moderate impedance. The Petersen scheme of power system grounding using reactors tuned with the capacitance to ground at fundamental frequency has not been generally accepted though it has been used successfully in a few locations. These schemes also have arc-suppression characteristics as discussed in a subsequent section. The introduction of neutral impedances, by limiting the severity of the fault, increases the stability limits. Two effects may be present. If the impedance is a pure reactance, the current is limited and the synchronizing power is increased thereby; if the impedance is a resistance, power is absorbed in it and the generator output increased and its acceleration is correspondingly retarded. The effects of these factors are illustrated in figure 3, which shows the stability limit as

**Table I—Normal Design Values of Reactance Constants of Synchronous Machines**

| | Reactance, Per Cent | | | | |
|---|---|---|---|---|---|
| | Synchronous* | | Transient** | Subtransient† | Negative-Sequence† |
| | Direct Axis $X_d$ | Quadrature Axis $X_q$ | $X_d'$ | $X_d''$ | $X_2$ |
| Turbogenerators | | | | | |
| 2 pole | 110 | 107 | 14 | 9 | 9 |
| 4 pole | 110 | 108 | 23 | 14 | 14 |
| Salient pole generators and motors with dampers | 100 | 65 | 35 | 24 | 24 |
| Salient pole generator without damper | 100 | 65 | 35 | 32 | 45 |
| Synchronous condensers | 160 | 100 | 40 | 28 | 24 |

* Unsaturated values. ** Rated current values. † Short circuit values

**Table II—Inertia Constants of Synchronous Machines and Acceleration Formula**

| Type | Inertia Constant H* |
|---|---|
| Turbogenerators | See figure 7*a* |
| Waterwheel generators | See figure 7*b* |
| Synchronous condensers** | |
| Large | 1.25 |
| Small | 1.00 |
| Synchronous motors | 2.00 |

* $H = \frac{\text{kw sec}}{\text{kva}} = \frac{0.231(WR^2)(RPM)^2 \times 10^{-6}}{\text{kva}}$

** Hydrogen cooled, 25 per cent less

ACCELERATION FORMULA

$$\alpha = \frac{180 f \Delta P}{\text{kva } H}$$

$\alpha$ = acceleration (or deceleration) in electrical degrees per second per second
$f$ = frequency
$\Delta P$ = kilowatts available for acceleration (or deceleration)
$WR^2$ = moment of inertia in pounds per foot²

a function of the duration of the fault and the connection of the neutral impedance for single and double line-to-ground faults on the high-voltage line at both the sending and receiving ends of a typical system. These curves show conclusively that neutral impedances, preferably resistance at the sending end and reactance at the receiving end, are beneficial in maintaining stability. The importance of the method of grounding in relation to power system stability has been minimized by the development of high-speed breakers and relays and the trend in the direction of basing system design upon the more severe types of faults. In general, however, factors such as lightning protection and relaying, and cost affected by insulation and interconnection with other systems, rather than stability, determine particular methods of grounding to be employed.

*Power System Operation*

Power system operation is often as great a factor as proper system design to insure system stability. The allocation of generator capacity in relation to the system load and circuit conditions is of considerable importance, particularly under abnormal circuit conditions. The stability problem may be accentuated by interconnection and is complicated by the related problems which arise when frequency control is applied or when the location of generating capacity is determined by maximum economy requirements rather than system load requirements.

Most power systems are designed for adequate stability under steady-state conditions. There are, however, many systems where a stability problem is encountered as a result of a fault and for economic reasons it is not always possible to eliminate this condition.

A consideration of certain basic operating principles will prevent exceeding the steady-state limits and insure prompt recovery following a fault.

Adequate spinning reserve capacity either in the form

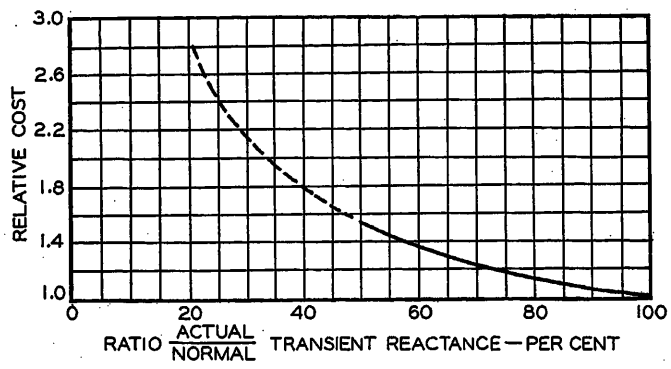



**Fig. 5. Approximate cost of decreasing the transient reactance of salient-pole synchronous generators**

of spare generators or reliable interconnections must be available in each load area to insure a steady-state limit in excess of the power and reactive kilovolt-ampere requirements in event of loss of a generating unit or loss of excitation.

The method of supplying excitation to a system has an important effect on stability. The choice of the value of bus voltages to be maintained or compensated for load and circuit changes may be of great importance. Voltage regulators tend to improve stability conditions by automatically changing the excitation in accordance with loads. They are capable of sustaining system voltages within safe limits for the loss of excitation on one of the units. They also tend to keep the field strength of individual units within reasonable limits, thereby preventing the cascading of trouble following the initial disturbance. Other characteristics of excitation systems and their control in relation to stability are discussed in a subsequent section.

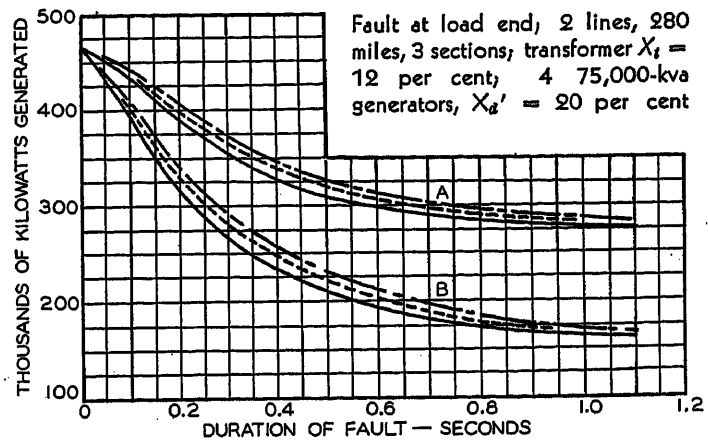



**Fig. 6. Effect of generator inertia upon system stability**

*A*—Single line-to-ground fault
*B*—Double line-to-ground fault

——— Minimum $WR^2$ (31 × $10^6$ pound-feet$^2$)
- - - - - 50 per cent additional $WR^2$
— - — 100 per cent additional $WR^2$

The increasing use of automatic devices, such as refrigerators, water heaters, water pumps, etc., which are not locked out following an outage, results in excess power requirements when service is restored. A recent outage resulted in a peak following restoration of service which was approximately 45 per cent in excess of the load interrupted.

Provision must be made for excess generator capacity for a short period following restoration of service or the service restored slowly to limit the temporary load until its diversity becomes normal.

The spinning reserve capacity for best results should be distributed in the several load areas so that its availability is not restricted by tie-line limitations.

The use of automatic load control on interconnecting tie lines has increased the practical load limits of these lines by preventing the usual drift in the tie-line load, thereby holding the scheduled load well below the tie-line limits. These devices are of no value for transient conditions.

Co-ordination of stability studies and operating instructions for abnormal conditions is a matter of considerable importance for insuring the maintenance of stability or avoidance of service interruption.

When synchronism is lost on a system having synchronous condensers, a state of equilibrium may be reached under which the system will neither accelerate nor retard until conditions are changed by switching operations, or by removal of synchronous condensers. The removal of synchronous condensers, either manually or by underspeed relays, relieves the system of superimposed low frequencies, due to condenser excitation, and permits a more rapid restoration of service.

## Characteristics of Apparatus

### *Synchronous Machines*

The characteristics of synchronous machines which are important from the standpoint of stability are substantially the same in the generator, motor, or condenser. In general, the characteristics of generators are of much more importance because they constitute the largest percentage of the total connected synchronous capacity and because they have such an important bearing on the overall system angles. The following discussion will be given in terms of synchronous generators with the understanding

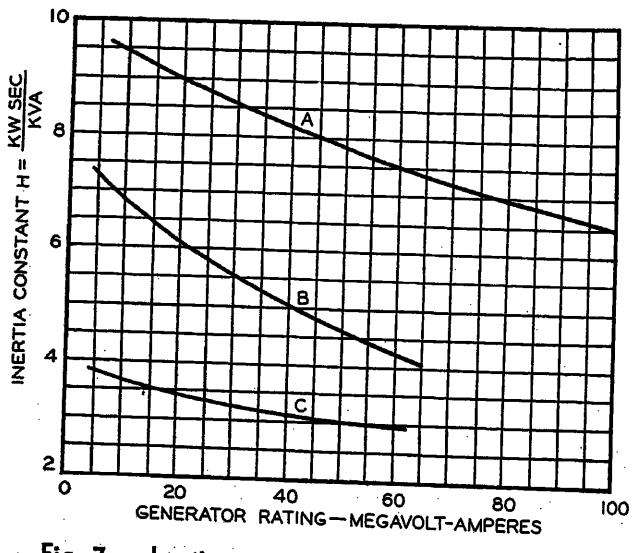



**Fig. 7a. Inertia constants of large turbogenerators, turbine included**

*A*—1,800 rpm condensing
*B*—3,600 rpm condensing
*C*—3,600 rpm noncondensing

that for synchronous condensers and motors the general features are the same but generally of relatively less importance.

The best criterion of generator performance under conditions in which system stability is determined chiefly by the transient characteristics is its transient reactance or more definitely, the direct axis component commonly designated as $X_d'$. The value of this reactance is affected to some extent by the saturation characteristics of the machine. The appropriate value to be used in a stability analysis also varies with the location and severity of the fault. From the standpoint of calculation it is usually impracticable to consider more than one value of transient reactance, which value should be selected considering the condition both during the fault and immediately after its isolation. The effect of decreasing the transient reactance of generators upon increasing the stability limits for a particular study is shown in the curve of figure 4. The normal values of the constants of various types of synchronous machines are shown in table I. The effect of decreasing the transient reactance upon the cost of a machine is indicated in a general way by the curves of figure 5. In a number of installations it has been found desirable to employ generators of less than normal transient reactance.

For a few present-day systems, steady-state stability limits will be found important. With increased application of faster breakers and relays and the logical attempt to increase the load carried on these circuits, the steady-

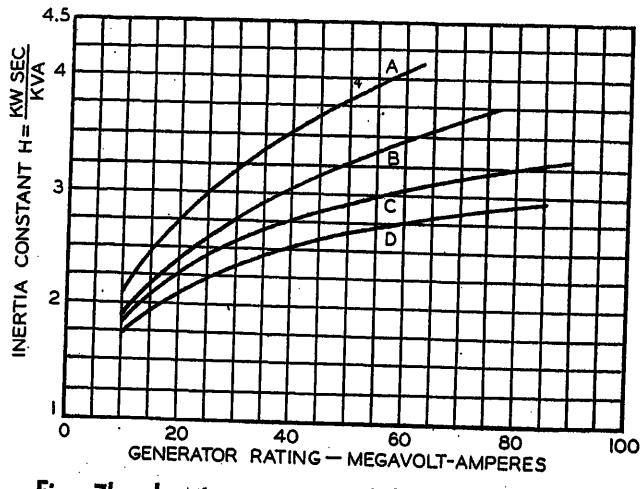



**Fig. 7b. Inertia constants of large vertical-type water-wheel generators, including allowance of 15 per cent for water-wheels**

*A*—450–514 rpm
*B*—200–400 rpm
*C*—138–180 rpm
*D*— 80–120 rpm

state stability limitations will become increasingly important. The best criterion of machine performance with reference to steady-state stability is equivalent synchronous reactance. This reactance differs from the ordinary synchronous reactance defined by the AIEE since it has been adjusted for the operating conditions in order to include the effects of saturation according to the load currents and excitation requirements.

Short-circuit ratio is in itself not directly a measure of the characteristics of the machine from the standpoint of stability. It is, however, of value as an approximate measure of the size of machine. Its value in this case depends upon the fact that to a considerable extent any reduction of reactance in a machine below its normal value is obtained by derating a larger machine and modi-

fying the current-carrying parts to meet the reduced values.

The inertia of a synchronous generator or motor is also a factor in the stability problem since it affects the natural period of system oscillation, or the time required to reach a point beyond which recovery would be impossible. Figure 6 shows the results of calculation for various values of generator inertia upon the stability limits for a particular system. The normal values of inertia constants of the various types of synchronous machines are indicated in table II. The curves of figure 7 show the inertia constants for steam turbine generators and vertical water-wheel generators. The effect of increasing the inertia of generators upon the cost is illustrated by the curves of

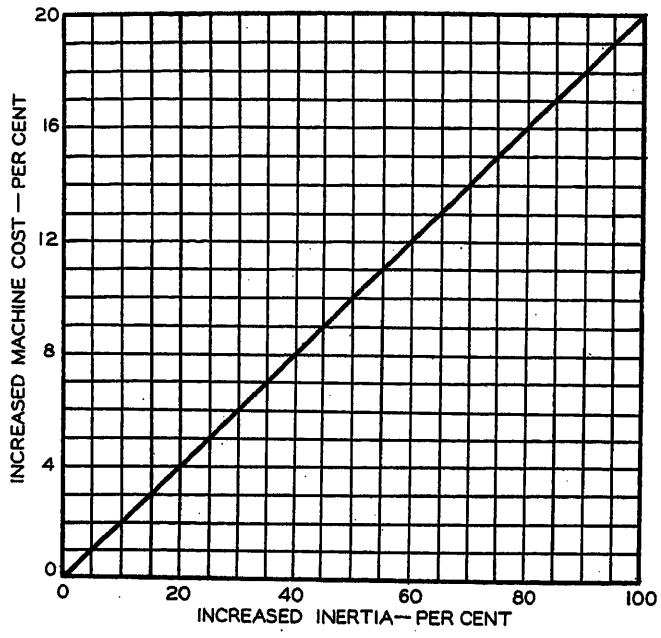



**Fig. 8. Approximate cost of increasing the inertia of large vertical-type water-wheel generators**

figure 8. In a few cases, where calculations have indicated that a particular system would operate relatively close to the stability limits, generators of higher than normal inertia have been installed.

The severity of unsymmetrical system faults is affected by the negative-sequence impedance of the connected machines. Amortisseurs or damper windings affect both the real and reactive components of this impedance. Machines without damper windings possess the highest negative-sequence reactance and from this viewpoint are the most desirable but on the other hand machines with high-resistance damper windings possess the highest negative-sequence resistance. The curves in figure 9 show the combined effect of the damper material upon the stability limit of a typical system for line-to-line and double line-to-ground faults on the high-voltage bus at the generator end. It will be observed that the improvement with high-resistance dampers is quite appreciable for faults of long duration but for faults of a duration comparable with that which can be obtained at present with high-speed breakers, the improvement is very much less. In the event of system oscillations low-resistance copper damper windings produce the greatest damping of the mechanical movement. However, this effect is unimportant during and following a system fault except in the rather rare case in which the system is so constituted that pull-out takes place as a result of compound oscillations following a disturbance. To obtain the partial

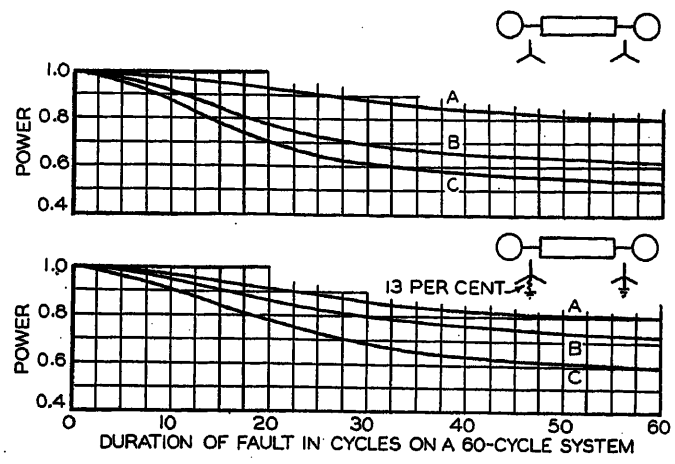



**Fig. 9. Effect of damper winding material upon stability limits**

System same as figure 3C

*A*—High resistance *B*—No dampers C—Copper
Upper curves for line-to-line fault
Lower curves for double line-to-ground fault

advantage of the high loss associated with high-resistance dampers at times of unbalanced faults and the damping of oscillations associated with low-resistance dampers, the generators for one installation were supplied with a new type of damper winding which consists of a double cage arrangement in which the outer row of bars is made of high-resistance material and the inner row of bars is made of a low-resistance material imbedded in the iron. For the double frequency associated with negative-sequence the copper bars possess a high reactance and, therefore, force most of the current through the high-resistance bars, but for the low-frequency associated with the system oscillations the current varies inversely with the resistance of the damper bars in which case most of the current flows through the copper winding. The benefits from high-resistance damper windings will be decreased as the fault duration is decreased by the use of faster breakers and relays. Damper windings also have characteristics which tend to suppress spontaneous hunting and to reduce system voltages and recovery rates arising from short circuits; in these respects, low-resistance copper dampers are somewhat more effective than high-resistance dampers.

With the increase in size of generator units, the greater concentration of power on a single bus has increased the duty on circuit breakers and the area affected by a fault on or near the bus. These effects have been greatly

minimized by the advent of the 2-winding generators in which the 2 armature windings are connected only through their mutual coupling which may be controlled by suitable design. Generators of this character lend themselves to incorporation as units in the system layout known as "synchronizing at the load" or its variations as described previously.

*Excitation Systems*

Control of the excitation system on synchronous machines provides a means for improving stability limits for transient conditions and also for steady-state conditions. Such systems operate to increase stability, (1) by overcoming partially the demagnetizing effect within a machine or (2) by positively increasing the machine fluxes and terminal voltages. Excitation systems that are effective from the standpoint of stability are commonly termed quick-response excitation systems, the principal features of which are:

1. Exciter of high rate of build up and of high "ceiling" voltage.
2. A reliable source of power to the exciter.
3. Quick-responding regulator.

Exciter response is the rate of build up or build down of the main exciter voltage when resistance is suddenly removed from or inserted in the main exciter field circuit by the action of the voltage regulator. The response of an exciter may be expressed as either volts per second or the ratio of the volts per second to some other designated value, e.g., the nominal collector ring voltage. In order to obtain the benefits of a high rate of response, it is necessary for the exciter to have a high ceiling voltage, i.e., a high ratio of maximum to normal operating voltage. The actual response depends upon the excitation system as a unit, on the initial value of the exciter voltage, and on the characteristics of the field and armature circuits of the main machine, and in general varies appreciably during the build-up and build-down process. Because of this variation, it has been found desirable to establish a definite basis for discussion, guarantees, and tests as defined under nominal exciter response.

The nominal exciter response is defined as the ratio to the nominal collector ring voltage of the slope, in volts per second, of that straight line voltage-time curve which begins at nominal collector ring voltage and continues for one-half second, under which the area is the same as under the no-load voltage time build-up curve of the exciter starting at the same initial voltage, and continuing for the same length of time.

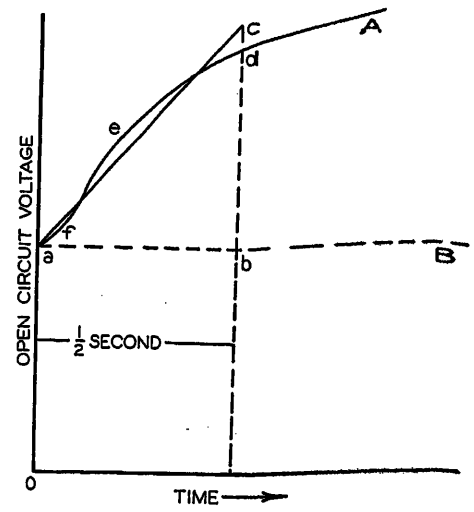
Note: Nominal collector ring voltage is the voltage across the collector rings required to generate rated kilovolt-amperes in the main machine, at rated voltage, speed, frequency, and power factor with the field winding at a temperature of 75 degrees centigrade.

Figure 10 illustrates how exciter response is determined.

The exciters for quick-response excitation systems are built so that the field circuits have low time constants usually obtained by subdividing the fields and using external resistances in series with them together with other changes in design proportions. Generally, it is found most practicable to provide a pilot exciter operating with resistance in series with the field circuits of the main exciter so that the short-circuiting of these resistances will quickly apply increased voltage to the main machine field. This combination is of further advantage in eliminating the necessity for main field rheostats. The requirement for a high ceiling voltage makes it necessary to supply exciters of more liberal design than was the case with slow-response excitation systems heretofore in common use. With quick-response excitation systems it is more important than with previous excitation systems to have a reliable source of power for the exciter, sufficiently ample to supply the heavy demands that are required when a fault occurs.

**Fig. 10. Determination of nominal exciter response**

*A*—Actual build-up curve
*B*—Nominal collector-ring voltage
Area *abc* = area *afedb*




$$\text{Nominal response} = \frac{\text{slope of straight line } ac \text{ in volts per second}}{\text{nominal collector-ring voltage}} = \frac{2bc}{Oa}$$

The voltage regulator characteristics desirable with quick-response excitation systems do not differ radically from some of the types heretofore available. The principal feature of the new regulator has been the introduction of means which make the regulator respond to a sort of average voltage of the different phases instead of from a single phase which was prior practice. This change was made because of the fact that on the occurrence of certain types of unbalanced faults the voltage of a particular phase may rise though the voltage on the remaining phases drops. Thus the old type of regulator connected to this phase would introduce a change in the excitation in the wrong direction from the standpoint of system stability. This feature has been incorporated in commercial regulators in several different forms operating from different quantities. The original form used a network for supplying positive-sequence voltage to the regulator. Subsequently, this result was approximated by the substitution of a torque motor, a polyphase motor, which develops a torque proportional to the difference of the squares of the positive- and negative-sequence voltages. More recently rectifying means giving the average of the 3 phase-voltages have been employed to give corresponding action.

Quick-response excitation systems today are commonly

controlled by the exciter rheostatic type regulator provided with special auxiliary means for momentarily increasing the excitation in case a severe system disturbance is indicated. The exciter rheostatic regulator has the advantage over the vibrating type of being "at rest" for a large percentage of the time in comparison with the vibrating type, which principle will result in reduced maintenance.

Quick-response excitation systems tend to improve stability limits of power systems in 3 ways.

1. Maintaining or increasing machine flux against demagnetizing action of fault currents.
2. Supplying deficiency in system excitation due to loss of other sources of excitation.
3. Increasing steady-state stability limits.

Quick-response excitation provided one of the earliest methods used for improving the transient stability limits of systems. Its importance in this respect has, however, been minimized by the developments of high-speed circuit

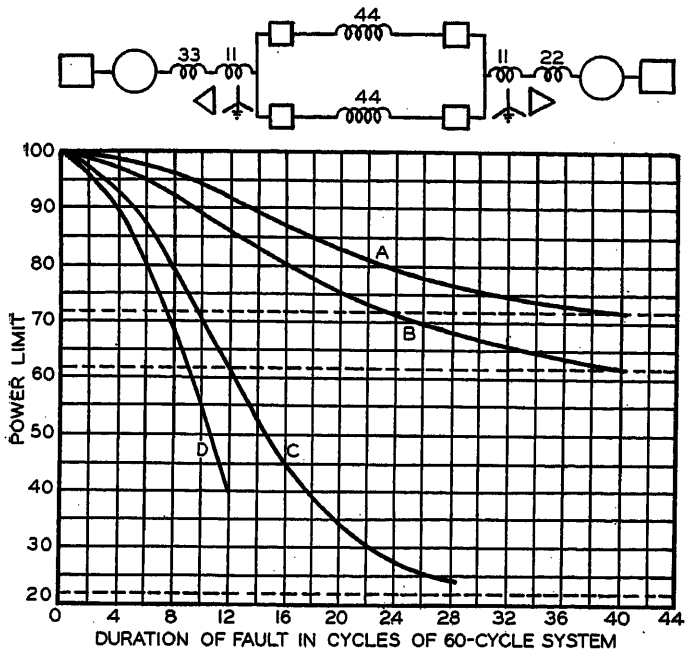



**Fig. 11. Effect of duration of fault on power limits for different kinds of faults**

*A*—Single line-to-ground fault
*B*—Line-to-line fault
*C*—Double line-to-ground fault
*D*—Three-phase fault

System reactance shown in per cent

breakers and relays which limit the duration of fault currents and their demagnetizing effects.

Another feature of quick-response excitation systems is the ability to increase the excitation to meet the requirements of a system arising from the loss of other sources of excitation as from the disconnection of a generator or condenser. This feature cannot, of course, be supplied by means of high-speed circuit breakers. In order to be effective in this respect a quick-response excitation system must have a relatively high ratio of ceiling to normal operating voltage and the regulating equipment must be such as to permit operation under these conditions for the length of time necessary for some readjustment in the system to be brought about.

Quick-response excitation systems also provide means for increasing the steady-state stability limits. Laboratory tests on miniature systems have indicated that quite large increases in the steady-state limits over the values possible with fixed excitation can be secured by the application of a suitable regulator and exciter. These increases vary from 300 per cent for a generator and a synchronous motor directly connected down to 25 per cent for the condition simulating the transmission power over a 200-mile line at 220 kv. The effect of the excitation system in this connection may be viewed as tending to make the steady-state stability limits depend upon transient instead of synchronous reactances. In general, however, since the steady-state limits are higher than the transient limits the use of a regulator to increase the steady-state limits has been without real significance. There is also a question as to the desirability of having the operation of a station at its rated load being dependent upon the functioning of a regulator. Consequently, the choice of regulator has been determined from its performance under transient conditions and its maintenance under ordinary operation. In these respects the exciter rheostatic regulator possesses advantage over the vibrating type though the latter would appear to be superior in improving dynamic steady-state limits.

*High-Speed Circuit Breakers and Relays*

The duration of a fault condition has a very important effect on the stability of a system. The fault condition reduces synchronizing power (1) directly by altering the equivalent circuit constants and (2) indirectly by reducing the effective machine voltages through the demagnetizing action of fault currents. The stability limits as affected by the speed of breaker and relay operation vary through a wide range from (1) the limits corresponding to sustained faults to (2) a mere switching operation assuming extremely fast fault isolation. High-speed circuit breakers and relays are capable of covering most of this range and thus constitute a very important measure for increasing the stability limits, particularly for transmission systems.

The relation between the speed of fault isolation and the transient stability limits for a typical transmission system is indicated in figure 11 which also gives the impedance constants of the various system elements. The system is assumed to be subjected to a fault on one line near the high-voltage bus at the sending end and is cleared by the opening of the 2 breakers simultaneously. The curves assume hydroelectric-type generators, and receiving-end machines of relatively high inertia. The calculations were made for the 4 different types of faults shown on the curves, which are plotted in terms of the time required for the isolation of the fault and the ratio of the power that can be transmitted to the power limit corresponding to the switching out of one section of the transmission line. The dotted lines show the loads which can be carried with sustained short circuits of the various

types assuming quick-response excitation systems capable of preventing demagnetization of the machines.

The curves in figure 11 just discussed apply to a system subjected to a fault at the sending end. The relative stability conditions for the fault at sending and receiving ends of a somewhat different system were given in figure 3 which has been discussed previously in connection with the use of neutral impedances. It will be noted that a moderate value of neutral resistance at the sending end may make the fault at the receiving end on a grounded neutral system relatively more severe than at the sending end. However, the gains in stability due to the use of high-speed circuit breakers are of the same order for faults at the sending or receiving ends of the transmission system.

On metropolitan type systems the permissible time for isolating the fault will be relatively longer than for transmission systems since the latter are usually operated closer to the stability limits. Thus in the metropolitan systems it is possible to introduce reactance in the system in such a way as to limit the duty on circuit breakers. This problem can conveniently be studied by means of curves characteristic of the type of system equivalent to the "2-machine problem" using reactances as defined in the insert on figure 12. These curves indicate that by taking advantage of the faster speeds made possible by the recent developments of circuit breakers, increased amounts of reactance may be introduced in the system which may be used to either reduce the duty on circuit breakers or increase the continuity of power supply or reliability of this service to the customer.

The speed of circuit breakers and relays in relation to power system stability may conveniently be analyzed under 3 headings as follows:

1. Conventional or slow-speed breakers and relays for fault isolation.

2. High-speed breakers and relays capable of isolating fault in time to improve stability limit.

3. High-speed breakers and relays with reclosure in time to improve stability limit.

Examination of the curves of figures 11 and 12 will show that conventional slow-speed circuit breakers and relays of the type commonly in use prior to 1929 were so slow from the stability point of view that the limits corresponded to sustained faults. In this connection it may be observed also that the power limit for the 3-phase fault is almost negligible with the conventional slow-speed breakers formerly in use. The benefits which arise from the use of high-speed circuit breakers and relays in maintaining stability depend upon isolating the fault in an interval of time which is short in respect to the period of system oscillation. The preceding discussion has been based on the isolation of the fault in a single step. For sequential operation the individual breaker times will be less than that shown but need not be reduced to half value. This is, of course, due to the fact that the stability conditions are generally much improved upon the operation of the first circuit breaker.

With the development of higher speed circuit breakers it is now possible to obtain speeds of operation of 8 cycles for the full range of transmission voltages. In addition for special cases still faster speeds of operation, such as 3-cycle breakers, have been developed to meet the particular situation.

With composite systems involving long transmission lines from a source of power with interconnecting lines between various parts of the receiver, system studies will frequently show the desirability of using high-speed circuit breakers and relays in order to increase the stability limits. In a number of such cases it will be important to extend the application of the high-speed breakers to interconnecting lines of the receiver system. Otherwise, the stability limits will be determined not by faults on the main transmission line but by faults on the receiving system even though it is operating at lower voltage with transformers between it and the transmission line.

This development in the speed of circuit breakers has brought about important changes in the relaying of transmission lines. With fast circuit breakers it is no longer feasible to contemplate relay operating times of $^1/_4$ second to 3 seconds or the use of time intervals as the basis of discrimination. This has led to the use of distance or current balance types of relays which are capable of simultaneous action for the middle section of a transmission line with high-speed sequential tripping for the end sections.

In cases where the transmission system will be operated relatively close to the stability limits there is considerable advantage in providing simultaneous breaker operation. In general, such relay operation can be obtained only through the use of fundamental frequency relays operating in conjunction with a signal transmitted by pilot wires or carrier current between the ends of the line section. This has brought about an important development in the application of high-speed relaying with superposed carrier frequency. Various proposals have been considered as to the type of carrier signal to be transmitted. The relay indication to be transmitted by carrier frequency was considered first as some electrical indication, such as direction of the flow of power, but more recently as the position of various fundamental frequency relay elements which indicates the existence of a fault on the system within predetermined zones. The carrier-current relay system also provides opportunity for including relay measures for the prevention of undesired breaker operations in the event that the system does pull out of step.

*Reclosing Circuit Breakers*

The use of reclosing circuit breakers provides a means for carrying one step further the advantages possible with high-speed breakers and relays for fault clearing. For lower voltage systems and feeder circuits the use of automatic reclosing breakers makes it possible to maintain the stability of a system with induction motor load. Disconnection of the source is required for the suppression of the arc in the fault but the total time required for disconnection and for reclosure should be made sufficiently short as to prevent pullout of induction motor load. Where synchronous machines may maintain the arc, it is

necessary to isolate the affected line and to reconnect it in a period of time that is relatively short with respect to the period of system oscillation if stability is to be attained. Hence, if automatic reclosing breakers are considered for maintaining the stability on a transmission system it becomes a practical necessity to use carrier current relaying. The existence of multiple or repetitive lightning discharges may constitute an important factor in limiting the application of reclosing breakers for maintaining stability.

Single-pole breakers have been proposed at frequent intervals as a means for improving the stability of a transmission system. This device has been advocated on the basis that the remaining phases may be used to transmit power and thus minimize the system disturbance during the transition from the condition before the fault to the condition after the fault when the faulty line is disconnected. Most line interruptions which do not permanently ground a transmission conductor are due to flashovers which must be isolated to put out the arc-to-ground. Thus it is usually permissible to reclose the faulty line and restore the system to its original condition without at any time reducing the power limits to as low a value as would be the case if all three conductors were disconnected. To minimize objection to residual earth current from the standpoint of inductive co-ordination, it has been proposed to use breakers which are operated as single-pole units for arc suppression and reclosure but which are gang-operated for sustained faults. The advantages of single-pole reclosing breakers are minimized by the trend in the direction of providing protection against the more severe types of faults. To date the single-pole breaker scheme has not been installed on any transmission system.

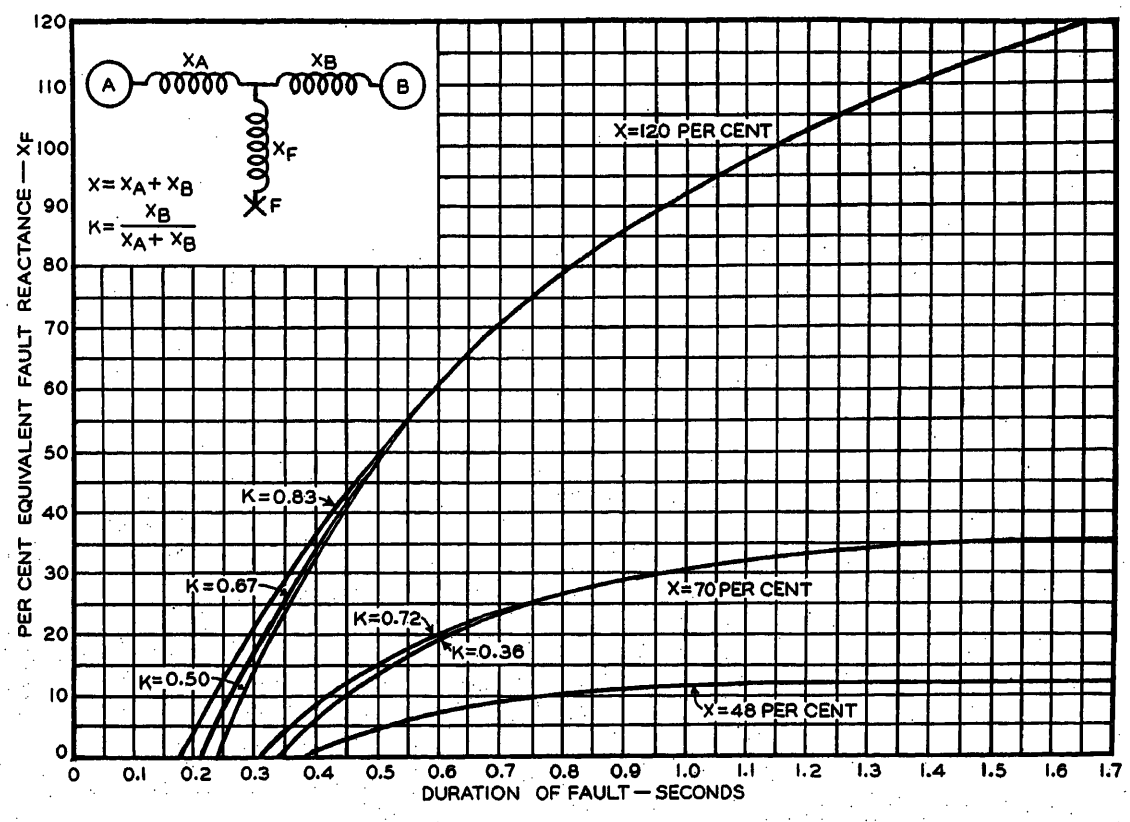



**Fig. 12. Stability limits for metropolitan-type systems with steam-turbine generators; no voltage regulators**

*A*—Steam turbine under consideration

*B*—System

## Other Methods of Increasing the Practical Operating Power Limits

### Flashover Prevention and Arc Suppression

Flashover prevention and arc suppression constitute a different type of measure for improving system operation. It is obvious, of course, that a system rarely subjected to faults may be operated relatively close to the stability limits. Consequently, under some conditions it is more advantageous to spend money for minimizing the likelihood of faults than in increasing the capacity of the system to withstand the system disturbances without loss of synchronism.

The principal cause of flashover on high-voltage lines is lightning. Much has been accomplished during the past 5 years to minimize flashovers resulting not only from induced strokes but particularly from direct strokes. Increased transmission line spacing and increased use of insulation in the form of insulator strings and wood have been generally adopted. On the higher voltage lines the use of ground wires is of great value when suitably located with respect to the conductors to be protected. Special efforts have been made to reduce the tower-footing resistance to a relatively low value in order to prevent a flashover of the insulator string as a result of the building up of high potential due to the flow of lightning current through the tower.

## Table III—Recent Practices

| | Los Angeles Bureau of Power & Light | Metropolitan Water District of So. California | Southern California Edison Co. | Pacific Gas & Electric Co. | | Puget Sound Power & Light Co. | |
|---|---|---|---|---|---|---|---|
| | Item I Boulder Dam-Los Angeles | Item I Boulder Dam Line | Item I Big Creek Line | Item I Tiger Creek-Newark | Item II Bucks Creek-Wilson | Item I Baker River Nos. 1 & 2 | Item II Rock Island No. 1 |
| **A. Transmission** | | | | | | | |
| 1. Voltage, kilovolts | 287.5 | 230 | 220 | 220 | 220 | 110 | 110 |
| 2. Distance, miles | 267 | 237 | 240 | 109 | 185 | 67 | 134 |
| 3. Frequency, cycles | 60 | 60 | 50 | 60 | 60 | 60 | 60 |
| 4. Power, kilowatts sent out | 240,000 | 330,000 | 400,000 | 150,000 | 120,000 | 40,000 | 25,000 |
| **B. Circuit arrangement** | | | | | | | |
| 1. Number of circuits | 2 | 1 | 3 | 2 | 2 | 2 | 1 |
| 2. Intermediate switching stations | 2 | None | 4 | None | 1 | 1 | None |
| 3. Load taken off at intermediate points, kilowatts | None | None | 135,000 | None | None | None | None |
| 4. Synchronous condenser, kva at intermediate points | None | None | None | None | None | None | None |
| 5. Bussing arrangements | | | | | | | |
| *a.* Sending end | H. T. | H. T. | H. T. | None | None | None | None |
| *b.* Receiving end | L. T. | H. T. | H. T. | None | None | None | None |
| 6. Grounding | | | | | | | |
| *a.* Sending end | Solid | Solid | Solid | Solid | Solid | Solid | Solid |
| *b.* Receiving end | Solid | Solid | Solid | Solid | Solid | Solid | Solid |
| **C. Generator** | | | | | | | |
| 1. Kilovolt-amperes | Each 82,500 | Each 82,500 | 15 units, total 397,000 | | | 39,000 | 66,668 |
| 2. Short circuit ratio (or synchronous reactance, per cent) | 2.4 | 2.4 | 1.6 | | | | |
| 3. Transient reactance $X_d'$ per cent | 17.5 | 17.5 | 22 | 27 | 27 | 23 | 30 |
| 4. Inertia constant $H$ | 9.5 | 4.7 | 3.74 | 4.1 | 4.1 | 4.05 | 4.45 |
| 5. Damper winding | Copper | Copper | None | None | None | Copper | Copper |
| **D. Excitation system** | | | | | | | |
| 1. Exciter response, per unit (figure 10) self- or pilot exciter | 0.5 Pilot | 0.5 Pilot | 1.0 Pilot | 1.5 | 1.5 | 240 volts/sec | 200 volts/sec |
| **E. Breakers and relays** | | | | | | | |
| 1. Breaker speed, cycles | 3 | 8 | 8-26 | 12 | 12 | 18 | 8 |
| 2. Relaying type | Carrier current and cross balanced between I circuits—3 cycles | Instantaneous overcurrent | Instantaneous overcurrent & simultaneous carrier current on some lines | Overload & directional residual | (Same as item I) | Balanced current | High speed distance |
| 3. Total time, cycles* | 6 | 8.5 | 8.5-31 | 13-14 | 13-14 | 27-54 | 9 |
| **F. Lightning protection** | | | | | | | |
| 1. Tower construction | Steel | Steel | Steel | Steel | Steel | Wood pole H frame | Steel over mountains, rest is wood pole H frame |
| 2. Ground wires | 2–50′ spacing on 1 circuit towers—40.5 on 2 circuit towers | None | 2 | None | None | None | None |
| 3. Counterpoises | Continuous —2 wires per tower line, cross connect to adjacent towers. | None | None | None | None | None | None |
| 4. Insulators | Susp: Single—24, 10″ x 5″ units Deadend: Double, 22 10½″ x 6″ units | Susp: 13–10″ diam., 5¾″ spacing Deadend: 15-same | Susp: 12–10″ units Deadend: 13-double, same | 13 5½″ units Semi-fog section, 14 5½″ units Fog section, 20 5½″ units | 14 5½″ units | Susp: 6–10″ units Deadend: 7-same | (Same as item I) |
| 5. Lightning arresters | Yes | None | None | None | None | Yes | Yes |

* Note—In certain cases of sequential tripping, time given applies to breaker only.

The use of the ground wire tends to reduce the zero-sequence impedence of the system and thus to increase the severity of the shock resulting from a single fault-to-ground or a double fault-to-ground. With the improvements in high-speed circuit breakers and relays these faults may be cleared promptly; consequently, the use of ground wires results in a gain from the stability point of view in reducing the number of flashovers which overbalances any disadvantage from the standpoint of the shock to the system in case fault occurs.

The fault suppression measures have as their object the interruption of the power-arc following a flashover without the necessity for isolating the affected circuit. The use of fused arcing rings or special tube type protectors in parallel with the insulators permits flashover to take place with the subsequent interruption of the power arc. Lightning arresters distributed along the line will accomplish this same general objective.

Arc-suppression devices of the Petersen type have received consideration for minimizing circuit outages in com-

## Regarding Stability Features

| | Southern Sierras Power Co. | Platte Valley Public Power & Irrigation Dist. | Union Electric Light & Power Co. | | The Milwaukee Electric Railway & Light Company | | Super Power Co. Ill. Ill. North. Utilit. Co. & Public Service of Northern Ill. | Super Power Co. of Illinois & Public Service Co. of Northern Illinois | |
|---|---|---|---|---|---|---|---|---|---|
| | Item I Boulder Dam Line | Item I North Platte-Columbus | Item I Osage-Cahokia | Item II Osage-Page | Item I Lakeside-Granville | Item II Port Washington-Granville | Item I Powerton-Waukegan | Item II Powerton-Waukegan | Item III Powerton-State Line |
| A | | | | | | | | | |
| 1 | 132 | 115 | 132 | 132 | 132 | 132 | 132 | 132 | 132 |
| 2 | 222 | 218.5 | 177.9 | 135.5 | 25 | 23 | 218.6 | 243.4 | 202.4 |
| 3 | 60 | 60 | 60 | 60 | 60 | 60 | 60 | 60 | 60 |
| 4 | 32,000 | 25,000 | 90,000 | 45,000 | | | 55,000 | 55,000 | 60,000 |
| B | | | | | | | | | |
| 1 | 1 | 1 | 2 | 1 | 1 | 1 | 1 | 1 | 53 mi: 2<br>149.4 mi: 1 |
| 2 | None | 2 | 2 | None | 1 | None | 2 | 4 | 4 |
| 3 | None | 12,000 | 20,000 | None | None | None | 30,000 | 50,000 | 35,000 |
| 4 | None | 8,000 | 50,000 | None | None | None | None | 20,000 | 15,000 |
| 5 | | | | | | | | | |
| *a* | None | L. T. | None | None | L. T. | L. T. | None | None | None |
| *b* | None | H. T. | L. T. | L. T. | H. T. | H. T. | H. T. | H. T. | L. T. |
| 6 | | | | | | | | | |
| *a* | Solid | Solid | Solid | Solid | Solid | Solid | Solid | Solid | Solid |
| *b* | Solid | Solid | Solid | Solid | None | None | Solid | Solid | Solid |
| C | | | | | | | | | |
| 1 | 40,000 | 2 units, each 14,500 | 4 units, each 23,888 | 2 units, each 23,888 | 375,000 | 94,000 | 61,765 | 61,765 | 116,666 |
| 2 | 1.6 | 115.5 | 1.15 | 1.15 | 0.87 & 1.24 | 0.92 | 120 | 120 | 107 |
| 3 | 26 | 32 | 30 | 30 | 15 | 15.5 | 23 | 23 | 20 |
| 4 | 3.8 | 2.05 | 3.56 | 3.56 | | | 5.75 | 5.75 | 5.5 |
| 5 | Copper | Copper | None | None | | | None | None | None |
| D | | | | | | | | | |
| 1 | 0.5 | 1.0 | 1.5 | 1.5 | Hand | Hand | 0.3 | 0.3 | 1.0 |
| 2 | Pilot | Pilot | Pilot | Pilot | regulation | regulation | Self | Self | Pilot |
| E | | | | | | | | | |
| 1 | 10 | 8 | 7 | 8 | 12 | 8 | 8-20 | 8-20 | 8-20 |
| 2 | Phase: Induction type impedance g'nd: directional induction | Distance | Distance | Distance | Induction type | Induction type | Distance | Distance | Distance |
| | 16 (Min.) | 9–10 | 8–10 | 9 | 93 | 39 | 10–56 | 10–74 | 10–74 |
| F | | | | | | | | | |
| 1 | Steel | Wood pole H frame | 120 mi. steel with wood arms; 58 mi. steel | Wood pole H frame | Steel | Steel | 166 mi.: steel<br>52 mi.: wood | Steel | Steel |
| 2 | None | None | 147 mi.—2;<br>31 mi.—1 | 2 | 1 | 1 | 185 mi: 2;<br>34 mi.: 1 | 187 mi.: 2;<br>57 mi.: 1 | 173 mi.: 2;<br>30 mi.: 1 |
| 3 | None | None | None | None | None | None | None | None | None |
| 4 | Susp: 9–10″ units<br>Deadend: 10-same | Susp: 7–10″ × 5¾″ units<br>Deadend: 8-same | 147 mi.: 11–5¾″ units<br>31 mi: 10–4¾″ units | 11–5¾″ units | Susp: 10–4¾″ units<br>Deadend: 12-same | (Same as item I) | 103.5 mi.: 12–OB25620<br>72.9 mi.: 10–5¾″ units<br>42.2 mi.: 8–JD2501 | 53 mi.: 12–OB25620<br>67.4 mi.: 13–OB25622<br>123 mi.: 8–JD2501 | 53 mi.: 12–OB25620<br>67.4 mi.: 13–OB25622<br>82 mi.: 8–JD2501 |
| 5 | Yes | Yes | Yes | Yes | Yes | Yes | 3 stations—yes<br>1 station—no | 3 stations—yes<br>3 stations—no | 4 stations—yes<br>2 stations—no |

nection with multiple-circuit system of the type in common use and with recently proposed single-circuit transmission line system. In America, however, little use is made of this type of arc-suppression device as dependence is placed on circuit-breakers and relays for automatically isolating a faulty section of line. This can be accomplished under favorable conditions even on high voltage circuits in about 12 cycles. This scheme has the merit of suppressing all types of faults that occur on systems regardless of whether they are of the single line-to-ground or more severe types. In addition it permits grounding the system so that the tendency for a single-phase fault to develop into a multiphase fault is minimized.

### High-Voltage Low-Frequency A-C and D-C Transmission

Low-frequency a-c systems have been proposed frequently for increasing the practical operating stability limits of long-distance transmission systems. More recently d-c transmission has been proposed as a means for

## Table III (Continued)—Recent Practices

| | Public Service Co. of Northern Illinois | | Northern Indiana Public Service Co. | | | Public Service Company of Indiana | | Detroit Edison Co. |
|---|---|---|---|---|---|---|---|---|
| | Item I Waukegan Northwest | Item II Waukegan Northwest | Item I Michigan City-State Line | Item II Michigan City-South Bend | Item III Mich. City-S. Bend Monticello | Item I Dresser-Lenore | Item II Columbia-Lenore | Item I Marysville Northeast |
| **A. Transmission** | | | | | | | | |
| 1. Voltage, kilovolts | 132 | 132 | 132 | 132 | 132 | 132 | 132 | 120 |
| 2. Distance, miles | 36.88 | 36.88 | 50.6 | 40.5 | 101.0 | 74.8 | 91.68 | 55.5 |
| 3. Frequency, cycles | 60 | 60 | 60 | 60 | 60 | 60 | 60 | 60 |
| 4. Power, kilowatts sent out | 80,000 | 80,000 | 80,000 | 55,000 | 25,000 | 40,000 | 10,000 | 40,000 |
| **B. Circuit arrangement** | | | | | | | | |
| 1. Number of circuits | 1 | 1 | 1 | 1 | 1 | 2 | 1 | 2 |
| 2. Intermediate switching stations | None | None | 1 | None | 1 | None | 1 | None |
| 3. Load taken off at intermediate points, kilowatts | None | None | 45,000 | None | 8,000 | None | None | None |
| 4. Synchronous condenser, kva at intermediate points | None | None | None | None | None | None | None | None |
| 5. Bussing arrangements | | | | | | | | |
| *a.* Sending end | H. T. | H. T. | H. T. | H. T. | H. T. | L. T. | L. T. | H. T. |
| *b.* Receiving end | L. T. | L. T. | L. T. | H. T. | L. T. | L. T. | L. T. | H. T. |
| 6. Grounding | | | | | | | | |
| *a.* Sending end | Solid | Solid | Solid | Solid | Solid | Solid | Solid | Solid |
| *b.* Receiving end | Solid | Solid | Solid | Solid | Solid | Solid | Solid | Ungrounded |
| **C. Generator** | | | | | | | | |
| 1. Kilovolt-amperes | 2 units, total 129,525 | 121,000 | 70,600 | 70,600 | 70,600 | 3 units, each 25,000 | 2 units, each 78,610 | 6 units, total 196,000 |
| 2. Short circuit ratio (or synchronous reactance, per cent) | 1 unit, 152; 1 unit, 154 | 161 | 111 | 111 | 111 | 122 | | 1.02 |
| 3. Transient reactance $X_d'$, per cent | 1 unit, 16.3; 1 unit, 18.6 | 18.4 | 23.9 | 23.9 | 23.9 | 13 | | 23.4 |
| 4. Inertia constant $H$ | 1 unit, 4.95 1 unit, 4.14 | 4.64 | 4.09 | 4.09 | 4.09 | 3.74 | | 6.6 |
| 5. Damper winding | None | None | None | None | None | None | None | None |
| **D. Excitation system** | | | | | | | | |
| 1. Exciter response, per unit (figure 10) self- or pilot exciter | 0.5 Self | 1.5 Pilot | 0.384 Self | 0.384 Self | 0.384 Self | Unknown Self | Self | Hand regulation |
| **E. Breakers and relays** | | | | | | | | |
| 1. Breaker speed, cycles | 8 | 8 | 12–25 | 8–12 | 8–12 | 6–7 | 7–13 | 6 |
| 2. Relaying type | Distance & overcurrent | Distance & overcurrent | Distance | Distance & overcurrent | Distance & overcurrent | Overcurrent | Overcurrent | Differential |
| 3. Total time, cycles* | 10–60 | 10–60 | 13–67 | 10–14 | 12–45 | Line: 9–67; G'nd: 9–25 | Line: 39–67; G'nd: 12–53 | 8 |
| **F. Lightning protection** | | | | | | | | |
| 1. Tower construction | Steel | Steel | Steel | Steel | Steel | Steel | Steel | Steel |
| 2. Ground wires | 2 | 2 | 1 | 1 | 1 | 1 | 1 | 1 |
| 3. Counterpoises | None | None | None | None | None | None | None | None |
| 4. Insulators | 8–JD2501 | 8–JD2501 | 8–6½″ units | 8–6½″ units | 8–6½″ units | Susp: 9–10″ x 4¾″ units Deadend: 11-same | (Same as item I) | Susp: 9–5″ units Deadend: 10-same |
| 5. Lightning arresters | None | None | Yes | Yes | Yes | Yes | Yes | Yes |

* Note: In certain cases of sequential tripping, time given applies to first breaker only.

avoiding the stability limits since such a system inherently provides a nonsynchronous tie. In America, 60-cycle alternating current is very generally established for utilization. Consequently, the proposals to use low-frequency a-c and high-voltage d-c transmission schemes have included conversion means at the receiving end. In general, the use of the low-frequency a-c system involves no new problem in apparatus or application so that its use is not hindered on this account, though static apparatus may find application in the field of frequency conversion. In the case of d-c transmission, however, the conversion from a-c generation to the d-c high voltage required for the transmission line involves rectifiers for which there is no comparable operating experience; in the case of the invert-

## Regarding Stability Studies

| | Consumers Power Company | | | | | | | | Tennessee Valley Authority | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Item I Saginaw-Flint | Item II Muskegon-Grand Rapids | Item III Croton-Grand Rapids | Item IV Jackson-Superior | Item V Flint-Delhi | Item VI Kalamazoo-Battle Creek | Item VII Delhi-Jackson | Item VIII Toronto-Akron | Item I Wilson-Norris | |
| A | | | | | | | | | | |
| 1 | 140 | 140 | 140 | 132 | 140 | 140 | 140 | 132 | 154 | |
| 2 | 43.3 | 36.2 | 47.1 | 28.8 | 19.4 | 14.3 | 26.5 | 64.0 | 233.4 | |
| 3 | 60 | 60 | 60 | 60 | 60 | 60 | 60 | 60 | 60 | |
| 4 | 100,000 | 50,000 | 67,800 | 77,500 | 25,000 | 25,000 | 65,000 | 50,000 | 50,000 | |
| B | | | | | | | | | | |
| 1 | 2 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | |
| 2 | None | None | None | None | None | None | None | None | None | |
| 3 | None | None | None | None | None | None | None | None | None | |
| 4 | None | None | None | None | None | None | None | None | None | |
| 5 | | | | | | | | | | |
| a | H. T. | H. T. | H. T. | Through transformer | H. T. | H. T. | H. T. | H. T. | H. T. | |
| b | H. T. | H. T. | H. T. | Through transformer | H. T. | H. T. | H. T. | L. T. | L. T. | |
| 6 | | | | | | | | | | |
| a | Isolated neutral | Isolated neutral | Isolated neutral | Isolated neutral | Isolated neutral | Isolated neutral | Isolated neutral | Solid | 2 reactors (each 35 ohms) | |
| b | Isolated neutral | Isolated neutral | Isolated neutral | Solid | Isolated neutral | Isolated neutral | Isolated neutral | Solid | Solid | |
| C | | | | | | | | | | |
| 1 | 140,000 | 50,000 | 50,000 | | | 50,000 | | 140,000 | 2 units, each 56,00 (at Norris) | |
| 2 | 1.0 | 1.0 | 1.0 | | | 1.0 | | 1.0 | 1.045 | |
| 3 | 10–12 | 10–12 | 10–20 | | | | | 10–12 | 40.7 | |
| 4 | | | | | | | | | | |
| 5 | | | | | | | | | Copper | |
| D | | | | | | | | | | |
| 1 | 2.0 Pilot | Pilot | Pilot | | | Pilot | | Pilot | 1.0 Pilot | |
| E | | | | | | | | | | |
| 1 | 8–20 | 8–20 | 8 | 8–20 | 8–20 | 8–20 | 8–20 | 8–20 | 8 | |
| 2 | Impedance | Step distance | Step distance | Impedance | Impedance | Impedance | Impedance | High-speed step distance | Simultaneous with carrier, or sequential with distance | |
| 3 | 20–32 | 10–22 | 10 | 20–32 | 20–32 | 20–32 | 20–32 | 10–22 | | |
| F | | | | | | | | | | |
| 1 | Steel | Steel | Steel | Steel | Steel | Steel | Steel | Steel | Steel except Tenn. R. to Monteagle (wood) | |
| 2 | 1 | 2 | 1 | 1 | 1 | 1 | 1 | 1 | 2 | |
| 3 | None | None | None | None | None | None | None | None | None | |
| 4 | Susp: 9–4¾″ units 9–5¾″ units 12–4¾″ units Deadend: 11–5¾″ units | Susp: 10–5¾″ units Deadend: 11-same | (Same as item II) | Susp: 10–5″ units Deadend: 12-same | Susp: 10–5¾″ units Deadend: 11-same | Susp: 9–4¾″ units Deadend: 12-same | Susp: 10–4¾″ units Deadend: 12-same | Susp: 10–5¾″ units Deadend: 11-same | 17.5 miles; Susp: 19–5⅛″ units Deadend: 21 same. 96 miles; Susp: 9–6½″ units Deadend: 11 same. 120 miles; Susp: 16–6½″ units or 19–5⅛″ units Deadends: 21–5⅛″ units | |
| 5 | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes | |

ers at the receiving end still less work has been done. Consequently, d-c transmission has received very little practical consideration, although a 5,000-kw experimental d-c transmission system, which will transmit power 17 miles at 30,000 volts, is being built to obtain operating experience.

At the present time the limitations in 60-cycle systems, from the standpoint of system stability, are not of sufficient importance as to justify the adoption of either low-frequency a-c or high-voltage d-c transmission. The possible field for d-c transmission will depend largely on the usefulness of its operating characteristics aside from stabilty and on the future development of conversion apparatus. In this connection it should also be recognized that

## Table III (Continued)—Recent Practices

| | Pennsylvania Water and Power Co. | | Philadelphia Electric Co. | | Pennsylvania Power & Light Co. | Pennsylvania and Public Service Electric & Gas Company of New Jersey | |
|---|---|---|---|---|---|---|---|
| | Item I Safe Harbor-Washington | Item II Safe Harbor-Perryville | Item I Conowingo-Plymouth Mtg. | Item II Plymouth Mtg.-Westmoreland | Item I Plymouth-Siegfried | Item I Roseland-Plymouth Mtg. | Item II Roseland-Siegfried |
| **A. Transmission** | | | | | | | |
| 1. Voltage, kilovolts | 230 | 132 | 220 | 66 | 220 | 220 | 220 |
| 2. Distance, miles | 92 | 30 | 57.6 | 10 | 38.8 | 75.8 | 83.7 |
| 3. Frequency, cycles | 60 | 25—1 phase | 60 | 60 | 60 | 60 | 60 |
| 4. Power, kilowatts sent out | 168,000 | 49,400 | 252,000 | 212,000 | 185,000 | 200,000 | 200,000 |
| Circuit arrangement | | | | | | | |
| 1. Number of circuits | 1 | 4 | 2 | 3 | 1 | 1 | 1 |
| 2. Intermediate switching stations | None | None | None | None | None | None | None |
| 3. Load taken off at intermediate points, kilowatts | None | None | None | None | None | None | None |
| 4. Synchronous condenser, kva at intermediate points | None | None | None | None | None | None | None |
| 5. Bussing arrangements | | | | | | | |
| *a.* Sending end | None | None | None | None | None | None | None |
| *b.* Receiving end | None | None | None | None | None | None | None |
| 6. Grounding | | | | | | | |
| *a.* Sending end | Solid | Midpoint of transfs. grounded through 330-ohm resistance | Solid | Solid | Solid | Solid | Solid |
| *b.* Receiving end | Solid | | Solid | Solid | | Interconnected with P. E. Co. | Interconnected with P.P. & L. Co. |
| **C. Generator** | | | | | | | |
| 1. Kilovolt-amperes | 5 units, total 155,500 | 35,000—Gen. 31,250—Freq. chgr. | 7 units, total 280,000 | | | | |
| 2. Short circuit ratio (or synchronous reactance, per cent) | | | | | | | |
| 3. Transient reactance $X_d'$, per cent | 26.7–29.0 | 27.5 | 26–28 | | | | |
| 4. Inertia constant $H$ | 3.31 | 4.3 | 2.84–3.69 | | | | |
| 5. Damper winding | Copper | Copper | None | | | | |
| **D. Excitation system** | | | | | | | |
| 1. Exciter response, per unit (figure 10) self- or pilot exciter | 225 volts/sec. | 200 volts/sec. | 3.2–3.5 | | | | |
| **E. Breakers and relays** | | | | | | | |
| 1. Breaker speed, cycles | 8 | 3.5 | 8–12 | 8 | 10 | 3.5 | 3.5 |
| 2. Relaying type | Distance | Voltage balance | Phase: Induction impedance g'nd: hi-speed diff. & hi-speed directional overcurrent | Phase: Differential g'nd: hi-speed induct type directional overcurrent | Phase: Distance g'nd: Instantaneous overcurrent | Distance | Sequential with distance |
| 3. Total time, cycles* | 9–10 | 8.5 | Phase: 9–18 G'nd: 9–18 | Phase: 20–60–150 Gn'd: 9–18–60 | 11–75 | 10 | 10 |
| **F. Lightning protection** | | | | | | | |
| 1. Tower construction | Steel | Steel | Steel | Steel | Steel | Steel | Steel |
| 2. Ground wires | 2 | 2 | 2 | 2 | 2 | 2 | 2 |
| 3. Counterpoises | Crowfoot system | Crowfoot system | None | Continuous type, 3.7 mile section | None | None except gndg. cable at high res. tower footings | (Same as item I) |
| 4. Insulators | 20–5¼" units | 12–5¼" units | Susp: 16–5¼" units Deadend: 18-same | Susp: 8–5¼" units Deadend: 9-same | Susp: 16–5¼" units Deadend: 18-same | Susp: 18–5¼" units Deadend: 20-same | (Same as item I) |
| 5. Lightning arresters | Yes | None | Yes | Yes | None | None | None |

* Note: In certain cases of sequential tripping, time given applies to first breaker only.

there is a possibility of an improvement in a-c transmission at normal frequencies.

## Recent Practices Regarding Stability Features

In order to summarize the present status of the stability problem from the practical standpoint of its effect on power system design, table III has been prepared. This table gives the principal installations made during the past 10 years and lists the data on the various stability measures employed. While the list of installations is obviously incomplete, nevertheless, it is believed that the list is representative of the practice in regard to stability.

## Future Developments

In concluding this "First Report on Power System Stability," it is natural to turn from consideration of the

## Regarding Stability Studies

| | New Jersey Interconnection | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Pennsylvania Power & Light Co. | Philadelphia Electric Co. | | Niagara-Hudson Power Corporation | | | New England Power Service Company | Hydro-Electric Power Comm. of Ontario | The Shawinigan Water & Power Co. | |
| | Item II Siegfried-Roseland | Item III New Hope-Plymouth Mtg. | Item IV Towamencin-Plymouth Mtg. | Item I Pleasant Valley-Dunwoodie | Item II Inghams-Rotterdam | Item III Buffalo-Lockport | Item I Comerford-Tewksbury | Item I Ottawa River-Toronto | Item I Ile Maligne-Quebec | |
| A | | | | | | | | | | |
| 1 | 220 | 220 | 220 | 132 | 110 | 110 | 230 | 220 | 187 | |
| 2 | 37.9 | 29.6 | 9.9 | 62.5 | 47 | 21 | 126 | 200 | 136 | |
| 3 | 60 | 60 | 60 | 60 | 60 | 60 | 60 | 25 | 60 | |
| 4 | 185,000 | 40,000 | 65,000 | 160,000 | 130,000 | 120,000 | 156,000 | 200,000 | 160,000 | |
| B | | | | | | | | | | |
| 1 | 1 | 1 | 1 | 2 | 2 | 2 | 2 | 3 | 2 | |
| 2 | 1 | None | None | 1 | None | None | 1 | None | None | |
| 3 | None | None | None | 20,000 | None | None | None | None | None | |
| 4 | None | None | None | None | None | None | None | None | 30,000 | |
| 5 | | | | | | | | | | |
| a | None | None | None | H. T. | H. T. | H. T. | H. T. | H. T. | L. T. | |
| b | None | None | None | H. T. | H. T. | L. T. | H. T. | H. T. | H. T. | |
| 6 | | | | | | | | | | |
| a | Solid | | | Solid | Solid | Solid | 30-ohm resistor | Solid | Solid | |
| b | Solid | Solid | Solid | Solid | Solid | Solid | 30-ohm reactor | Solid | Solid | |
| C | | | | | | | | | | |
| 1 | | | | On P. V. 1,388,000; On Ingh. 979,000; On Bflo. 225,000; On Dun. 1,900,000; On Rott. 2,300,000; On Lock. 3,060,000 | | | 4 units, each 39,000 | Each 23,500 to 28,500 | 11 units, each 30,000 | |
| 2 | | | | | | | 81 | 1.25 | 90 | |
| E | | | | | | | | | | |
| 1 | 10 | 8 | 8–12 | 8 | 8 | 8 | 8 | 3.5–4 (Some—8–10) | 10–12 | |
| 2 | Phase: Distance g'nd: instantaneous overcurrent | Phase: hi-speed imp. directional relay g'nd: directional overcurrent | (Same as item III) | Simultaneous with carrier current | Overcurrent with instantaneous & differential | Differential current & distance | Sequential with balanced current & distance | Sequential with impedance distance | Parallel line protection with a directional impedance standby | |
| 3 | 11–25 | Phase: 9–60 Gnd: 9–18 or 50–60 | Phase: 9–75 G'nd: 9–35 or 70–90 | 12 | 10 | 12 | 9–11 | 5–5½ (Some—20) | 12 up | |
| F | | | | | | | | | | |
| 1 | Steel | Steel | Steel | Steel | Steel | Steel | Steel | Steel | Steel | |
| 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | |
| 3 | None | None | None | None | None | None | None | None | Part continuous type & part 250' on each side of tower | |
| 4 | Susp: 14 or 16 5¾" units Deadend: 18-same | Susp: 16–5¾" units Deadend: 18-same | (Same as item III) | Susp: 12 units Deadend: 13 units | Susp: 8 units Deadend: 9 units | Susp: 7 units Deadend: 9 units | Susp: 15–5¾" units Deadend: 17-same | Susp: 18–5" units Deadend: 18-same | Susp: 10 units Deadend: 12 units | |
| 5 | None | Yes | Yes | Yes | Yes | Yes | Yes | Receiving end | No | |

past practices and the present status and to contemplate the future. Probably the best forecast of the future can be made from an examination of the problems which are receiving active consideration at the present time. These problems include the development of faster breakers and relays, particularly of relays to meet the wide range of system conditions to be encountered. Flashover-prevention and arc-suppression measures are receiving a great deal of attention, particularly from the standpoint of the application of ground wires and lower tower-footing resistance on high-voltage lines, and flashover protector tubes for intermediate-voltage lines. Further study is being given to the reactances of synchronous machines, particularly as to the proper equivalent value to be used in stability studies. Reclosing breakers are receiving favorable consideration but much remains to be done to determine the extent of their proper field of application. The interconnection of individual power systems, each

with automatic frequency control for time-keeping purposes, has introduced problems which are receiving active consideration. Stability limits of particular systems are being examined from the standpoint of providing better instruction for the guidance of system operators during unusual or emergency circuit conditions.

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This is arranged in 2 parts. Part I is intended to give a substantially complete list of references to stability papers available in English, and part II gives a highly selected list of references to papers dealing with the solution of network problems which are inevitable in stability calculations. Foreign references have not been included because of their unavailability to the AIEE membership generally and also because of lack of space.

The arrangement of the bibliography contains some features requiring additional comment. The references are arranged in chronological order by years. However, within each year the papers are arranged alphabetically according to the authors' names. The arrangement has been selected for facilitating the search for a particular article, whether by author's name, title, or time of publication. In addition the character of papers is indicated from the standpoint of their present interest by means of the following symbols:

*H*—Historical interest
*A*—Analysis including methods of calculation
*M*—Discussion of measures for improving stability
*T*—Stability tests in the laboratory or in the field
*O*—Operating experience including means employed on specific projects
*P*—Physical explanation of stability phenomena
*R*—General review of stability problem

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## Part II—Selected References on Network Solutions

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# News

## Of Institute and Related Activities

### A Feature of the AIEE 1937 Summer Convention

Opportunity to inspect the new Port Washington power plant of The Milwaukee Electric Railway and Light Company will be among the high spots of the AIEE summer convention, to be held in Milwaukee, Wis., June 21–25, 1937. Convention headquarters will be in the Schroeder Hotel.

Since placed in regular service December 1, 1935, this modern steam-electric generating station has achieved new world records for economy in operation. Latest available figures, for the first 10 months of operation, show an average coal consumption of 11,094 Btu per kilowatt-hour of station output. International recognition was given this plant recently when it was visited by 73 delegates, representing 15 foreign nations, to the Third World Power Conference (held in Washington, D. C., September 7–12, 1936).

The plant is designed on the unit plan, with a single boiler for each turbo-generator; also one set of transformers, one 132-kv transmission line and one set of auxiliaries for each unit. The present installation of 80,000 kw capacity is the first of a probable ultimate capacity of 400,000 kw in 5 units. Throttle pressure is 1,230 pounds per square inch, and steam temperature at both throttle and reheat point 825 degrees Fahrenheit. Generator voltage is 22 kv.

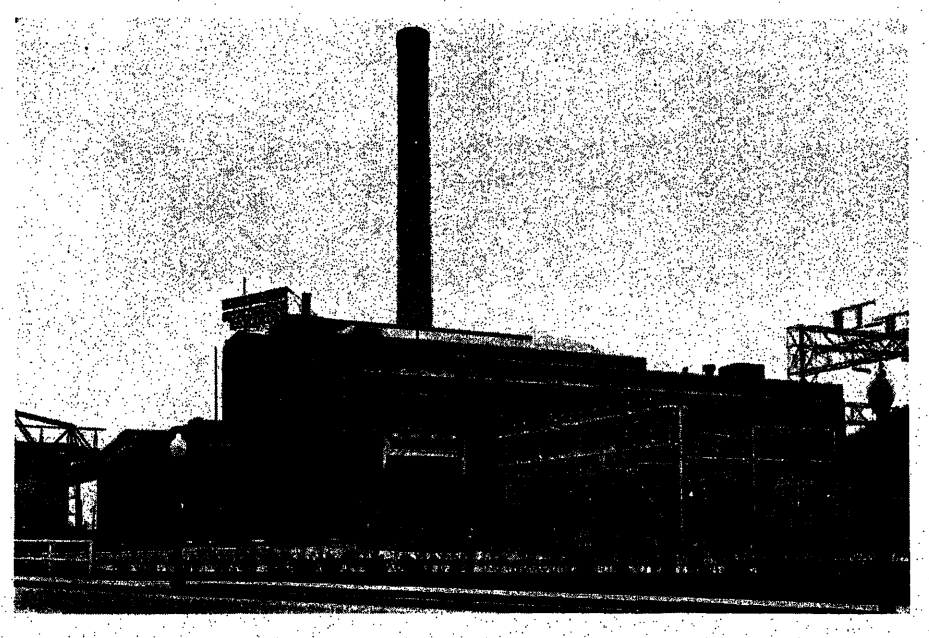
The convention transportation committee is making plans for transporting AIEE delegates to the plant, which is located at Port Washington on the shore of Lake Michigan about 28 miles north of Milwaukee.

The personnel of the 1937 summer convention committee is as follows: Otto H. Falk, *honorary chairman;* K. L. Hansen, *chairman;* L. H. Hill, *vice-chairman;* C. H. Krueger, *secretary;* W. E. Crawford, *treasurer;* R. R. Benedict, A. G. Dewars, C. F. Harding, H. S. Osborne, G. G. Post, J. A. Potts, D. L. Smith, and W. H. Timbie. Subcommittee chairmen: J. F. H. Douglas, technical program; E. W. Seeger, finance; L. W. Copeland, entertainment; C. D. Brown, transportation; W. O. Helwig, registration and housing; W. E. Gundlach, publicity; G. F. Crowell, sports; S. H. Mortensen, inspection trips, and Mrs. A. C. Flory, ladies.

### Washington Award for 1937 Announced

Doctor Frederick Gardener Cottrell, Washington, D. C., who perfected the process by which the cost of helium gas was reduced from $1,700 to 10 cents per cubic foot, has been chosen to receive the Washington Award for 1937 "for his social vision in dedicating to the perpetuation of research the rewards of his achievements in science and engineering." A bronze plaque set in marble, the tangible symbol of the award, will be presented to Doctor Cottrell on February 23. Doctor Cottrell is president of Research Associates, Inc., and is widely known as a chemist and metallurgist, a former director of the United States Bureau of Mines, and director of the fixed nitrogen laboratory of the United States Department of Agriculture. Besides his achievements in the cheap production of helium, he is famous for his work in nitrogen fixation, for his processes of cleansing gases of dust and dirt by electrical precipitation, and for research in petroleum technology.

Doctor Cottrell is the fourteenth noted American engineer to receive this coveted award since it was founded in 1916 by John Watson Alvord of Chicago. The award is administered by the Western Society of Engineers in co-operation with the American Society of Civil Engineers, the American Institute of Mining and Metallurgical Engineers, The American Society of Mechanical Engineers, and the AIEE. The award is made annually—providing the members of the commission agree on a deserving candidate—as an honor conferred on a brother engineer by his fellows for accomplishments which pre-eminently promote the happiness, comfort, and well-being of humanity. There have been several years when no award was made.



**Port Washington plant of Milwaukee (Wis.) Electric Railway and Light Company**

### Winter Convention to Be Reported in March Issue

As this issue goes to press, the Institute's 1937 winter convention is under way at New York. Marking the resumption of a 5-day winter convention schedule, the meeting has all appearances of being a highly successful affair. First day's registration was 470, compared with 602 in 1936, 633 in 1935, and 433 in 1934. On the second day 357 registered, compared with 444 in 1936, 301 in 1935, and 433 in 1934.

A complete report of the convention and its various features is scheduled for inclusion in the March issue.

### Columbia University Offers E.E. Scholarship

The governing bodies of Columbia University have placed at the disposal of the AIEE each year a scholarship in electrical engineering in the school of engineering of Columbia University for each class. The scholarship pays the annual tuition fees of $380. Reappointment of the student to the scholarship for the completion of his course is conditioned upon the maintenance of a good standing in his work.

To be eligible for the scholarship, the candidate recommended will have to meet the regular admission requirements in,

regard to which full information will be sent without charge upon application to the secretary of the University or to the national secretary of the Institute.

In a letter addressed to the national secretary of the Institute, an applicant for this scholarship should set forth his qualifications (age, place of birth, education, reference to any other activities, such as athletics or working way through college, references, and photograph). A committee composed of W. I. Slichter, *chairman*, Francis Blossom, and H. C. Carpenter will consider the applications and will notify the authorities of Columbia University of their selection of a candidate. The last day for filing of applications for the year 1937–38 will be June 1, 1937.

The course at the Columbia school of engineering is a graduate course which may be either elective leading to the degree of master of science or prescribed leading to the degree of electrical engineer. For the former, requirement for admission is the completion of 4-year course in electrical engineering as evidenced by a bachelor's degree from an approved institution. For the professional degree, the requirements are more specific as to course content and include a considerable proficiency in mathematics, physics, and chemistry, and some knowledge of the humanities, as well as the usual undergraduate technical courses. The candidate is admitted on the basis of his previous collegiate record without undergoing special examinations. Other qualifications being equal, members of the student Branches of the AIEE will be given preference.

The purpose of this advanced course is to produce a high type of engineer, trained in the humanities as well as in the fundamentals of his profession. It is hoped that Enrolled Students and others qualified will show a keen interest in this scholarship.

## Who's Who in Engineering

That all qualified engineers will be included in the fourth (1937) edition of "Who's Who in Engineering," is the expressed hope of those participating in the preparation of that volume. First issued in 1922–23, reissued in 1925 and 1931, "Who's Who in Engineering" has made a place for itself as a reference and record volume. Its principal failing has been that many qualified engineers have not been included, a deficiency that apparently came about through the failure of individuals to return questionnaires with the data required for the preparation of entries. Through the active co-operation of American Engineering Council, it is now hoped that this earlier deficiency can be overcome, although the final answer still rests with individuals.

Questionnaires were mailed some weeks ago "to every engineer for whom a permanent address [was] available, so that none may be missed." Chairman Potter of AEC's committee urges Institute members to co-operate by promptly filling and returning these questionnaires. It is pointed out that "space in the volume cannot be purchased," and that there is no obligation.

## Electronic Tube Nomenclature Being Studied

| Generic Term | Output Energy | Character of Space | Control Means | Type Cathode | Names | Definition |
|---|---|---|---|---|---|---|
| *Electronic Tubes (or Tanks) | Electrical | High-Vacuum | None | Thermionic | Kenotron | A high-vacuum thermionic tube in which no means is provided for controlling the unidirectional current flow |
| | | | | Photoelectric | Phototube | A vacuum tube in which electron emission is produced directly by radiation falling upon an electrode. A high-vacuum phototube is one that is evacuated to such a degree that its electrical characteristics are essentially unaffected by gaseous ionization |
| | | | Electrostatic | Thermionic | Pliotron | A high-vacuum thermionic tube in which one or more electrodes are employed to control the unidirectional current flow |
| | | | Electromagnetic | Thermionic | Magnetron | A high-vacuum thermionic tube in which a magnetic field is employed to control the unidirectional current flow |
| | | Gas-Filled | None | Thermionic | Phanotron | A hot-cathode gas-discharge tube in which no means is provided for controlling the unidirectional current flow |
| | | | | Cold | Glow Tube | A cold-cathode gas-discharge tube in which no means is provided for controlling the unidirectional current flow |
| | | | | Pool | Pool Tube (or Tank) | A gas-discharge tube (or tank) with a pool-type cathode (liquid or solid) in which no means is provided for controlling the unidirectional current flow |
| | | | | Photoelectric | Phototube | See phototube definition under "high-vacuum tubes." A gas phototube is one into which a quantity of gas has been introduced, usually for the purpose of increasing its sensitivity |
| | | | Electrostatic Electrode | Thermionic | Thyratron | A hot-cathode gas-discharge tube in which one or more electrodes are employed to control electrostatically the starting of the unidirectional current flow |
| | | | | Cold | Grid-Glow Tube | A cold-cathode gas-discharge tube in which one or more electrodes are employed to control electrostatically the starting of the unidirectional current flow |
| | | | | Pool | Grid-Pool Tube (or Tank) | A gas-discharge tube (or tank) with a pool-type cathode (liquid or solid) in which one or more electrodes are provided for controlling electrostatically the starting of the unidirectional current flow |
| | | | Ignition Electrode | Pool | Ignitron | A gas-discharge tube (or tank) with a pool-type cathode (liquid or solid) in which an ignition electrode is employed to control the starting of the unidirectional current flow in each operative cycle |
| | | | Electromagnetic | | | (Not used at present) |
| | Light | | | | | |
| | Ultraviolet | | | | | |
| | X-Ray | | | | | |
| | Cathode-Ray | | | | | |

* "Electronic Tube" is a generic term, applied to various designs of tubes (or tanks) consisting of 2 or more elements in a container, usually of glass, and having a high vacuum or filled with gas at reduced pressure.

AN important preliminary step toward alleviation of the chaotic situation that has prevailed in connection with the multifarious names of electronic tubes has been achieved, according to recent advices from the American Standards Association, of which the Institute is an active member-body. As a tentative basis for the simplification of tube nomenclature, both the General Electric and the Westinghouse Electric & Manufacturing companies have agreed to abandon any trademark rights either company had in the several names indicated in the accompanying tabulation, "in the hope that this agreement will pave the way for the adoption of these names as American standards." It is recognized that this is but an initial step, and that its principal significance is in connection with the names of tubes now commonly used for industrial purposes. As a forward step, however, this list of names is hailed with satisfaction in many quarters, and, until something better becomes available, has been adopted for use in ELECTRICAL ENGINEERING. Comments are invited.

## Committee on Broadening of Institute Activities

To meet the insistent and repeated demand for a broadening of the Institute's activities to cover discussions of social and economic subjects having engineering aspects, the AIEE executive committee, at its meeting of December 10, 1936, authorized the appointment of a special committee on broadening of Institute activities. The committee appointed consists of the following:

H. S. OSBORNE, *chairman* (chairman, technical program committee)

T. F. BARTON (chairman, committee on legislation affecting the engineering profession)

H. V. CARPENTER (chairman, committee on code of principles of professional conduct)

L. W. W. MORROW (chairman, committee on coordination of Institute activities)

R. W. SORENSEN (chairman, committee on economic status of the engineer)

I. M. STEIN (chairman, publication committee)

W. H. TIMBIE (chairman, Sections committee)

J. B. WHITEHEAD (chairman, committee on Institute policy)

Circumstances leading up to this action are outlined briefly in the following extract from the minutes of the executive committee:

"Further consideration was given to the subject of broadening Institute activities to cover discussions of social and economic subjects that have engineering aspects. At its October meeting, the board of directors passed a motion concurring in the suggestion that such topics are of general interest to electrical engineers, calling attention to 'the fact that the Institute has always offered facilities and organization for discussion of such questions,' and suggesting that papers on these subjects be submitted to the proper committees of the Institue for consideration for national presentation and publication.

"President MacCutcheon reported the impressions which he received when visiting Sections in the West and Middle West, and analyzed the attitude of the Institute membership as follows: Approximately 80 per cent of Institute members are in favor of a judicious broadening of Institute activities, but 60 per cent are strongly opposed to undertaking anything that would not be in the interest of the Institute, and about 20 per cent of them are inclined to go so far as to be in danger of damaging the profession and the Institute. He met with the executive committee of the Chicago Section and explained to them the board's attitude toward the suggestions of the group of Chicago members concerning the broadening of Institute activities. So far as Institute publications are concerned, it appeared that unquestionably 90 per cent of the members with whom he came in contact thoroughly agreed that they do not want to see any of the necessary technical material omitted, but they also desire something more; and that, Mr. MacCutcheon pointed out, will be taken care of by the appropriation in the budget for 100 additional pages in ELECTRICAL ENGINEERING. He then referred to his efforts to secure papers on subjects of general interest from certain prominent men, and suggested the desirability of each member of the board making a similar effort, so that in 2 or 3 months such papers will be coming in.

"Then followed a discussion on the best procedure for handling the papers on social and economic subjects which may be submitted, or for procuring such papers. It was pointed out that in the Institute organization there are the technical committees to make sure that papers on technical subjects are forthcoming, but that there is no one who has particular jurisdiction over the papers on economics, administration, etc., which the membership seems to want. The desirability of setting up a particular committee for this purpose was discussed. The

## Future AIEE Meetings

**North Eastern District Meeting**
Buffalo, N. Y., May 5–7, 1937

**Summer Convention**
Milwaukee, Wis., June 21–25, 1937

**Pacific Coast Convention**
Spokane, Wash., Date to be determined

**Middle Eastern District Meeting**
Akron, Ohio, Fall 1937

## Westinghouse Commemoration at ASME Convention



THE ninetieth anniversary of the birthday of George Westinghouse was commemorated December 1, 1936, during the 57th annual meeting of The American Society of Mechanical Engineers, by a special 2-session program which consisted of an afternoon session at which former friends and associates of Mr. Westinghouse brought personal testimony of his engineering achievements, and an evening session at which formal addresses were delivered. The group on the platform during the afternoon session is shown above; they are, standing, left to right: J. F. Miller, vice-chairman of the Westinghouse Air Brake Company, Pittsburgh, Pa.; N. W. Storer (A'95, F'13, member for life) retired consulting railway engineer of Westinghouse Electric & Manufacturing Company, East Pittsburgh, Pa.; Thomas Campbell, veteran employee of the Westinghouse Air Brake Company; Francis Hodgkinson (A'02) consulting mechanical engineer and former turbine expert for the Westinghouse company, New York, N. Y.; A. W. Berresford (A'94, F'14, member for life, past-president) New York, N. Y.; C. R. Beardsley (A'08, F'30) superintendent of distribution of the Brooklyn (N. Y.) Edison Company; Roy V. Wright, editor of *Railway Age*, New York, N. Y.; and Charles F. Scott (A'92, F'25, HM'29, member for life, past-president) professor of electrical engineering emeritus of Yale University, New Haven, Conn.; seated, left to right: L. B. Stillwell (A'92, F'12, member for life, past-president) consulting engineer, Princeton, N. J.; W. W. Nichols, assistant to the chairman, Allis-Chalmers Manufacturing Company, New York, N. Y.; Frank W. Smith (A'05, M'12) president of the Consolidated Edison Company, New York, N. Y.; E. R. Hill (A'99, F'12, member for life) consulting engineer, Gibbs and Hill, New York, N. Y.; J. V. B. Duer (A'15, F'29) chief electrical engineer of the Pennsylvania Railroad Company, Philadelphia; and Samuel Vauclain, chairman of the board of the Baldwin Locomotive Works, Philadelphia. W. L. Batt and Ralph Budd also took part in the ceremonies.

## Membership—

Mr. Institute Member:

Without your assistance your membership committee is definitely handicapped. Examine the roster of electrically interested individuals in your acquaintance and forward the names of men you would choose as Institute members, who are not now members, to the chairman of your Section membership committee. Personally obligate yourself to secure one new member for the Institute—YOUR INSTITUTE—your professional organization.

James M. Dodds

Vice-Chairman, District No. 4
National Membership Committee

suggestion was made that the matter should be handled in a positive, rather than a negative, manner, by recognizing the demand on the part of the membership for the type of papers under discussion and taking the initiative in procuring such papers from the proper sources, so that dependence need not be placed entirely upon papers that originate spontaneously. The thought was expressed that diplomatic situations may arise unless there is some centralized specifying authority to investigate the possibilities before seeking a paper, and that a man who is approached to write a paper should be given the specifications for such paper.

"VOTED that a special committee on broadening of Institute activities be appointed, consisting of the chairman of the technical program committee as chairman, and the chairmen of the committees on code of principles of professional conduct, co-ordination of Institute activities, economic status of the engineer, Institute policy, legislation affecting the engineering profession, publication, and Sections."

**Johns Hopkins Engineers to Mark 25th Anniversary.** The school of engineering of The Johns Hopkins University, Baltimore, Md., will celebrate during the latter part of February 1937, the 25th anniversary of its founding. Plans include an "engineering show" that will involve displays of engineering equipment and principles, and from various sources exhibits are being gathered. At the "commemoration day" exercises to be held February 22, Dr. Karl Taylor Compton (F'31) president of the Massachusetts Institute of Technology is scheduled to deliver the principal address. During the exercises, honorary degrees will be conferred upon a small group of prominent engineers.

**Arc-Welding Foundation Established.** In order to stimulate scientific development, the Lincoln Electric Company has completed plans for establishing a fund and foundation to encourage study and research for the benefit of the industry. The fund has been named "The James F. Lincoln Arc Welding Foundation" in honor of the president of the company. Principal direction of the work of the foundation will be given by Doctor E. E. Dreese (M'25) chairman of the electrical engineering department of Ohio State University. Commenting on the action, Mr. Lincoln (A'08, M'20) stated

". . . . The sole purpose of this new foundation is to challenge the attention of manufacturers whose products benefit society; and to stimulate the ingenuity of every engineer and skilled worker interested in extending the frontiers of knowledge and achievement."

## AIEE Members Among "12 Greatest Inventors"

Three deceased members of the AIEE were named among those chosen recently as America's "12 greatest inventors for the past century." The list of names was presented dramatically during a dinner held in Washington, D. C., to celebrate the 100th anniversary of the institution of the United States Patent Office. Those honored and their principal achievements were:

ALEXANDER GRAHAM BELL (A'84, M'84, deceased August 2, 1922) the telephone

THOMAS ALVA EDISON (A'84, M'84, HM'29, deceased October 18, 1931) the electric light and the phonograph

ROBERT FULTON, the first commercial steamboat

CHARLES GOODYEAR, the vulcanization process for rubber

CHARLES MARTIN HALL, aluminum manufacture

ELIAS HOWE, the first practical sewing machine

CYRUS HALL MCCORMICK, the first practical reaper

OTTMAR MERGENTHALER, the linotype

SAMUEL F. B. MORSE, the electric telegraph

GEORGE WESTINGHOUSE (A'02, deceased March 12, 1914) the air brake

ELI WHITNEY, the cotton gin

WILBUR WRIGHT, the airplane

# American Engineering Council

## Seventeenth Annual Meeting Held in Washington, D. C.

THE AIEE was represented at the seventeenth annual assembly of American Engineering Council in Washington, D. C., January 14 to 16, 1937, by its 5 delegates, President A. M. MacCutcheon, William McClellan, C. O. Bickelhaupt, C. E. Stephens, and National Secretary H. H. Henline. Many other Institute members were present at the several sessions either as members of committees, representatives of local clubs, or speakers, among which were included F. J. Chesterman, general chairman of the public affairs committee of AEC: Thomas R. Tate, chief of the power resources division of the Federal Power Commission and secretary of the AIEE Washington Section; and Harry W. Osgood, chairman of the Washington Section and member of the engineers dinner committee. Representatives of the 48 national, state, and local societies which comprise the Council were present. A report of the AEC meeting and the seventh conference of engineering society secretaries, as furnished by Frederick M. Feiker, executive secretary follows:

A session on programs of united action for member societies opened the conference of secretaries of engineering societies on the morning of January 14, O. L. Angevine, secretary of the Rochester (N. Y.) Engineers' Club presiding as chairman of the conference. Among the many discussions were those by A. A. Potter, president AEC, who spoke on intersociety co-operation, Watson Davis, of Science Service, whose subject was publicity, and F. J. Chesterman, who talked about public affairs. The conference continued throughout the afternoon with discussions on the co-ordination of programs and meeting dates, the Third World Power Conference, and various programs local societies had found to be successful.

That afternoon was also the occasion for meeting in informal round-table discussion of the AEC divisional committees. With F. M. Feiker, executive secretary, AEC, presiding, A. A. Potter, president, AEC, opened the discussion on operating commit-

tees. The session was devoted to a preliminary discussion of reports of AEC committees that were presented on January 15. Secretary and Mrs. Feiker entertained the delegates at a reception and tea at their home at the close of the session.

At a symposium on public affairs held on Thursday evening, F. J. Chesterman, chairman, several important questions engaging the attention of the administration and the nation were discussed, such as social security, old age and unemployment compensation, industrial co-operation with and without government supervision, conservation of natural resources, national, state, and local public works activities and rural electrification. The speaker on social security was Arthur J. Altmeyers, of the Social Security Board. Colonel E. W. Clark, executive assistant, Public Works Administration, in his address, made a plea for greater social-mindedness in engineers. In his discussion of natural resources, Thomas R. Tate, chief, power resources division, Federal Power Commission, displayed numerous large-scale maps of power systems in the United States, including one showing the geographical regions into which it is proposed to divide the nation for purposes of power production and distribution.

### Reports of Committees

At the business session on Friday morning, A. A. Potter presiding, a roll call of representatives was followed by the president's address, and reports of the executive secretary, treasurer, and numerous operating committees.

President Potter spoke briefly on the efforts Council had made during the year to encourage the activities of the committees and to co-ordinate the work of engineering societies. He spoke of the need for more factual data on the impart of technology on social security and urged the active support of Council in efforts to assist in their determination and dissemination, in the hope that the public more generally may come to regard engineering and the engineer in their true economic and social significance.

Mr. Feiker read a report which covered the varied and important work of Council and its numerous committees. Unfortunately, limitations of space forbid even a summary of Mr. Feiker's report, but plans are under consideration to bring Council's activities before the readers of Electrical Engineering in later issues.

The report of the treasurer showed successful operation of Council's financial affairs within the income received and a balance of approximately $2,000 to carry over into 1937. A budget of estimated expenditures for 1937, amounting to $39,431 was adopted. Reports were presented on publicity, membership and representation, regional activities, finance, constitution and by-laws, and nominations.

Abel Wolman, chairman of the water resources committee, addressed the assembly luncheon on the engineer's opportunities and responsibilities in the conservation of natural resources.

Mr. Wolman's excellently delivered address reviewed the steps by which, from the pressure of PWA activities, and the work of the Mississippi Valley committee and the water planning board the water resources committee was evolved. He described briefly some of the more important principles of action of the water resources committee. One was the development of coordinated national water plans. Another was that national water development concerned people primarily, rather than merely water. It was necessary, he said, to effect a centralization of points of view on a river basin as a whole in order to obtain a necessary perspective. He then described briefly some specific undertakings of the committee and the work of several subcommittees that experience had shown that it was necessary to organize.

Following the luncheon, reports of numerous public-affairs committees of AEC were presented. F. J. Chesterman presided.

Although it is impossible to summarize the numerous reports presented, it may be stated that extensive discussions followed the presentation of the reports on patents, R. S. McBride, chairman; public works, Alonzo J. Hammond, chairman; rural electrification, L. F. Livingston, chairman; conservation and utilization, Leonard J. Fletcher, chairman, and surveys and maps, John S. Dodds, chairman. These reports were accepted and referred to the executive committee for action.

Morris L. Cooke, administrator, Rural Electrification Administration, spoke on the achievements of the REA which he characterized as "rural electrification in spite of the experts." His 3 levels of interest in the work, were, he said, (1) that of "gadgets," the electrical devices themselves, (2) that of the "cultural renaissance for agriculture," and (3) national survival as threatened by unwise use of soil and water.

### "All Engineers' Dinner"

As usual, the high point of the AEC annual assembly was the "all engineers' dinner," held on the night of January 15 with about 450 in attendance and President A. A. Potter presiding. A reception preceded the dinner. A feature of the dinner program was the presentation of honorary membership of the ASME to Admiral Cone, retired, of the United States Navy.

Acting as toastmaster was Colonel D. H. Sawyer, director, Federal Employment Stabilization Board, who introduced Messrs. Angevine, Bickelhaupt, MacCutcheon, Mead, Coleman, Feiker, and Blasinghame and spoke on the construction during the depression.

Admiral Cone was presented by M. X. Wilberding, chairman of the ASME Washington section. In introducing Admiral Cone, Mr. Wilberding spoke briefly of his naval career.

In responding to the speech of presentation by J. H. Herron, president of the ASME, Admiral Cone expressed his appreciation of the honor done him, and said that he would maintain the high standards set by those distinguished engineers who had previously been elected to honorary membership in the ASME.

The principal addresses at the dinner were by Rear-Admiral Harold J. Bowen, engineer-in-chief of the United States Navy, who spoke on national defense, by Hon. J. C. O'Mahoney, senator from the State of Wyoming, on the interstate regulation of business by federal license, and by C. F. Hirshfeld, whose subject was the engineer's responsibilities in social and economic questions. Because of Mr. Hirshfeld's illness his address was read by R. L. Sackett.

Admiral Bowen said that a modern navy is highly mechanized and depends on the engineer for maintenance, and called attention to the diversity and extent of the vessels, aircraft, shore establishments, and communication systems of which it is comprised. He gave many examples of the stimulation to naval engineering coming from industry, as well as that received by industry from the Navy. In closing he asserted that naval defense is a struggle between applied science as utilized by the combatants and that a navy cannot rise above the level of the engineering development of the nation to which it belongs.

In his penetrating and carefully reasoned address Mr. Hirshfeld urged the engineer to enlarge the sphere of his influence by accepting a larger measure of responsibility in solving social and economic problems resulting from the impacts of applied science. He made a plea for a factual study of such grave questions as technological unemployment, relative returns to capital and labor of the fruits of industry, and competition. As examples of public questions in which engineers might interest themselves in their own communities as a public service he mentioned traffic regulation, air pollution, noise abatement, and public transportation. He closed by asking whether or not the engineer would have the fortitude to serve humanity in the future in the same grand manner in which he had served it on technological matters in the past.

Senator O'Mahoney gave numerous examples of corporation created under the laws of a single state which do business in several or all states and in world trade, and argued that there exists a need for the regulation of interstate business by means of federal licenses. He explained some of the principal features of a bill before the Congress introduced by him as a device for the regulation he proposed.

### Session on Engineering Economics

Continuing its meeting on Saturday morning with a session on engineering economics, the assembly listened to further reports. Mr. Chesterman made a plea for engineers to take a broader view of their profession in line with the thoughts expressed in Mr. Hirshfeld's address at the dinner, and had a discussion on effective publicity on engineers and their work.

C. E. Stephens reported for several of the united action committees; and a resolution was passed in favor of an extension of the merit system.

In presenting a report of the engineering economics committees Ralph E. Flanders reviewed the status of the third progress report of the committee on consumption, economics, and distribution. For the committee on special surveys and studies he made the proposal, which was referred to the executive committee by vote of the assembly, that Council bring about co-operation between its engineering economics committees and social-science groups.

J. Frederic Dewhurst, of the committee on social security of the Social Science Research Council, spoke briefly on social science and engineering. The engineering profession, he said, was in a position to make a con-

tribution to the preventive side of social security.

Officers elected at the assembly meeting were, for vice-presidents C. O. Bickelhaupt, and John S. Dodds, representing the state and local member organizations. C. E. Stephens was elected treasurer. In all cases these were re-elections. The term of president is for 2 years, and as Dean Potter has served but one, he will continue in that office for 1937. Representatives and alternates to the assembly were also elected from the 6 geographical districts into which AEC membership organizations are divided. F. M. Feiker was re-elected executive secretary. Chairmen of committees selected were William McClellan, finance; C. O. Bickelhaupt, membership and representation; and F. J. Chesterman, public affairs.

# Letters to the Editor

CONTRIBUTIONS to these columns are invited from Institute members and subscribers. They should be concise and may deal with technical papers, articles published in previous issues, or other subjects of some general interest and professional importance. ELECTRICAL ENGINEERING will endeavor to publish as many letters as possible, but of necessity reserves the right to publish them in whole or in part, or reject them entirely.

ALL letters submitted for consideration should be the original typewritten copy, double spaced. Any illustrations submitted should be in duplicate, one copy to be an inked drawing but without lettering, and other to be lettered. Captions should be furnished for all illustrations.

STATEMENTS in these letters are expressly understood to be made by the writers; publication here in no wise constitutes endorsement or recognition by the American Institute of Electrical Engineers.

## An Analysis of Electrical Engineering Graduates

*To the Editor:*

In the article, "An Analysis of Electrical Engineering Graduates," which appeared on pages 952-3 of the September issue of ELECTRICAL ENGINEERING, Brown University, at Providence, R. I., unfortunately was omitted from the list of American colleges offering a 4-year course in electrical engineering, leading to a degree of bachelor of science in electrical engineering or its equivalent. Since the publication of that article, information from Duke University, Durham, N. C., also has been made available.

Students at Brown who specialize in electrical engineering receive the degree of bachelor of science in engineering on completion of the 4-year course. Following are the numbers of graduates who specialized in electrical engineering at Brown during the period of the survey: 1927-28—14; 1928-29—13; 1929-30—11; 1930-31—6; 1931-32—5; 1932-33—12; 1933-34—11; 1934-35—9.

Duke University, which offers a 4-year course leading to the degree of bachelor of science in electrical engineering, graduated the following numbers of electrical engineers: 1927-28—2; 1928-29—6; 1929-30—3; 1930-31—5; 1931-32—4; 1932-33—10; 1933-34—13; 1934-35—11.

Very truly yours,

CLIFFORD A. FAUST (A'35)
President, National Executive Council, Eta Kappa Nu Association; In Charge of Power Utility Division of Advertising, Ohio Brass Company, Mansfield

## Preparation of Institute Papers

*To the Editor:*

We note your interest in readers' comments on the new paper and format of ELECTRICAL ENGINEERING. The new page is indeed pleasing and easier to read. We regret, however, that you are now breaking up the continuity of articles in the usual magazine fashion. The continuation of articles on back pages, fostered by editors chiefly in order to take the reader into the advertising columns of ordinary magazines, is a nuisance which is probably unnecessary in a publication of this type.

At various times instructions are issued regarding the methods of preparing papers for the Institute. We feel that a few comments might be pertinent at this time.

It might be presumed that Institute papers, while of greater interest to the specialist in whose field they are written, are also to be read by many with a normal curiosity and the desire to keep informed in related subjects, even though the mathematics may be unfamiliar. Papers might better be written with the idea more clearly in mind that the reader knows less about the subject than the writer, and that the time and effort of the former are to be conserved as much as possible. Several suggestions can be made as an aid to easier reading.

Even though the aim of the paper might be well presented in the introduction, the reader can follow the processes much more readily if the aim of each step in the development of the paper is presented in a brief statement. This, combined with shorter paragraphs and more frequent subtitles, is a great aid to rapid scanning and easier grasp.

The reader who expects to make use of the material presented, would be aided if more careful attention were given to the following considerations:

1. More adequate definition of symbols and terms used. If they are obscure, a brief background or more complete references would be useful. (Many symbols are not adequately defined by the title, as for instance, "synchronous reactance.") Understanding of differential equations is frequently aided by identifying the type to which they belong with a brief statement of the manner of solution.

2. "Word derivations" of equations are helpful. Lack of space may frequently make complete mathematical development inadvisable. Yet if the equation is important to the material at hand, the primary assumptions on which it is based and an outline of the steps followed could be given in a brief paragraph. Such explanations are especially necessary if simplifying assumptions have been made in the development.

3. Time and wasted effort could be saved the reader if more care were taken to indicate (when known) the limitations of various data. This is especially true when the exact process of obtaining data is not given and the user has small opportunity of determining the inherent limitations.

4. Many Institute papers would be greatly improved if the author kept more firmly in mind that he must avoid the slightest suspicion of aiming at a display of his own erudition rather than to present the reader with interesting and useful information.

Several years ago Professor Karapetoff made the prediction that the time would come when electrical engineers would concern themselves more with the fundamental nature of classical vector theory. Papers presented before the Institute for the past year indicate that this prediction was justified.

In view of the present growth of such application and its probable continuation, it might be well through adequate definition, to avoid the confusion which may readily arise. Classification of a term as a *vector* may no longer be an identification at all, when one considers that the writer may have in mind the complex number vector, those of classical vector analysis, those based on the work of Hamilton, of Gibbs-Wilson, or the more modern concepts and variations of them associated with certain forms of tensor analysis, the complex vector of A. Pen-Tung Sah, etc.

It would be well to remember that experiments (and this might hold for mathematical developments as well) are accepted by science only if they are susceptible to reproduction. Hence, while one may have no reason to doubt that a writer has obtained the results or made the analyses he claims, nevertheless, through inadequate definition of symbols, unannounced assumptions in his derivations, and a presentation not aimed to be of maximum value to the reader, the latter may frequently be unable to reproduce the work presented. Such reproduction is necessary to progressive growth and development of a science.

Very truly yours,

A. F. PUCHSTEIN (A'20, M'27)
Chief Engineer

T. C. LLOYD (A'31)
Development Engineer
Robbins & Myers, Inc., Springfield, Ohio

## Electrical Engineering's New "Easy-Reading Page"

*To the Editor:*

... You are to be congratulated on the makeup of the January 1937 issue of ELECTRICAL ENGINEERING. I admit my first reaction to the cream-colored paper was negative. However, as I sat in my special chair last evening reading your "easy-reading page" under our IES lamp, I found my technical reading to be a pleasure indeed. I hope you do not go back to the white paper. I find this paper very much more restful, for my eyes are quite sensitive to glare. Listing the author and title at the bottom of each page is an improvement. The 2 pages which include the be-

ginning of an article always have an uncanny way of sticking together. The titles and page numbers are so much more convenient at the bottom than they would be at the top. When this information is given at the top, one either must open the magazine wide or lean halfway across the desk. I'm sorry that I can't offer any constructive criticism. You are too far ahead of me . . .

Very truly yours,

V. P. HESSLER (A'29)
Instructor in Electrical Engineering, Iowa State College, Ames

*To the Editor:*

. . . The new style paper appeals to me, since it seems to hold what was promised, elimination of glare. I believe the carrying over of the name of author and abbreviated title on all pages of the papers will help considerably in locating desired references.

Very truly yours,

J. H. HAGENGUTH (A'28)
Electrical Engineer, High Voltage Engineering Laboratory, General Electric Company, Pittsfield, Mass.

*To the Editor:*

As one whose eyes are sensitive to glare, due undoubtedly to poor lighting and "hard-reading pages" in youth, I want to commend you most heartily on the adoption of the "easy-reading page."

Very truly yours,

FREDERICK HOLMES (A'22, M'27)
President, Duncan Electric Manufacturing Company, Lafayette, Ind.

*To the Editor:*

. . . I think that a very great improvement has been made in the general style and make-up . . .

Very truly yours,

A. S. LANGSDORF (A'03, F'12)
Dean of the Schools of Engineering and Architecture, Washington University, St. Louis, Mo.

*To the Editor:*

I find that the new "easy-reading page" is exactly that. I hope that you will continue to use it.

WILLIS W. SNYDER (A'35)
Meter Department, Niagara Alkali Company, Niagara Falls, N. Y.

*To the Editor:*

I wish to comment very favorably on the change you have just made in the paper on which ELECTRICAL ENGINEERING is printed. The light buff color is far easier on the eyes and under artificial light the glare is reduced almost to the vanishing point.

Also I like very much your initial page entitled "High Lights." It is an excellent idea to have a brief summary of this sort given first. One can see at a glance what articles are of most interest and will then be induced to look them up and read them more thoroughly.

I certainly hope that both of these features are continued.

Yours very truly,

R. W. WARNER (M'28)
Professor and Head of the Department of Electrical Engineering, University of Kansas, Lawrence

*To the Editor:*

I would like to register enthusiastic approval of the new type and tinted paper used in ELECTRICAL ENGINEERING. I think the paper color very well chosen since the temptation usually is to use too yellow a stock.

Very truly yours,

L. J. BUTTOLPH (M'36)
Electrical Engineer, General Electric Vapor Lamp Company, Hoboken, N. J.

*To the Editor:*

May I add my word of approval of your continued efforts to make ELECTRICAL ENGINEERING the best possible kind of publication?

The "easy-reading page" which you present with the January issue is, in my opinion, a significant contribution of the electrical engineering profession to human welfare. There is no doubt but what this sort of thing has long been needed, and I trust that continued efforts may be fruitful along this line.

Sincerely yours,

M. S. COOVER (A'16, M'32)
Head of Electrical Engineering Department, Iowa State College, Ames

*To the Editor:*

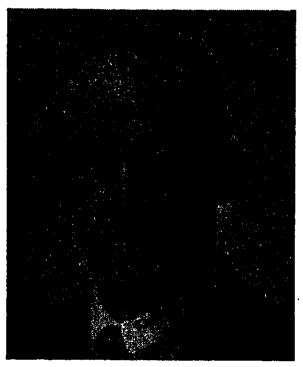
I was very much interested in your easily read page which appeared in the January 1937 issue of ELECTRICAL ENGINEERING. . . all comments which I have heard have been favorable. . . After I had gotten over my first unfavorable impression of seeing the yellowed edges of the sheets before the book was opened, I liked it very much. . . .

Very truly yours,

WILLARD CHAMPE (A'25, M'35)
Electrical Engineering Department, The Commonwealth & Southern Corporation, Jackson, Mich.

# Personal Items

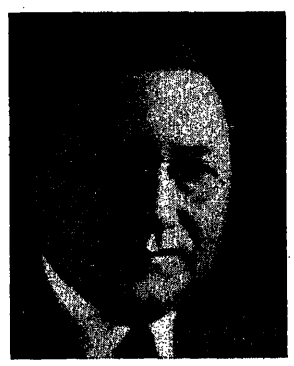
ASGER VILSTRUP (A'20, M'27) chief electrical engineer, British Columbia Electric Railway Company, Ltd., has been elected president of the Engineering Profession in British Columbia for the year 1937. Mr. Vilstrup was born at Borris, Denmark, in 1884, and received his technical education at the College of Electrical Engineering, in Copenhagen, Denmark. Upon completion of his studies, he was employed by several



ASGER VILSTRUP

electrical companies in England, including British Insulated and Helsby Cables, Ltd., during the period 1903–09. In 1911 Mr. Vilstrup went to Canada to become field draftsman and subforeman on hydroelectric construction at Lake Buntzen for the British Columbia Electric Railway Company, Ltd. Three years later he was made assistant engineer in the electrical department of that company at Vancouver. In that position he was engaged in the design of substations and transmission and distribution lines, and in the maintenance of the power plant and distribution systems. In 1929 Mr. Vilstrup was appointed assistant plant manager, and during the year 1935–36 was acting plant manager. He was made chief electrical engineer in 1936. He has been active in the affairs of the Institute's Vancouver Section for several years (chairman 1925–26) and was active in the arrangements and administration of the AIEE Pacific Coast convention held at Vancouver in 1932.

P. S. MILLAR (A'03, M'13) president, Electrical Testing Laboratories, Inc., New York, N. Y., was elected president of the United States National Committee of the International Commission on Illumination at the recent annual meeting of the Committee. Mr. Millar was born at Andover,



P. S. MILLAR

N. J., in 1880, and obtained his formal technical eduction at Paterson Classical and Scientific School and through the International Correspondence Schools. In 1897 he entered the employ of the Lamp Testing Bureau (now Electrical Testing Laboratories, Inc.) and in 1899 became assistant

manager of that company. He became general manager in 1914, and has been president since 1930. Mr. Millar has done much original work in illumination research, being co-inventor of the Sharp-Millar photometer, and has contributed liberally to the technical press. He has been a member of the Institute's committees on electrophysics, 1917–18; meetings and papers (now technical program), 1925–28; and a member since 1924 and chairman from 1925 to 1928 of the committee on production and application of light. Mr. Millar is a fellow of the American Physical Society, member of the council of the Association of Consulting Chemists and Chemical Engineers, secretary-treasurer of the Association of Edison Illuminating Companies, member and past-president of the Illuminating Engineering Society, and director of the Thomas Alva Edison Foundation.

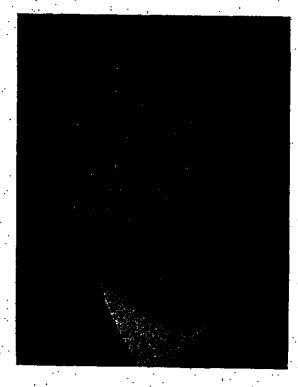
WILLIAM KELLY (F'25) formerly president of the Buffalo, Niagara, and Eastern Power Corporation, recently was elected president of the Niagara, Lockport, and Ontario Power Company. Colonel Kelly was born in New York, N. Y., in 1877, attended the Sheffield Scientific School of Yale University, and was graduated from the United States Military Academy in 1899. During 1902–03 he pursued graduate work in the U.S. Army Engineer School of Application. Upon graduation in 1899, Colonel Kelly was placed in charge of design of electrical installations for sea coast defenses. He continued to serve in that capacity, and concurrently (1906–10) as assistant engineer commissioner of the District of Columbia, until 1913. During the World War he served as chief engineer of the 42nd Division and Fourth Army Corps, and reported for the peace conference on several rivers that were internationalized. When the Federal Power Commission was organized in 1920, Colonel Kelly was appointed its chief engineer and, while serving in that capacity, presented a report on the Colorado River as a source of hydroelectric power and irrigation supply. He was also an active member of the superpower committee for the northeastern area of the United States and a member of the American section of the International Board of Engineers, investigating the St. Lawrence waterway project. In 1925 he was appointed director of engineering of the National Electric Light Association, and in the following year became affiliated with the Buffalo, Niagara, and Eastern Power Corporation. Colonel Kelly became president of that company in 1933. He is a member of the Society of American Military Engineers and the American Society of Civil Engineers; he received the James Laurie prize of the latter society in 1925.

H. M. SHARP (M'34) superintendent of the Huntley stations, Buffalo General Electric Company, Buffalo, N. Y., has been elected a vice-president of the Buffalo, Niagara, and Eastern Power Corporation. Mr. Sharp was born at Buffalo, N. Y., in 1892, and received the degree of mechanical engineer at Cornell University in 1915. Following his graduation, he served briefly as an instructor in mechanical engineering at Cornell University, as an assistant engineer with the Bethlehem Steel Company, Lackawanna, N. Y., and with the U.S. Army, before becoming efficiency engineer at Huntley station in 1919. In 1926 he accepted a similar position with the Indiana Electric Corporation, Terre Haute, Ind., but returned to the Buffalo General Electric Company in 1928 as assistant chief engineer of Huntley station. On completion of the second Huntley station, Mr. Sharp was made assistant superintendent of both stations in 1930; in 1931 he became superintendent, which position he has held for the last 6 years.

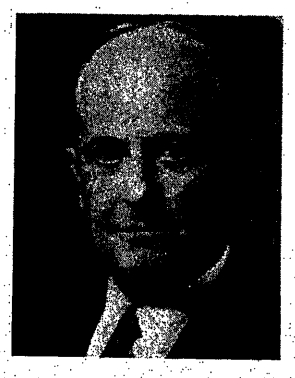
N. R. GIBSON (M'32) vice-president of the Buffalo, Niagara, and Eastern Power Corporation, Buffalo, N. Y., has been appointed vice-president of the Buffalo General Electric Company and the Niagara, Lockport, and Ontario Power Company, and director of the Niagara Electric Service Corporation. Mr. Gibson was born at Guelph, Ont., Canada, in 1880, and was graduated from the University of Toronto in 1901, with a diploma in mechanical and electrical engineering; in 1904 he received the degree of bachelor of arts and sciences, and in 1931 the honorary degree of doctor of engineering at the same institution. Following his graduation in 1904 he served briefly with several contracting companies before becoming associated (1908) with Smith, Kerry, and Chase, consulting engineers in Toronto, Ont., Canada, where he was in charge of the civil and hydraulic department. During 1913–15 Mr. Gibson served as consulting engineer to the Ontario Power Company, Niagara Falls, Ont., and the Electric Power Company, Ltd., Toronto; later, he served as chief engineer for the Ontario Power Company, 1915–16, and assistant chief engineer of the Electric Power Company, 1916–17. From 1918 to 1925 he was hydraulic engineer of the Hydraulic Power Company (now Niagara Falls Power Company), Niagara Falls, N. Y., later serving as executive engineer, chief engineer, and vice-president and chief engineer; concurrently he was vice-president and chief engineer of the Buffalo, Niagara, and Eastern Power Corporation and vice-president of the Niagara Hudson Power Corporation, New York, N. Y. Mr. Gibson is a member of the American Society of Civil Engineers and The American Society of Mechanical Engineers.

L. T. BLAISDELL (A'20, M'22, vice-president) southwestern district manager, General Electric Company, Dallas, Texas, has been elected a commercial vice-president of the company. Mr. Blaisdell was born at Carlisle, Mass., in 1886, and following his graduation from the Massachusetts Nautical Training School, in 1904, he entered the employ of the General Electric Company as a student engineer at Lynn, Mass., where he remained until 1907. During the period 1907–11 he served as construction engineer, in which capacity he supervised the installation of power-plant equipment on many naval vessels built along the Atlantic coast and served as engineer on many trial trips. From 1911 to 1917 he served as commercial engineer in the Baltimore, Md., offices of the General Electric Company, and in 1917 was transferred to the Washington, D. C., offices to follow various activities of the federal government. He served in that position until 1923 when he was transferred to Dallas as southwestern district manager. Mr. Blaisdell was chairman of the AIEE Washington Section, 1922–23, and of the Dallas Section, 1930–31.

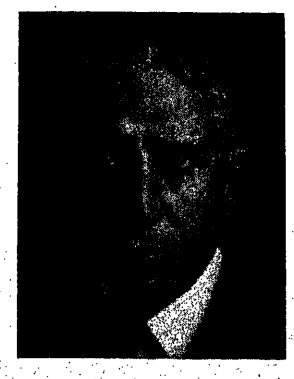
R. B. HOWLAND (A'11, M'22) formerly assistant to the president of United Engineers & Constructors, Inc., Philadelphia, Pa., recently was elected a vice-president and director of that company. Mr. Howland was born at Marion, Mass., in 1885, and received the degrees of bachelor of arts (1906) and bachelor of science in electrical engineering (1910) at Drury College and Purdue University, respectively. Following his graduation in 1910, he became associated



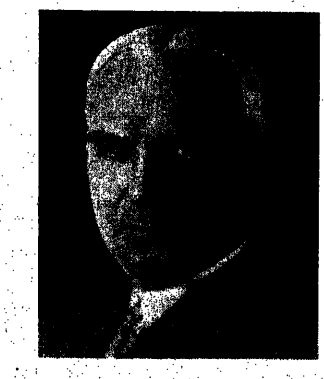
L. T. BLAISDELL



WILLIAM KELLY



R. B. HOWLAND



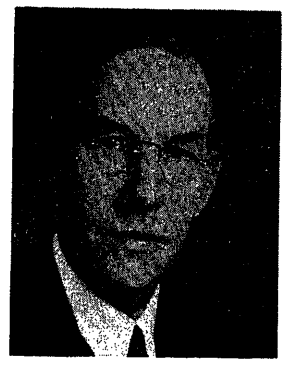
N. R. GIBSON



M. O. TROY



F. M. FARMER



H. J. MAC LEOD



E. D. UHLENDORF

with the Stone and Webster Company, first as an electrician and switchboard operator for the Pacific Coast Power Company, Sumner, Wash., and later as assistant general superintendent of the Mississippi River Power Company, Keokuk, Iowa. In 1917 Mr. Howland accepted a position as superintendent of power, and subsequently as superintendent of power and utilities, with the American International Shipbuilding Corporation, Hog Island, Pa. He returned briefly to the services of the Mississippi River Power Company in 1919, and then became affiliated with Dwight P. Robinson & Co., Inc., New York, N. Y., as assistant electrical engineer. When Dwight P. Robinson & Co. was merged with 3 other engineering organizations to form United Engineers & Constructors, Inc., in 1929, Mr. Howland was made assistant to the president of the new organization, and has held that position since. He is a member of Tau Beta Pi.

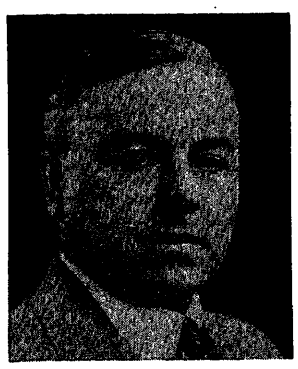
M. O. TROY (A'08, M'12) manager of the central station department, General Electric Company, Schenectady, N. Y., has been elected a commercial vice-president of the company. Mr. Troy was born at Burlington, N. C., in 1872, and received the degree of bachelor of science in electrical engineering at the University of Virginia in 1896, following which he entered the employ of the General Electric Company as a test engineer. He was transferred to the West Lynn works of that company as foreman of transformer test in the following year, and in 1898 became associated with Prof. Elihu Thomson (A'84, M'91, F'13, HM'28, Edison Medalist '09, past-president) in development work on constant-current transformers. In 1901 Mr. Troy was made assistant engineer of the a-c engineering department of the West Lynn works and was later transferred to the transformer sales department. In 1907 he became manager of sales of transformers, lightning arresters, and voltage regulators, and in 1923 was appointed executive assistant manager of the central station department. Mr. Troy became manager of the department in 1928.

P. H. THOMAS (A'00, F'12, past vice-president, member for life) formerly chief of the power requirements division, National Power Survey, Federal Power Commission, Washington, D. C., has been appointed regional director of the Commission, with offices at Atlanta, Ga. Mr. Thomas was born at Boston, Mass., in 1872, and received the degree of bachelor of science in electrical engineering at the Massachusetts Institute of Technology in 1893. Following his graduation, he entered the engineering department of the Westinghouse Electric & Manufacturing Company, East Pittsburgh, Pa., where his work consisted of lightning-arrester and high-voltage engineering, and remained with that company until 1903, when he became chief engineer of the Cooper-Hewitt Electric Company. In 1907 Mr. Thomas established his own consulting engineering offices at New York, N. Y., and continued his private practice until he was appointed consulting electrical engineer to the firm of Guggenheim Brothers, in 1916. In 1928 he re-established his own consulting engineering offices, continuing until he was appointed chief of the power requirements division of the National Power Survey in 1934. Mr. Thomas was manager of the Institute, 1907–10; vice-president, 1910–12; and has been a member of the committees on electrophysics, meetings and papers (now technical program), standards, power transmission and distribution, award of Institute prizes, Lamme Medal, and Edison Medal. He is a member of The American Society of Mechanical Engineers.

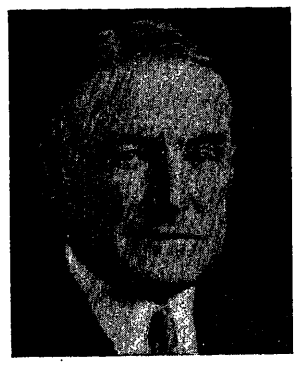
E. D. UHLENDORF (A'13) formerly a member of the operating committee, Byllesby Engineering and Management Corporation, Chicago, Ill., has been appointed executive engineer of Public Utility Engineering and Service Corporation, successor to the Byllesby company. Mr. Uhlendorf was born at Chicago in 1887, and attended the Armour Institute of Technology, specializing in civil engineering. He has been associated with Public Utility Engineering and Service Corporation and its predecessor continuously since 1911, with the exception of a 3-year period during which he was engaged in special public utility evaluation work. He has had charge of many important appraisal projects for rate making and security issues, and has appeared as expert witness before several commissions and courts. Mr. Uhlendorf became a member of the operating committee of the Byllesby Engineering and Management Corporation in 1925. He is a member of the American Society of Civil Engineers and the Society of American Military Engineers.

F. M. FARMER (A'02, F'13, director) vice-president and chief engineer of the Electrical Testing Laboratories, Inc., New York, N. Y., has been elected chairman of the standards council of the American Standards Association for the year 1937. Mr. Farmer was born at Ilion, N. Y., in 1877, and was graduated from Cornell University in 1899. In 1903, after spending a year in the test department of the General Electric Company and 2½ years in the inspection division of the U.S. Navy at the Brooklyn (N. Y.) Navy Yard, he joined the staff of the Electrical Testing Laboratories, Inc., then known as the Lamp Testing Bureau. Mr. Farmer has been active in various phases of ASA work, as chairman of 2 sectional committees and member of 2 others, and as a member of the electrical standards committee and the United States National Committee of the International Electrotechnical Commission. In addition, he is active in Institute affairs, having been member or chairman of many of the technical committees, and is at present a member of the board of directors. Since 1935 he has been Institute representative on the Engineering Foundation board and on the engineering societies monograph committee. Mr. Farmer is a past-president of the American Welding Society and of the American Society for Testing Materials, a fellow of the American Association for the Advancement of Science, and a member of the Institution of Electrical Engineers and The American Society of Mechanical Engineers.

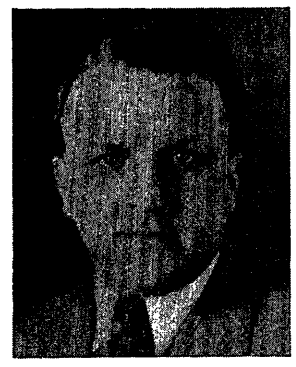
H. J. MAC LEOD (A'23) formerly professor of electrical engineering, University of Alberta, Edmonton, Canada, has been appointed head of the department of mechanical and electrical engineering at the University of British Columbia, Vancouver. Professor Mac Leod was born at New London, Prince Edward Island, in 1887, and received the degrees of bachelor of science (1914) and master of science (1916) from McGill University and the University of Alberta, respectively. In 1921 he received the degrees of master of arts and doctor of philosophy at Harvard University. Following his graduation from McGill University, he served for 2 years as lecturer in electrical engineering at that institution, and after 3 years' (1916–19) army service, entered Harvard University to pursue graduate work in electrical physics. In 1921 he was appointed associate professor of electrical engineering at the University of



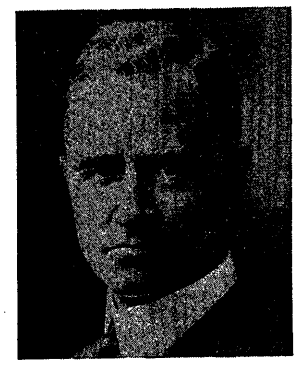
A. L. JONES



E. H. GINN



J. M. COSTELLO



T. S. KNIGHT

Alberta and in 1924 professor of electrical engineering. He is a member of the Engineering Institute of Canada.

T. S. KNIGHT (A'05) New England district manager, General Electric Company, Boston, Mass., has been elected a commercial vice-president of the company. Mr. Knight was born in Massachusetts in 1882, and was graduated from Tufts College in 1903, with the degree of bachelor of science in electrical engineering. Following his graduation, he entered the testing department of the Stanley Electric Company, and in the following year was transferred to the switchboard engineering department. When the Stanley Electric Company became a part of the General Electric Company, Mr. Knight was retained in the switchboard engineering department at the Schenectady, N. Y., works of the new company. In 1908 he was transferred to the Boston, Mass., offices of the General Electric Company, and placed in charge of switchboard engineering there. He has been New England district manager since 1926.

A. L. JONES (A'07, M'26) Rocky Mountain district manager, General Electric Company, Denver, Colo., has been elected a commercial vice-president of the company. Mr. Jones was born at Balston, N. Y., in 1879, and received the degree of mechanical engineer in electrical engineering at Cornell University in 1904. Upon graduation, he entered the testing department of the General Electric Company, at Schenectady, N. Y., continuing as a test engineer until he was transferred to the power and mining engineering department in 1906. In 1909, Mr. Jones was transferred to the Denver offices of the General Electric Company as district engineer, in which capacity his work consisted of engineering supervision of construction and construction contracts. He was appointed district manager in 1928.

J. M. COSTELLO (A'27) vice-president and general manager, The Syracuse Lighting Company, Inc., Syracuse, N. Y., has been elected a vice-president of the Niagara, Lockport, and Ontario Power Company. Mr. Costello was born at Clyde, N. Y., in 1891, and has been affiliated with the Niagara, Lockport, and Ontario Power Company, and its associated companies, since 1911. During his service of more than 25 years, he has acted as division superintendent and as district manager of that company; also as district manager and as general manager of the Livingston-Niagara Power Company. Mr. Costello was made executive manager of the Niagara, Lockport, and Ontario Power Company in 1928, and vice-president and general manager of The Syracuse Lighting Company in 1930.

E. H. GINN (A'03) southeastern district manager, General Electric Company, Atlanta, Ga., has been elected a commercial vice-president of the company. Mr. Ginn was born at Worcester, Mass., in 1878, and was graduated from the Worcester Polytechnic Institute in 1900. Following a year's graduate study at the same institution, he entered the testing department of the General Electric Company, Schenectady, N. Y., and after a brief service as test engineer was transferred to the railway engineering department in the Atlanta offices of that company. He was appointed district sales manager in 1918 and district manager in 1922.

THOMAS FITZGERALD (A'02) vice-president and general manager, Pittsburgh (Pa.) Railways Company, has been elected a member of the board of directors of the Philadelphia Company. Mr. Fitzgerald is a native (1878) of Baltimore, Md., and a graduate of The Johns Hopkins University in the class of 1898. Following his graduation, he entered the employ of the Baltimore and Ohio Railroad Company as an inspector, and after serving with several companies, eventually became general manager of the Cincinnati (Ohio) Traction Company in 1913. In 1917 he resigned that position to join the U.S. Army, and following the World War Mr. Fitzgerald established his own consulting engineering offices at Pittsburgh, Pa. In 1924 he became vice-president of the Pittsburgh Railways Company, and later vice-president and general manager.

L. S. BOGGS (A'93, M'98, member for life) service engineer, Westinghouse Electric & Manufacturing Company, East Pittsburgh, Pa., has retired from active service. Mr. Boggs was born at Lafayette, Ind., in 1867, and was graduated from Purdue University in 1888 with the degree of bachelor of mechanical engineering; in 1892 he obtained the advanced degree of mechanical engineer from the same institution. Following his graduation in 1888, he entered the employ of the Sprague Electric Railway Company, remaining there until 1891. After a year of graduate study, Mr. Boggs was appointed engineer of power for the Columbian Exposition at Chicago, Ill., in 1893 and in 1894 he held a similar position at the Cotton States and International Exposition at Atlanta, Ga. In 1896 he became superintending engineer for the Pioneer Electric Power Company, Ogden, Utah, where he remained for 4 years before becoming associated with Sargent and Lundy, Inc., Chicago, Ill. Mr. Boggs has been associated with the Westinghouse company since 1904, having started as a construction engineer. He took an active part in many major railway electrification projects, both in the United States and in South America.

E. W. JUDY (A'26) vice-president of the Duquesne Light Company, Pittsburgh, Pa., recently was elected a member of the board of directors of the Philadelphia Company. Following a 3-year preliminary training, Mr. Judy became associated with the Stone and Webster Company at Seattle, Wash., in 1909, where he remained until 1914, when he became superintendent of construction for the Southern Sierras Power Company, Riverside, Calif.; later he became local superintendent and district manager for that company. In 1923 he joined the Duquesne Light Company as superintendent of overhead lines, subsequently becoming superintendent of the distribution department, operating manager, and vice-president.

E. F. NUEZEL (A'27) formerly underground transmission and distribution engineer, Union Gas and Electric Company, Cincinnati, Ohio, has become superintendent of the underground department of the Cincinnati Gas and Electric Company. Mr. Nuezel is a native of Cincinnati, and an electrical engineering graduate of the University of Cincinnati. Upon graduation, he entered the electrical distribution department of the Union Gas and Electric Company in 1922 as assistant engineer on maintenance and construction. In 1927 he joined the engineering staff of the Colum-

bia Engineering and Management Corporation as assistant engineer on engineering planning, but later returned to the Union Gas and Electric Company as underground transmission and distribution engineer.

L. O. DORFMAN (A'19, M'28) manager of the engineering division, Westinghouse Electric & Manufacturing Company, Cincinnati, Ohio, has been made engineering manager of the New England district of that company, with offices at Boston, Mass. Mr. Dorfman was born at Pittsburg, Texas, in 1892, and received the degree of electrical engineer at the University of Texas in 1916. He entered the employ of the Westinghouse Electric & Manufacturing Company, East Pittsburgh, Pa., immediately following his graduation, and his service with that company has been uninterrupted, except for a period of service with the U.S. Army during the World War. He was transferred to the Cincinnati offices of the Westinghouse company in 1927.

A. H. MORTON (A'24) National Broadcasting Company, New York, N. Y., has been appointed manager of the department of managed and operated stations of the National Broadcasting Company. Mr. Morton is a native (1895) of Chicago, Ill., and an engineering graduate of the University of Illinois. During 1917–19 he served in the U.S. Army, and following his resignation was associated with the General Electric Company for 2 years before joining the Radio Corporation of America as manager of the Washington, D. C., offices of that company. In 1923 Mr. Morton was transferred to the New York, N. Y., offices as head of the commercial department of RCA Communications, and in 1929 was made European manager for the Radio Corporation of America.

D. S. MACCORKLE (A'30) has resigned as cable engineer in the engineering department of the New York and Queens Electric Light and Power Company, Flushing, N. Y., and is now associated with the Habirshaw Cable and Wire Corporation, Yonkers, N. Y., as a sales engineer. Mr. MacCorkle is a native (1905) of Flushing, N. Y., and an electrical engineering graduate of Washington and Lee University. Upon graduation, he entered the student training course of the Westinghouse Electric & Manufacturing Company, East Pittsburgh, Pa., in 1926. After spending a year as a sales engineer for the Westinghouse company, he accepted a position as assistant engineer for the New York and Queens Electric Light and Power Company in 1928.

J. E. M. MITCHELL (A'27) formerly southern district sales manager, Jeffrey DeWitt Insulator Company, Kenova, W. Va., has been advanced to the position of general sales manager of the company. Mr. Mitchell is a native (1890) of Edisto Island, S. C., and an electrical and mechanical engineering graduate of Clemson College. Following his graduation, he entered the employ of the General Electric Company, Schenectady, N. Y., as a test engineer, and for a time served under Dr. C. P. Steinmetz. Mr. Mitchell served briefly with several companies, and with the U.S. Army Corps of Engineers, before becoming southern district sales manager for the Jeffrey DeWitt Insulator Company in 1924.

H. W. EALES (A'17, F'25, past vice-president) who has been chief electrical engineer of the Byllesby Engineering and Management Corporation, Chicago, Ill., has been appointed chief electrical engineer of the Public Utility Engineering and Service Corporation, Chicago, successor to the Byllesby organization. Mr. Eales has been active in Institute affairs, having been a member of many of the technical committees and a vice-president (1921–26) representing the South West District. He has also been active in committee work of the Edison Electric Institute and the Association of Edison Illuminating Companies, and is a member of Phi Beta Kappa and Sigma Xi.

G. H. JUMP (A'18, M'30) engineer in the Buffalo, N. Y., offices of the General Electric Company, has been appointed New England district engineer for the company, with headquarters at Boston, Mass. Mr. Jump was born at Binghamton, N. Y., in 1888, and received the degree of electrical engineer at Syracuse University in 1910. Immediately following his graduation, he entered the employ of the General Electric Company, Schenectady, N. Y., as a student engineer and has since been associated with that company in various capacities. He was transferred to the Buffalo offices in 1916 and was appointed engineer in charge in 1918.

R. A. JONES (A'20) engineer in the Syracuse, N. Y., offices of the General Electric Company, has been transferred to the Buffalo, N. Y., offices in a similar capacity. Mr. Jones is a native (1892) of Wabasha, Minn., and an electrical engineering graduate (1916) of the University of Minnesota. Upon his graduation, he entered the testing department of the General Electric Company, Schenectady, N. Y. In 1917 he was transferred to the power and mining engineering department of that company, and was appointed to the Syracuse offices in 1923.

D. J. DEBOER (A'34) formerly assistant electrical engineer, Sargent and Lundy, Inc., Chicago, Ill., recently was appointed chief electrical engineer of the Loup River Public Power District, Columbus, Nebr. Mr. DeBoer is a native (1897) of Corsica, S. D., and an electrical engineering graduate (1922) of South Dakota State College. He has been associated with the Sargent and Lundy firm, directly and indirectly, since 1927.

W. B. RITTENHOUSE (A'03) for many years associated with H. M. Byllesby and Company and the Byllesby Engineering and Management Corporation, Chicago, Ill., has been appointed assistant manager of the engineering division of the Public Utility Engineering and Service Corporation, successor to the Byllesby Engineering and Management Corporation.

F. H. LANE (M'23) for 19 years manager of engineering and construction for the Byllesby Engineering and Management Corporation, Chicago, Ill., has been appointed manager of the engineering division of the Public Utility Engineering and Service Corporation, successor to the Byllesby organization, with which Mr. Lane has been associated continuously since 1904.

H. L. HAZEN (A'26) assistant professor of electrical engineering at Massachusetts Institute of Technology, Cambridge, recently was made associate professor. Professor Hazen, a graduate of that institution, was employed by the General Electric Company at Schenectady, N. Y., for a year prior to joining the faculty in 1925.

A. B. BERRESFORD (A'31) an electrical engineering graduate (1929) of Cornell University, recently passed the examinations of the National Board of Medical Examiners and expects to enter the general practice of medicine at Ithaca, N. Y., in the near future.

PETER FRIES, JR. (A'34) an electrical engineering graduate (1933) of the College of the City of New York, recently was admitted to the bar of the State of New York, and has opened offices for the general practice of law at New York, N. Y.

G. A. PRICE (A'33) formerly employed in the engineering department of the Susquehanna Silk Mills, Sunbury, Pa., now is employed as general draftsman for the Hygrade Sylvania Corporation, St. Marys, Pa.

H. A. WARREN (A'36) formerly a draftsman for the Florida Mapping Project, Gainesville, now is an electrical maintenance engineer for the United Clay Mines Corporation, Trenton, N. J.

G. E. MULLIN, JR. (A'36) sales engineer, General Electric Company, Indianapolis, Ind., has been transferred to the rural electrification section of that company at Schenectady, N. Y.

T. S. BAKER (A'28) formerly chief engineer, Press Wireless, Inc., Hicksville, N. Y., recently was appointed superintendent of radio construction for the U.S. Signal Corps, with headquarters at Washington, D. C.

L. H. DEE (A'36) has resigned his position with Fairbanks, Morse, and Company, New York, N. Y., to become associated with Standard Air Conditioning, Inc., New Rochelle, N. Y.

H. A. BOYCE (A'34) formerly division transmission engineer, American Telephone and Telegraph Company, Cleveland, Ohio, has been transferred to the Cincinnati, Ohio, offices of that company.

G. M. COFFMAN (A'35) formerly a radio engineer for the George W. Taylor Company, Williamson, W. Va., now is employed by the American Rolling Mill Company, Ashland, Ky.

C. M. MACKEY (A'34, M'36) manager of the Oklahoma City (Okla.) branch of the Westinghouse Electric Supply Company, has been transferred to the Houston, Texas, offices of that company.

B. P. RUCKER (A'03, F'13) engineer, Federal Power Commission, Washington, D. C., recently was transferred to the Atlanta, Ga., regional offices of the Federal Power Commission.

R. D. GOODRICH (A'33) formerly an electric dredge engineman, U.S. Engineers, Fort Peck, Mont., now is a junior hydraulic engineer with the U.S. Geological Survey, St. Louis, Mo.

M. L. KHANNA (A'31) formerly a student engineer for The Vilter Manufacturing Company, Milwaukee, Wis., has been transferred to Lahore, India, as a representative of that company.

R. W. RHODES (A'23) who has been an electrical engineer for Charles H. Tenney and Company, Boston, Mass., now is with the New England Power Service Company, Worcester, Mass.

T. L. BERRI (A'35) formerly a junior engineer, Southwestern Light and Power Company, Lawton, Okla., now is employed in the relay department of the Public Service Company of Colorado, Denver.

U. N. HALLIDAY (A'28) formerly district manager, Pacific Electric Manufacturing Corporation, San Francisco, Calif., now is employed by the John Roebling's Sons Company, Los Angeles, Calif.

# Obituary

EDWARD BARNARD MEYER, of Newark, N. J., junior past-president of the Institute, died January 30, 1937, just as these pages were going to press. For additional information, see the March issue of ELECTRICAL ENGINEERING.

FRANK ARTHUR LAWS (A'09, M'12, F'28) emeritus professor of electrical measurements, Massachusetts Institute of Technology, Cambridge, died in November 1936. Professor Laws was born May 28, 1867, at North Bridgewater, Mass., and was graduated from Massachusetts Institute of Technology in 1889, with the degree of bachelor of science, following which he was retained on the faculty as an assistant in physics. In 1891 he was made an instructor in physics, and in 1894 an instructor in electrical measurements. From 1897 until 1902 he served as assistant professor of physics before being appointed assistant professor of electrical testing. In 1906 he was appointed associate professor of electrical testing, and continued in that capacity until 1913, when he received a professorship of electrical engineering. He was retained at that time by the Massachusetts Gas and Electric Commission to make tests of electric meters, and later performed special work in electrical measurements for the Edison Electric Illuminating Company of Boston, the General Electric Company, and various electric light and power companies throughout New England. He was appointed professor of electrical measurements in 1921. Professor Laws was the author of many technical papers dealing with the subject of electrical measurements, and on that subject prepared a textbook, which became widely used and acknowledged to be one of the leading textbooks of its kind in the English language. He served the Institute during 1917–19 and 1920–22 as a member of the committee on standards, and during 1929–33 as a member of the committee on instruments and measurements. He was a member of the National Electric Light Association and a fellow of the American Academy of Arts and Sciences.

WILLIAM BENJAMIN JACKSON (A'97, M'98, F'13, Life Member, past vice-president) retired rate consultant to The New York Edison Company, New York, N. Y., died January 20, 1937. Colonel Jackson was born June 23, 1870, at Kennett Square, Pa., and was graduated from Pennsylvania State College in 1890 with the degree of bachelor of science; he received the degree of mechanical engineer from the same institution in 1895. After serving with several companies from 1890 to 1894, he was employed by The United Electric Light and Power Company, New York, N. Y., as an inspector, but shortly thereafter entered the testing department of the Stanley Electric Manufacturing Company at Pittsfield, Mass., and finally became assistant to the chief engineer of that company. In 1895 Colonel Jackson became manager of the Lowell (Mich.) Water and Light Company, and in 1897 he accepted a similar position with the Peninsular Light and Power Company, Grand Rapids, Mich. During 1898–99 he was chief engineer and superintendent of the New York and Staten Island Electric Company and consulting engineer of the Staten Island Electric Railway Company; from 1899 to 1901 he served as chief engineer and superintendent of the Colorado Electric Power Company, Cripple Creek. Beginning in 1901, and for 2 years thereafter, he was special engineer abroad for the Stanley Electric Manufacturing Company, and from 1903 until 1918 Colonel Jackson was a member of the consulting engineering firm of D. C. and William B. Jackson, of New York. He served The New York Edison Company from 1919 until his retirement in 1933. He presented many papers before the Institute and was a member of several of the technical committees; in addition, he served as the Institute's manager from 1912 to 1915 and as a vice-president during 1918–19. He was a member of the American Society of Civil Engineers, Society of American Military Engineers, and The American Society of Mechanical Engineers.

ALBERT T. PERKINS (M'25, Life Member) consulting tranportation engineer, St. Louis (Mo.) Union Trust Company, died November 22, 1936. Colonel Perkins was born October 2, 1865, at Brunswick, Me., and received the degree of bachelor of arts at Harvard University in 1887; he also received the honorary degree of master of arts from Harvard University in 1919. Following his graduation, he entered the employ of the Chicago, Burlington, and Quincy Railroad Company, and during the period 1887–96 held various positions in that company. From 1897 to 1902 he was superintendent of terminals in the St. Louis division of that company, and from 1902 until 1906 held a similar position in the St. Joseph division. In 1906 Colonel Perkins became consulting engineer and railroad adviser to the St. Louis Union Trust Company, and served in that capacity continuously for 30 years; however, he served at the same time as president of the Brownsville and Matamoros Bridge Company; Marshall and East Texas Railway Company; Chicago, Milwaukee, and Gary Railway Company; New Iberia and Northern Railway Company; Appalachicola Northern Railroad Company; and the West Texas Abstract and Guarantee Company. In addition, he was consulting engineer for the Southern Traction Company of Texas and manager for the receiver of the United Railways Company of St. Louis. Colonel Perkins had a brilliant military record during the World War and was awarded the Distinguished Service Medal and the British Order of St. Michael and St. George.

THOMAS EDWARD PENARD (A'08) assistant superintendent, station engineering department, Edison Electric Illuminating Company of Boston, Mass., died October 27, 1936. Mr. Penard was born May 7, 1878, at Paramaribo, Dutch Guiana, and was graduated in electrical engineering at the Massachusetts Institute of Technology in 1900, following which he was engaged briefly as a draftsman for 2 structural companies before becoming associated with the Edison Electric Illuminating Company of Boston in 1901. His first position with that company was as a draftsman, but he later became an electrical engineer, and in that capacity was active in the design of the company's electrical systems. He became assistant superintendent of the station engineering department in 1931. Mr. Penard was active in education work, having served as instructor and superintendent of several evening schools in Boston, and for a time was dean of the evening school of Northeastern University. He served the Institute as a member of the committees on industrial and domestic power (now general power applications), 1920–21, and instruments and measurements, 1927–29.

ARTHUR JOHN RALPH (A'22, M'31) technician in the electrical engineering department of Yale University, New Haven, Conn., died February 11, 1936, according to word just received at Institute headquarters. Mr. Ralph was born February 23, 1861, at Berkshire, England, and received his electrical training by serving an apprenticeship in the philosophical instrument trade in England. He came to the United States in 1889 and entered the instrument department of the Schuyler Electric Company, Middletown, Conn., in 1890. When the General Electric Company absorbed the

Schuyler Electric Company in 1892, Mr. Ralph was placed in charge of the experimental laboratory of the Middletown works, where he remained until he accepted a position as superintendent of the New Haven, Conn., plant of The Walker Electric Company. In 1898 the Walker Electric Company was absorbed by the Westinghouse Electric & Manufacturing Company, and Mr. Ralph was retained as assistant in the detail department of the New Haven plant. He remained in that position until 1900, when he became factory superintendent of the Kidder Motor Vehicle Company, New Haven. In 1904 he became head of the assembling department of the Connecticut Computing Machine Company, New Haven, and in 1911 a designer of automatic ammunition machinery for the Winchester Rifle Company. He joined the staff of Yale University as technician in the electrical department in 1916.

CHARLES JOYCE RUSSELL (A'04, member for life) vice-president in charge of rates and standard practice of the Philadelphia (Pa.) Electric Company, died December 8, 1936. Mr. Russell was born March 10, 1864, at Norway, Me., and attended the Lawrence Scientific School and Massachusetts Institute of Technology. In 1886 he became associated with the Holtzer Cabot Electric Company, where he did general electrical installation and storage battery work. After serving for one year as superintendent of the H. B. Cutter Company, Philadelphia, and a similar period as superintendent of the electrical department of the Tacony Iron and Metal Company, Philadelphia, he became superintendent of the Manufacturers Electric Company in 1891. In 1899 Mr. Russell became superintendent of the combined Manufacturers and Suburban Electric Companies, retaining that position until the companies were absorbed by the Philadelphia Electric Company in 1904, when he became district manager. He retained that position until he was appointed vice-president in charge of the commercial department in 1925; later he became vice-president in charge of rates and standard practice.

FRANCIS EUGENE DONOHOE (A'06, member for life) special representative, General Cable Corporation, New York, N. Y., died December 2, 1936. Mr. Donohoe was born October 28, 1863, at Lowell, Mass., and received his education in the public schools of Boston, Mass. He started his technical career in the experimental laboratories of the American Bell Telephone Company, Boston, Mass., and after 3 years of service with that company, joined the Edison General Electric Company as a salesman in 1889. In 1891 he became associated with the Safety Insulated Wire and Cable Company, New York, N. Y., where he remained for 3 years before accepting the position of western manager of the American Electrical Works, Chicago, Ill., in 1894. In 1906 Mr. Donohoe was appointed eastern sales manager of the same company, and was transferred to New York, N. Y., where in 1913 he became sales manager of the National Conduit and Cable Company. In 1925 he returned to the employ of the Safety Insulated Cable and Wire Company as special agent, and when that company was merged with another to form the General Cable Corporation, Mr. Donohoe was retained in the same capacity in the new company.

DAVID HENRY KELLY (A'17) district manager, Allis-Chalmers Manufacturing Company, Philadelphia, Pa., died December 7, 1936. Mr. Kelly was born at Steubenville, Ohio, July 2, 1883, and attended the University of Illinois, where he was graduated with the degree of electrical engineer in 1904. After a brief period of employment with the El Paso Smelting and Refining Company, he entered the employ of the Bullock Electric Manufacturing, Company, Norwood, Ohio, at about the time that company became a part of the Allis-Chalmers Company. Mr. Kelly served as sales engineer in that company's Cincinnati (Ohio), Philadelphia (Pa.), and Washington (D. C.) offices, and at the conclusion of his service in the World War was transferred to the New York, N. Y., offices. He had been manager of the Philadelphia offices since 1920. He was active in local Institute affairs, and was chairman of the Philadelphia Section during 1930–31.

LESTER ROBLEY SAILER (A'31, M'36) instructor in electrical engineering, Columbia University, New York, N. Y., died December 13, 1936. Mr. Sailer was born July 14, 1906, at New York, N. Y., and received the degrees of bachelor of arts (1929), bachelor of science in electrical engineering (1930), and electrical engineer (1935) at Columbia University. Following his graduation in electrical engineering, he was appointed an instructor in electrical engineering, at Columbia University, and was retained in that position continuously; he also served as an assistant in physics for the 3 scholastic years during 1927–30. In addition to his regular teaching duties, Mr. Sailer undertook consulting engineering assignments from several commercial organizations in New York, N. Y., and from Columbia University. He was a member of the Society for the Promotion of Engineering Education.

CHARLES V. WOODWARD (A'24) manager of the Baltimore, Md., offices of the Westinghouse Electric & Manufacturing Company, died November 19, 1936. Mr. Woodward was born July 23, 1878, and received his formal technical education at Pennsylvania State College. Upon completion of his studies he entered the employ of the Westinghouse Electric & Manufacturing Company at the East Pittsburgh, Pa., works in 1906, but was transferred in 1909 to the Philadelphia, Pa., offices, where he specialized in transportation and power engineering. He was identified with the development of several light traction companies in the state of Pennsylvania. In 1923 Mr. Woodward was transferred to the Baltimore offices of the Westinghouse company in the capacity of manager, which position he retained continuously for 13 years.

ALBERT GEORGE THOMAS GOODWIN (A'20) chief electrical engineer, The Broken Hill Proprietary Co., Limited, Newcastle, N. S. W., Australia, died November 12, 1936. Mr. Goodwin was born July 6, 1893, at Melbourne, Vic., Australia, and received his technical education at Working Men's College (Australia). In 1910 he was apprenticed to the Melbourne Electric Supply Company, and after having served in the field positions of shift engineer and technical assistant, was made a station superintendent. In 1917 Mr. Goodwin was employed by The Broken Hill Associated Smelters, as assistant to the power plant erecting engineer, and in the following year was made power plant engineer in charge of plant. Later he was transferred to the iron and steel works of The Broken Hill Proprietary Co., Limited, and eventually became chief electrical engineer.

LOUIS FERDINAND REINHARD (A'10, M'13, F'20) sales engineer, Geuder, Paeschke & Frey Co., Milwaukee, Wis., died in June 1936, according to word just received at Institute headquarters. Mr. Reinhard was born at Milwaukee, October 1, 1884, and was graduated in electrical engineering from the University of Wisconsin in 1907. Immediately following his graduation, he entered the engineering department of the Mechanical Appliance Company, Milwaukee, and was appointed chief engineer of that company in 1909. He remained in that position until 1920, when he accepted a position as engineer with Geuder, Paeschke & Frey Co. Later Mr. Reinhard was made a sales engineer, and eventually became sales manager in the contract stamping division of that company.

FRANCIS RAYMOND WELLES (A'87, member for life) retired, Altadena, Calif., died December 14, 1936, at Vernet-les-Bains, France. Mr. Welles was born at Athens, Pa., in 1854, and was graduated from the University of Rochester in 1875 with the degree of bachelor of arts. During the 5 years following his graduation, he was associated in business with E. M. Barton (A'87) founder of the Western Electric Company, and in 1880 left the United States to establish factory branches of that company in foreign lands. In 1882 he formed the first branch at Antwerp, Belgium, where the first multiple telephone switchboard used in Europe was manufactured. Mr. Wells served as manager of that branch until he retired in 1913.

JOHN JENKINSON (A'22) superintendent of the meter department of the British Columbia Electric Railway Company, Ltd., Vancouver, died October 14, 1936, according to information received at Institute headquarters. Mr. Jenkinson was born April 20, 1870, at Askan, Lancashire, England, and received his formal education in that country. In 1898 he went to Canada and accepted a position with the British Columbia Electric Railway Company, Ltd., where he remained continuously for 38 years. He was in complete charge of the meter department of that company from the time of its establishment.

# Membership

## Recommended for Transfer

The board of examiners, at its meeting on January 20, 1937, recommended the following members for transfer to the grade of membership indicated. Any objection to these transfers should be filed at once with the national secretary.

**To Grade of Member**

Aiken, E. H., supervisor of division of operations, District 5, Works Progress Administration, San Bernardino, Calif.

Davis, F. E., engineer, Commonwealth and Southern Corporation, Jackson, Mich.

Greenfield, E. W., cable research engineer, Anaconda Wire and Cable Company, Hastings-on-Hudson, N. Y.

Hall, Sherman M., assistant manager, statistical bureau, Consolidated Edison Company, New York, N. Y.

Hase, R. C., transmission engineer, Southwestern Bell Telephone Company, St. Louis, Mo.

Isenberg, H. D., vice-president, Federal Insulation Company, Chicago, Ill.

Karsten, E. J., electrical engineer, United Light and Power Engineering and Construction Company, Kansas City, Mo.

Langdell, J. C., engineer, Commonwealth and Southern Corporation, Jackson, Mich.

Leslie, J. O., operating electrical engineer, E. M. Gilbert Engineering Corporation, Reading, Pa.

Likel, H. C., chief engineer, Pacent Engineering Corporation, New York, N. Y.

MacGillivray, A. L., telephone engineer, Western Electric Company, New York, N. Y.

McDowell, L. G., assistant engineer, New York and Queens Electric Light and Power Company, Flushing, N. Y.

Petit, F. W., assistant engineer, Brooklyn Edison Company, Inc., Brooklyn, N. Y.

Platt, C. J., Jr., superintendent, service inspection bureau, New York Edison Company, Inc., New York, N. Y.

Siskind, R. P., assistant professor of electrical engineering, Harvard University, Cambridge, Mass.

Smith, W. A., consulting engineer, Jacksonville, Fla.

Sommerman, G. M. L., research engineer, American Steel and Wire Company, Worcester, Mass.

Underhill, J. E., assistant engineer, British Columbia Electric Railway Company, Vancouver, B. C., Canada.

Van Sickle, R. C., engineer, switchgear engineering department, Westinghouse Electric & Manufacturing Company, East Pittsburgh, Pa.

**19 to Grade of Member**

## Applications for Election

Applications have been received at headquarters from the following candidates for election to membership in the Institute. If the applicant has applied for direct admission to a grade higher than Associate, the grade follows immediately after the name. Any member objecting to the election of any of these candidates should so inform the national secretary before February 28, 1937, or April 30, 1937, if the applicant resides outside of the United States or Canada.

Abbott, E. G., General Electric Company, Chicago, Ill.

Andersen, J. R. (Member), New York and Queens Electric Light and Power Company, Flushing, N. Y.

Anderson, H. C., Oregon State Highway Commission, Salem, Ore.

Anderson, N. E., Homestake Mining Company, Lead, S. D.

Angevine, O. L. Jr., Stromberg-Carlson Telephone Manufacturing Company, Rochester, N. Y.

Ashe, F. C. (Member), Carnegie Institute of Technology, Pittsburgh, Pa.

Atwood, E. M., Washington Water Power Company, Troy, Idaho

Bacon, F. S., Jr., Westinghouse Electric & Manufacturing Company, East Pittsburgh, Pa.

Baranovsky, C., J. R. Longstaffe, Ltd., Toronto, Ont., Canada

Barrows, W. M., Public Service Electric and Gas Company, Hackensack, N. J.

Bennett, R. M., General Electric Co., Schenectady, N. Y.

Bernhard, G. K., Ohio Power Company, Canton, O.

Bissiri, A. Jr., 2409 Silver Lake Drive, Los Angeles, Calif.

Blaese, A. C., Porcelain Products, Inc., Chicago, Ill.

Boast, W. B., Iowa State College, Ames, Iowa.

Bobe, C. P. (Member), 1530 Olive Street, St. Louis, Mo.

Boehmer, F. D., Louis Allis Company, Milwaukee, Wis.

Bosworth, P. N., General Electric Company, Schenectady, N. Y.

Bower, G. L., Crane Company, Chicago, Ill.

Brandenburger, L., Wagner Electric Corporation, Salt Lake City, Utah.

Brigham, F. W., Washington Pulp and Paper Company, Port Angeles, Wash.

Bromley, J. E., Public Service Commission, New York, N. Y.

Brown, C. A., Southern California Telephone Company, Los Angeles, Calif.

Brown, S. S., Brown Brockmeyer Company, Dayton, O.

Bullock, E. S., Federal Power Commission, Atlanta, Ga.

Capy, P. L., 725 Paulus Street, Dallas, Texas.

Carlson, A. B., Southern New England Telephone Company, New Haven, Conn.

Carlson, H., Associated Press, New York, N. Y.

Casiano, L. J., Carnegie Illinois Steel Corporation, Youngstown, O.

Clasgens, A. E., New York State Electric and Gas Corporation, Brewster, N. Y.

Clifford, L. V., General Electric Company, Philadelphia, Pa.

Collings, L. W. Jr., General Electric Company, Schenectady, N. Y.

Coons, T., Potomac Electric Power Company, Washington, D. C.

Crates, R. R., Memphis Light and Water Commission, Tenn.

Craven, W. D., New York and Queens Electric Light and Power Company, Flushing, N. Y.

Croden, W. T., Metropolitan Water District, Banning, Calif.

Cutler, L. B., Armstrong Cork Products, Boston, Mass.

Davies, M. (Member), Langley Manufacturing Company, Ltd., Vancouver, B. C., Canada

Davis, E. W. (Member), 1478 Municipal Building, New York, N. Y.

Davis, M. F., Young Men's Christian Association, Zanesville, O.

Davis, P. C., Donnelly Electric and Neon Company, Boston, Mass.

de Anda, E., El Paso Electric Company, El Paso, Texas

Decker, H. D., Consolidated Edison Company, New York, N. Y.

Dillon, D. A., Century Electric Co., St. Louis, Mo.

Dorey, F. M., General Electric Company, Schenectady, N. Y.

Dumser, W. T., International Business Machines Corp., Chicago, Ill.

Durst, N. J., Cincinnati and Suburban Bell Telephone Company, Ohio.

Ellis, E. A., Boston and Maine Railroad, Billerica, Mass.

Emery, W. L., University of Utah, Salt Lake City, Utah.

Esval, O. E., Sperry Gyroscope Company, Inc., Brooklyn, N. Y.

Evans, A. J., Public Service Commission, New York, N. Y.

Evans, L. M., Worthington Pump and Machinery Corporation, Buffalo, N. Y.

Everest, F. A., Oregon State College, Corvallis.

Eysenbach, H. A., Crouse-Hinds Company, Syracuse, N. Y.

Fein, H., Belyea Company, Inc., New York, N. Y.

Ferrell, J. T., Brooklyn Edison Company, Brooklyn, N. Y.

Finley, A. R., Reliance Electric and Engineering Company, Cleveland, Ohio.

Fisher, R. L., Emerson Electrical Manufacturing Company, St. Louis, Mo.

Forsyth, W. H., Florida City, Fla.

Fowles, G. A., Anaconda Wire and Cable Company, Pawtucket, R. I.

Fox, E. L., 715 Sanford Street, Peoria, Ill.

Fraser, J. D., Jersey Central Power and Light Company, Allenhurst, N. J.

Frieseke, A. H., Southern Line Material Company, Birmingham, Ala.

Frith, J. M., American Telephone and Telegraph Company, New York, N. Y.

Fuller, J. L., Reliance Electric and Engineering Company, Cleveland, O.

Gago, F. J., University of Florida, Gainesville, Fla.

Gallagher, F. W., Franklin Institute, Philadelphia, Pa.

Ganzar, J. A., Carnegie Illinois Steel Corporation, Gary, Ind.

Gaynor, A. M., I. Gaynor, Inc., New York, N. Y.

Getting, M., Jr., Allis-Chalmers Manufacturing Company, Pittsburgh, Pa.

Gissel, E. A., Central Arizona Light and Power Company, Phoenix, Ariz.

Glas, F. J., New York and Queens Electric Light and Power Company, Flushing, N. Y.

Gordy, T. D., General Electric Company, Pittsfield, Mass.

Gosney, W. A., Trumbull Electrical Manufacturing Company, Ludlow, Ky.

Greentree, C. D., General Electric Company, Schenectady, N. Y.

Griesinger, F. D., Buffalo General Electric Company, Buffalo, N. Y.

Hamilton, J. P., Tennessee Valley Authority, Wilson Dam, Ala.

Hamilton, R. A., University of British Columbia, Vancouver, Canada.

Hansen, A. Jr., General Electric Company, Schenectady, N. Y.

Harris, C. S., Federal Telegraph Company, Newark, N. Y.

Hemmerich, F. J., New York and Queens Electric Light and Power Company, Flushing, N. Y.

Hepler, M. M., Textile Machine Works, Reading, Pa.

Hertel, R. F., General Electric Company, Schenectady, N. Y.

Higbee, C. W. (Member), United States Rubber Company, New York, N. Y.

Hillman, E. C., 815 Crotona Park North, New York, N. Y.

Hine, C. R., Pennsylvania Railroad, Wilmington, Del.

Houle, A. U., University of Toronto, Ont., Can.

Howell, J. C., Public Service Electric and Gas Company, Irvington, N. J.

Hufford, G. V., Century Electric Company, St. Louis, Mo.

Hughes, B. T., Westinghouse Electric and Manufacturing Company, East Pittsburgh, Pa.

Hunt, F. B., Green Mountain Power Corporation, Wells River, Vermont

Hunt, R. McP., General Electric Company, Schenectady, N. Y.

Hutchcraft, H. W., Tennessee Valley Authority, Wilson Dam, Ala.

Imle, H. R., Carter Oil Company, Tulsa, Okla.

Johnson, J. S., Iowa State College, Ames.

Johnson, S. E., General Electric Company, Oakland, Calif.

Jones, J. N., Westinghouse Electric and Manufacturing Company, East Pittsburgh, Pa.

Kaup, J. A., Doble Engineering Company, Medford Hillside, Mass.

Kelly, C. M. Jr., Guided Radio Corporation, New York, N. Y.

Kennedy, L. F., General Electric Company, Philadelphia, Pa.

King, H. W., New York (N. Y.) Edison Company, Inc.

Kirby, R. N., Deming Ice and Electric Company, Deming, N. M.

Kirkpatrick, P. E., Montreal Engineering Company, Ltd., Regina, Sask., Canada.

Kyle, W. D. Jr., Milwaukee, Wisconsin Electric Railway and Light Company.

Lank, W. J., Potomac Electric Power Company, Washington, D. C.

Larson, S. R., Jackson and Moreland, Boston, Mass.

Lear, T. J., New York and Queens Electric Light and Power Company, Long Island City, N. Y.

Lester, S. L., Transducer Corporation, New York, N. Y.

Levine, L. J., Westinghouse Electric and Manufacturing Company, East Pittsburgh, Pa.

Lightfoot, T. C. (Member), General Electric Company, Philadelphia, Pa.

Lillybridge, C. R., U. S. Bureau of Reclamation, Boulder City, Nevada.

Lockett, H. E., General Electric Company, Philadelphia, Pa.

Logan, J. E., Jersey Central Power and Light Company, Allenhurst, N. J.

MacCutcheon, R. H., Western Reserve University Law School, Cleveland, O.

Marsh, R. H., Southern California Edison Company, Ltd., Los Angeles, Calif.

Martens, J. J., New York and Queens Electric Light and Power Company, Jamaica, N. Y.

Matson, D. L., Jr., 101 Fifth Avenue, New York, N. Y.

Matthew, M. P., General Electric Company, Schenectady, N. Y.

Mauritz, F. E., General Electric Company, Schenectady, N. Y.

Maxwell, A. (Fellow), Edison Electric Institute, New York, N. Y.

McGee, H. M., Pennsylvania Power and Light Company, Sunbury, Pa.

McLean, L. V., Louisiana State University, Baton Rouge.

McNamara, C., Commonwealth Edison Company, Chicago, Ill.

Meehan, J. M. Jr., 12-14 West 37th Street, New York, N. Y.

Meudell, A. Y. Jr., General Electric Company, Schenectady, N. Y.

Miller, E. F., American Telephone and Telegraph Company, New York, N. Y.

Misenheimer, H. N. (Member), Bell Telephone Laboratories, Inc., New York, N. Y.

Mohan, A. R., 58 Hammond Street, Cambridge, Mass.

Montgomery, W. D., Cincinnati and Suburban Bell Telephone Company, Norwood, O.

Moon, A. W., New York State Transit Commission, New York, N. Y.

Moore, P., Hancock Brothers, San Francisco, Calif.

Muller, H. N. Jr., Westinghouse Electric & Manufacturing Company, East Pittsburgh, Pa.

Mundt, O. T., Montana Dakota Utilities Company, Williston, N. D.

Nason, H. E., Westinghouse Electric & Manufacturing Company, Chicago, Ill.

Nicholson, J. R., General Electric Company, Schenectady, N. Y.

Norton, V. E., General Controls Company, Minneapolis, Minn.

Oldfield, R. T. (Member), Public Service Commission, New York, N. Y.

Osborn, R. M., Allis-Chalmers Manufacturing Company, Milwaukee, Wis.
Osenbaugh, C. L., Light and Water Division, City of Memphis, Tenn.
O'Shea, C. L., Curtis Lighting, Inc., New York, N. Y.
Palmer, L. T., Burns and McDonnell Engineering Company, Kansas City, Mo.
Parrott, J. A. (Member), American Telephone and Telegraph Company, New York, N. Y.
Partington, R. M., General Electric Company, Pittsfield, Mass.
Pawluk, J., Sarvas Electric Company, Brooklyn, N. Y.
Pipes, L. A., Rice Institute, Houston, Texas.
Poey, C. D. (Member), New York and Queens Electric Light and Power Company, Long Island City, N. Y.
Pollyea, M. H., C. J. Tagliabue Manufacturing Company, Brooklyn, N. Y.
Pope, R., Bell Telephone Laboratories, Inc., New York, N. Y.
Pugh, H. C., Cast Iron Pipe Company, Birmingham, Ala.
Ratliff, A. H., Oklahoma Gas and Electric Company, Shawnee, Okla.
Razovsky, A. M., Laclede Gas Light Company, St. Louis, Mo.
Relson, M., National Park Service, Washington, D. C.
Rhodes, W. E., Stone and Webster Engineering Company, Richmond, Va.
Rowe, I., 652 Lafayette Avenue, Brooklyn, N. Y.
Roby, F. H., 710 South 3rd Street, Milwaukee, Wis.
Roehmann, L. F. (Member), 310 West 113th Street, New York, N. Y.
Rogers, E. T., Bishop Wire and Cable Corporation, New York, N. Y.
Rutledge, G. A., Allis-Chalmers Manufacturing, Company, Pittsburgh, Pa.
Sanders, J. W., Long Island Lighting Company, Roslyn Heights, N. Y.
Santiago, F., Aldrich Pump Company, Allentown, Pa.
Schroedel, H. E., Chicago, Milwaukee, St. Paul, and Pacific Railroad, Milwaukee, Wis.
Simmons, H., Georgia Power Company, Atlanta.
Sitkin, A., Century Lighting Equipment, Inc., New York, N. Y.
Skoog, A. W., Kingsbury Machine Tool Corporation, Keene, N. H.
Slusser, J. A., National Broadcasting Company, Inc., Denver, Colo.
Smith, P. D., Cansfield Electrical Works, Toronto, Ont., Canada.
Sokasits, F. M., Gibbs and Hill, New York, N. Y.
Sparrow, K. M., Westinghouse Electric & Manufacturing Company, East Pittsburgh, Pa.
Stafford, A. B., Westinghouse Electric & Manufacturing Company, East Pittsburgh, Pa.
Steinmetz, C. L., General Controls Company, Minneapolis, Minn.
Stratford, J. P., 821 North Normandie Avenue, Los Angeles, Calif.
Sukava, L., Reno Gold Mines, Ltd., Salmo, B. C., Canada.
Swanson, M. C. W., American Locomotive Company, Schenectady, N. Y.
Taborelli, R. V., 512 14th Street, Union City, N. J.
Taylor, O. L., Arrow-Hart and Hegeman Electric Company, Hartford, Conn.
Tyvand, J. A. (Member), Iowa Farm Bureau Federation, Des Moines, Iowa.
Upham, N. C., General Electric Company, Lynn, Mass.
Van Winkle, E. W., Best Manufacturing Company, Inc., Irvington, N. J.
von Roeschlaub, F., General Electric Company, Schenectady, N. Y.
Wagner, E., 6235 West Roosevelt Road, Berwyn, Ill.
Walter, J. H., Milwaukee (Wis.) Electric Railway and Light Company.
Watkins, D. L., American Steel and Wire Company, Worcester, Mass.
Way, K. J., Bell Telephone Laboratories, Inc., New York, N. Y.
Wells, F. B., Stone and Webster Engineering Corporation, Richmond, Va.
Wells, R. M., New York and Queens Electric Light and Power Company, Flushing, N. Y.
West, F. L., Niagara, Lockport, and Ontario Power Company, Buffalo, N. Y.
White, J. C., Air Reduction Sales Company, Corning, N. Y.
Wilcox, H. L. (Member), Electric Controller and Manufacturing Company, Cleveland, O.
Wilke, E. A., 6025 Melrose Avenue, Chicago, Ill.
Williams, S. B. (Member), *Electrical World*, New York, N. Y.
Winkelman, H. T., Jr., City of Memphis (Tenn.), Water and Light Division.
Wuerch, L. W., City of Tacoma, (Wash.), Public Utilities.
Wopat, R. M., Iowa Continental Telephone Company and Interior Telephone Company, Grinnell, Iowa.
Wyckoff, P. H., California Institute of Technology, Pasadena.
Zimmer, C. S., Bussmann Manufacturing Co., St. Louis, Mo.

195 Domestic

**Foreign**

Bedil, S. D., Public Works Department, Electricity Branch, Lahore, India.
Bhat, V. D., 50 New Street Vepery, Madras, India,
Cordero, C. L., Puerto Rico Reconstruction Administration, Guayama.
Desai, N. N., c/o AEG India Electric Company, Ltd., Bombay, India.
Fukushima, K., Shibaura Engineering Works, Ltd., Yokohama, Japan.
Jadeja, K. R. (Member), Nawanagar State Power House, Jamnagar, India
Kumar, C. R., Electrical Supply Companies, Ltd., Cuttack, India
Meneghelli, H. A., 4 Calle Oriente number 38, San Salvador, El Salvador.
Miyamoto, c/o S., Shibaura Engineering Works, Yokohama, Japan.
Murray, H. H. Jr., Compañia Eléctrica de Santo Domingo, Ciudad Trujillo, Dominican Republic.
Napper, R. E. (Member), Booker Brothers, McConnell and Company, Ltd., Georgetown, British Guiana.
Suryabandara, A. V., Government Electrical Undertakings, Colombo, Ceylon.

12 Foreign

## Addresses Wanted

A list of members whose mail has been returned by the postal authorities is given below, with the addresses as they now appear on the Institute record. Any member knowing of corrections to these addresses will kindly communicate them at once to the office of the secretary at 33 West 39th St., New York, N. Y.

Burns, Arthur B., 1958 E. 29th St., Brooklyn, N. Y.
Eller, E. E., 101 Brookline Court, Upper Darby, Pa.
Godoy, Ernesto R., Cia. Tel. y Tel. Mex., 16 de Septiembri No. 13, Mexico, D. F., Mex.
Jones, Harry Kenneth, 5511 Kenmore Ave., Chicago, Ill.
Koch, Joseph Stanley, 11 Howe Ave., New Rochelle, N. Y.
Little, Leroy C., 3414—17th St., N., Cherrydale, Va.
Ludwig, Leon R., 434 Burling Road, Forest Hills, Pittsburgh, Pa.
Millheisler, Charles A., 1417 Catalpa Ave., Chicago, Ill.
Miyota, Nath S., 916½ Howell St., Seattle, Wash.
Moore, Everett, 821 Sunset Blvd., Los Angeles, Calif.
Peach, Paul S., Upperville, Va.
Pollastro, John B., Helper, Utah.
Sawyer, Fred E., 811 E. Wisconsin Ave., Milwaukee, Wis.
Wong, Harry Y. L., 771 Broadway, West New York, N. J.

14 Addresses Wanted

# Engineering Literature

## New Books in the Societies Library

Among the new books received at the Engineering Societies Library, New York, recently, are the following which have been selected because of their possible interest to the electrical engineer. Unless otherwise specified, books listed have been presented gratis by the publishers. The Institute assumes no responsibility for statements made in the following outlines, information for which is taken from the preface of the book in question.

ELECTRICAL ENGINEERING in RADIOLOGY. By L. G. H. Sarsfield and V. E. Pullin. Pittsburgh, Instruments Publishing Co., 1936. 284 p., illus., 9x6 in., cloth, $6.00. Deals exclusively with the electrical engineering aspects of X-ray equipment for engineers not familiar with the work.

CONTROL of ELECTRIC MOTORS. By P. B. Harwood. N. Y., John Wiley and Sons, 1936. 390 p., illus., 9x6 in., lea., $4.50. Describes the characteristics of various types of motors and explains how they are used for purposes of control. Discusses the design, construction, and operating characteristics of controllers.

PHYSICAL CONSTANTS of PURE METALS. Ed. by National Physical Laboratory. Lond., His Majesty's Stationery Office, 1936. 27 p., tables, 10x6 in., paper, 6d. (obtainable from British Library of Information, New York, $0.20.) Presents results prepared by the National Physical Laboratory.


**Engineering Societies Library**
29 West 39th Street, New York, N. Y.

MAINTAINED as a public reference library of engineering and the allied sciences, this library is a co-operative activity of the national societies of civil, electrical, mechanical, and mining engineers.

Resources of the library are available also to those unable to visit it in person. Lists of references, copies or translation of articles, and similar assistance may be obtained upon written application, subject only to charges sufficient to cover the cost of the work required.

A collection of modern technical books is available to any member residing in North America at a rental rate of five cents per day per volume, plus transportation charges.

Many other services are obtainable and an inquiry to the director of the library will bring information concerning them.


NATURE of PHYSICAL THEORY. By P. W. Bridgman. Princeton (N. J.) University Press, 1936. 138 p., 9x6 in., cloth, $2.00. Presents a critical analysis of the points of view and methods in trying to understand the simpler aspects taken to be within the domain of physics.

TELEVISION RECEPTION, Construction and Operation of a Cathode Ray Tube Receiver for the Reception of Ultra-Short Wave Television Broadcasting. By M. von Ardenne, translated by O. S. Puckle. Lond., Chapman and Hall, 1936. 121 p., illus., 9x6 in., cloth, 10s. 6d. Intended to stimulate the interest of amateurs in experimentation with television.

TELECOMMUNICATIONS, Economics and Regulation. By J. M. Herring and G. C. Gross. N. Y. and Lond., McGraw-Hill Book Company, 1936. 544 p., illus., 9x6 in., cloth, $5.00. Deals with the economic and public service aspects of the telegraph and telephone industries. Presents the background of development of these industries, deals with the sources of revenue and the factors affecting costs and rate structures. Includes a detailed analysis of the Communications Act of 1934.

ORGANIZATION and MANAGEMENT in Industry and Business. By W. B. Cornell. N. Y., Ronald Press Company, 1936. 802 p., illus., 8x5 in., cloth, $4.50. Aims to provide a course of training in the organization, management, and operation of every department of a business concern.

OLD WIRES and NEW WAVES, the History of the Telegraph, Telephone, and Wireless. By A. F. Harlow. N. Y. and Lond., D. Appleton-Century Company, 1936. 548 p., illus., 9x6 in., cloth, $5.00. A popular history of the origins and development of the telegraph and telephone systems of America. The human side of the story is emphasized.

LESSONS and PROBLEMS in ELECTRICITY. By N. C. Page. N. Y., Macmillan Company, 1936. 356 p., illus., 9x6 in., cloth, $2.75. Based upon a course in the fundamentals of electricity which has been given to sophomore students at Massachusetts Institute of Technology. Planned for students with some training in mechanics and calculus.

HANDBOOK of CHEMISTRY and PHYSICS, 21 ed. Cleveland, Ohio, Chemical Rubber Publishing Company, 1936. 2023 p., 7x4 in., lea., $6.00. The latest annual edition of a well-known reference book.

ELECTRICITY: For Use or for Profit. By B. Ostrolenk. N. Y. and Lond., Harper Brothers, 1936. 211 p., tables, 8x5 in., cloth, $2.00. Discusses one aspect of the power problem: the influence of private utility companies on the standard of living. Considers the social and economic significance of present rate policies.

AUTOMATIC VOLUME CONTROL. ed. and published by J. F. Rider, N. Y., 1936. 94 p., illus., 8x5 in., cardboard, $0.60. Affords a description of the general principles of automatic volume control in radio receivers and of their use in current commercial sets.

ELECTRICAL ENGINEERS' HANDBOOK, 2 volumes (Wiley Engineering Handbook Series, volumes 4 and 5) ed. by H. Pender, W. A. Del Mar and K. McIlwain. 3 ed. N. Y. and Lond., John Wiley and Sons, 1936. illus., 9x5 in., lea. (volume 1, $6.00; volume 2, $5.00). A new edition in 2 volumes; one on power, the other on communications, which may be purchased separately.

# Industrial Notes

**General Electric Report for 1936.**—Orders received by General Electric Co. during the year 1936 amounted to $296,748,219, compared with $217,361,587 during 1935, an increase of 37 per cent. Orders for the quarter ended December 31 amounted to $84,857,181, compared with $58,417,822 for the last quarter of 1935, an increase of 45 per cent.

**Reward for "Lost" Meter Socket.**—A reward of $50.00 has been offered by the Westinghouse Elec. & Mfg. Co., for the return of the two-millionth type S meter socket. It is properly marked and identified as the two-millionth socket. The finder will be rewarded upon return of the socket to the company at Newark, N. J.

**New Cable Accessory.**—To meet a widespread demand for a simple and effective device for interconnecting single conductor secondary insulated cables in manholes and vaults, the G & W Electric Specialty Co., Chicago, has developed the "Multitap" which eliminates the use of tape and solder. This splicing device is suitable for cables with or without lead sheath. The copper bus is covered with molded G & W "Resistoyl" oil and moisture resistant rubber compound. The connectors and cable ends are covered with a molded Bakelite insulator sealed at the ends by means of a Resistoyl bushing compressed on the cable with a gland nut. Cable heads are interchangeable and made for all conductor sizes up to 500 mcm. A wrench is the only tool required for installation.

**General Electric Expands in Texas.**—A 3-story, concrete and brick addition to the General Electric building at Dallas is under construction, adjoining the present office and warehouse building and will provide all departments of the company with permanent headquarters in Dallas. It is expected construction will be completed about June 1. The annex will front 80 ft on Lamar Street and extend 174 ft on Corbin Street. A new $200,000 building in Houston, located on the block recently purchased by the company, bounded by Polk, St. Charles, Clay, and Live Oak Streets, is being erected. The building, of brick and steel construction, will be 2 stories in height and will be used to house the offices, warehouses, and service shops of the General Electric Co., the General Electric Supply Corp., and the General Electric X-Ray Corp.

**Factory Built Switchgear Units.**—A standard line of factory-built, metal enclosed switchgear, for shipment as a complete assembly, has been announced by the Westinghouse Elec. & Mfg. Co. Suitable for small industrial installations or auxiliary circuits in steam power stations, the units are factory assembled and tested so that cross connections do not have to be made in the field. This metal enclosed switchgear consists of cubicles in which are mounted circuit breakers, buses, disconnecting switches, instrument transformers and similar auxiliaries. On the front panels, which are hinged, are mounted required relay and meter equipment.

**New Electric Flow Meters.**—The Bristol Co., Waterbury, Conn., announces the addition of a complete line of electric flow meters for steam, liquids, and gases to its line of mechanical flow meters. These flow meters operate on the Bristol Metameter principle of telemetering, which the company has used for several years in instruments to transmit readings of pressure, liquid level, temperature, and motion from the point of measurement to a distant point where they are recorded or indicated on a dial. The electric flow meters can be furnished for recording, integrating, and indicating flow. The readings are transmitted over a simple 2-wire circuit, telephone circuits included, which does not enter into the calibration of the instruments.

**Condit Now Allis-Chalmers Unit.**—The Allis-Chalmers Mfg. Co., Milwaukee, announces that its subsidiary company, Condit Electrical Mfg. Corp., of Boston, is now operating as a company unit and known as Allis-Chalmers Mfg. Co.—Condit Works. It will continue to specialize in the manufacture of switchgear products as a division of the electrical department under R. S. Fleshiem, manager. The personnel, with headquarters at Hyde Park, will be as follows: George A. Burnham, assistant manager of the electrical department in charge of sales and engineering of the switchgear division; W. S. Edsall, manager of sales, switchgear division; and H. V. Nye, engineer in charge of the switchgear division, with headquarters at Milwaukee. Frank W. Young is works manager.

# Trade Literature

**Motors.**—Bulletin 2-1, 8 pp. Describes single phase motors, repulsion start induction, brush lifting, 1/8 to 40 horsepower. Century Electric Co., 1806 Pine St., St. Louis, Mo.

**Connectors.**—The "Burndy News," 16 pp., in the form of a tabloid newspaper, profusely illustrated, describes numerous applications of various forms of electrical connectors. Burndy Engineering Co., Inc., 459 East 133rd St., New York City.

**Network Equipment.**—Bulletin 1184, 8 pp. Describes a complete line of low-voltage, a-c network apparatus, comprising transformers of both vault and subway types, disconnecting and ground switches, and network protectors for all applications. Allis-Chalmers Mfg. Co., Milwaukee, Wis.

**Motors.**—Illustrated folder, "Making Commutators," describes methods for manufacture, testing and inspection of commutators for d-c motors and generators. Folder, "Making Bobbin-Type Field Coils," illustrates manufacture of field coils for the same apparatus. The Reliance Electric & Engg. Co., 1086 Ivanhoe Road, Cleveland, O.

**Insulator Tester.**—Catalog 11, Sec. 2, 6 pp. Describes a new device, the "Hipot" insulator tester, a portable outfit for live line testing of individual porcelain insulators in a string or pin type insulator assembly; for operating voltages of 11,000 to 132,000 volts and higher. The equipment consists of three Bakelite sections and a handle section which screw together, an indicating instrument, a ground prod and the necessary cable and connectors. Roller-Smith Co., 233 Broadway, New York City.

**Time Delay Relay.**—Bulletin 362, 2 pp. Describes a new motor driven time delay relay, in which time ranges start with a maximum of 35 seconds and include 1 3/4, 5 1/4, 12 1/4, 26 1/4, 42 and 63 minutes. Differential gearing eliminates the use of troublesome clutches and a magnetically operated brake has been designed for the differential gear train. A standard midget relay, built into the device, provides various load contact combinations including double pole, double throw. The relay is designed for 110 and 220 volt a-c operation, and is immediately recycling. Quick make-and-break contacts are furnished with all contact combinations. Ward Leonard Electric Co., Mt. Vernon, N. Y.

**Electrostatic Voltmeters.**—Bulletin, 4 pp. Describes a new line of electrostatic voltmeters for a-c and d-c measurements, available in full scales ranging from 150 to 25,000 volts. The instruments are suitable for direct connection on either alternating or direct current for readings up to 3500 volts and are entirely independent of wave form, frequency and temperature. Flush, projecting and portable types may be had in all ranges up to 3500 volts. Applications include cable testing, determining insulator leakage, insulation testing, measuring high impedance circuits, etc. Ferranti Electric, Inc., 30 Rockefeller Plaza, New York City.

**Equipment Depreciation Analysis.**—A 176-page bulletin on the determination of the probable lives of various types of railroad, public utility and other physical equipment has been published by the Iowa Engineering Experiment Station as Bulletin 125, "Statistical Analyses of Industrial Property Retirements" by Robley Winfrey, research engineer, and will be sent free of charge on request to the Station at Iowa State College, Ames, Iowa. Five methods of constructing survivor curves for the determination of probable life are explained and compared with the "turnover" method. The method of comparison with type curves is simple, accurate, and quickly applied, all in contrast to involved mathematical methods. The bulletin will be helpful to those engaged in depreciation studies.

# Electrical Engineering

Registered U. S. Patent Office

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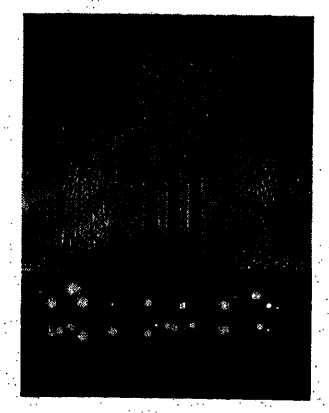
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## The Cover

**Ashtabula, Ohio, plant of the Cleveland Electric Illuminating Company, at twilight**



# High Lights

**Induction-Motor Constants.** The constants of single-phase induction motors usually are computed by means of polyphase formulas, with special adaptations to single-phase motor construction. A method of calculating electrical constants has been developed specifically for the single-phase capacitor motor, but is equally applicable to other types of single-phase motors (*pages 333–8*).

**Flux Locus.** A concept for the locus of rotor flux in a single-phase induction motor has been suggested in which the flux is referred to axes fixed with respect to the rotor; this concept is said to be less involved than either the cross-field or revolving-field theories although it does not lend itself to quantitative mathematical treatment (*pages 331–2*).

**Inductance of Solenoids.** A paper in this issue presents the derivation of series expansion formulas for calculating the mutual inductance of solenoids. The new formulas are derived from basic formulas of the National Bureau of Standards, and replace some of the older absolute formulas that require exacting numerical computations (*pages 347–53*).

**Train Heating.** Weather conditions have marked effects on the electrical energy requirements for traction and heating of trains, cold weather causing considerable increase in operating expense when power is purchased. A study of the relations of energy and temperature is reported in this issue (*pages 361–2*).

**Rectifier Circuit.** Measurement of transient oscillations of small angular swing in synchronous machines, when made by the method employing a pilot alternator connected to the main machine, may be simplified by a circuit employing rectifier tubes that enables the oscillograph to plot the actual displacement curve directly (*pages 339–40*).

**Copper-Oxide Rectifiers.** An equivalent circuit has been developed for representing copper-oxide rectifiers by replacing the rectifier element with 2 constant resistances effective during the 2 directions of current flow. Circuits are analyzed and the computed results obtained by this method are compared with oscillograms (*pages 354–60*).

**Carbon Arcs.** Low-intensity, high-intensity, and flame arcs, 3 distinct types of carbon arcs, have individual characteristics, and each is affected differently by variations in arc conditions. Effective application requires consideration of these characteristics, and adaptation of operating conditions to them (*pages 319–24*).

**Railway-Motor Standards.** Advancements in railway motor design, and the development of new types of equipment for which no standards have existed, have made necessary a revision of the AIEE standards in this field; the new standards have been adopted as "American Tentative Standards" (*pages 312–13*).

**Lightning Protection.** Some 75 per cent of all interruptions on overhead electric power transmission circuits are attributed to lightning. To reduce these interruptions and thus improve service, several methods of protecting power lines against lightning have been developed (*pages 314–18*).

**Committee Meetings.** During the Institute's 1937 winter convention, meetings of many Institute committees and subcommittees were held (*pages 380–2*). Four technical conferences also were held at the convention under auspices of Institute committees (*pages 383–4*).

**Nominations for Institute Officers.** In accordance with the AIEE by-laws, the national nominating committee met during the recent winter convention. At that meeting, nominees for Institute offices for the year 1937–38, were designated (*page 375*).

**Report on Dues.** The final report of the special committee appointed several years ago to consider dues and related matters was presented to the Institute's board of directors at its meeting held during the recent winter convention; the committee recommended no change in dues (*pages 388–9*).

**Vehicle Lighting.** Railroad cars, trolley cars, and motor coaches are now being equipped with decorative and highly effective lighting installations that greatly improve reading conditions for passengers; illumination levels are from 10 to 20 foot-candles at the reading plane (*pages 302–04*).

**Core Loss.** The magnitude of intersheet eddy-current loss in laminated cores, which may be important in large cores and with high clamping pressure, has been investigated, and a more rigorous formula for eddy currents in rectangular sections has been derived (*pages 344–6*).

**Current Loci.** The variation of currents and voltages in a general linear a-c network connected to a single adjustable branch in which the current is adjusted under some given restriction is considered in a paper in this issue; the various loci are shown (*pages 325–30*).

**Circular Loci.** The method of circular loci may be conveniently applied in the calculation of the variation of currents and voltages when self impedances are changed in various types of circuits operated at constant frequency. This method has been applied to the delta-star connection (*pages 341–3*).

**Lamme Medal Awarded.** The Institute's Lamme Medal for 1936 has been awarded to Frank Conrad of the Westinghouse company, for "his pioneering and basic developments in the fields of electric metering and protective systems" (*page 388*).

**Edison Medal Presented.** The 1936 Edison Medal, highest award of the AIEE, was presented to Alex Dow, president, Detroit Edison Company, at a special session of the Institute's recent winter convention (*pages 378–80*).

**Institute Members Honored.** Five Institute members were honored recently by Eta Kappa Nu, honorary electrical engineering society, in connection with the naming of America's outstanding young electrical engineer for 1936 (*pages* 389–90).

**Capacitance.** Calculation of the capacitance of a parallel-plate air capacitor may be made exact by a method that takes into account the fringing of the flux; several approximate formulas are also useful (*pages 363–6*).

**Power and People.** Social relations of technical advances, considered from the aspect of the arts of energy production and distribution, are discussed in an address delivered upon the occasion of the presentation of the Edison Medal for 1936 (*pages 305–11*).

**Winter Convention.** Reports of the various activities at the Institute's 1937 winter convention held during the last week in January are given in this issue (*pages 371–87*).

**Directors Meet.** For the first time, the AIEE board of directors met on 2 successive afternoons during the 1937 winter convention; many matters of importance to the Institute were acted upon (*pages 374–5*).

**North Eastern District Meeting.** Plans for the Institute's North Eastern District meeting to be held in Buffalo, N. Y., May 5–7, 1937, are progressing (*page 390*).

**Discussions.** Some of the papers presented at the AIEE South West District meeting at Dallas, Texas, in October 1936 are discussed in this issue (*pages 367–70*).

# DISCUSSIONS

Appearing in this issue are discussions of the following papers:


A Disturbance Duration Recorder—Frier . . . 367
Electrical Features of the Texas Centennial Central Exposition—Fies . . . . . 368
Experiences With a Modern Relay System—Gerell 369



Statements and opinions given in articles and papers appearing in ELECTRICAL ENGINEERING are the expressions of contributors, for which the Institute assumes no responsibility. Correspondence is invited on all controversial matters. ¶ Subscriptions—$12 per year to United States, Mexico, Cuba, Porto Rico, Hawaii, Philippine Islands, Central and South America, Haiti, Spain, Spanish Colonies; $13 to Canada; $14 elsewhere. Single copy $1.50. ¶ Address changes must be received by the fifteenth of the month to be effective with the succeeding issue. Copies undelivered because of incorrect address cannot be replaced without charge. ¶ ELECTRICAL ENGINEERING is indexed annually by the Institute, weekly and monthly by *Engineering Index*, and monthly by *Industrial Arts Index*: abstracted monthly by *Science Abstracts* (London).


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# Electrical Engineering

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# Speaking of Conventions—

## A Message From the President

AN almost universal characteristic of the human family is the desire "to come together"—"*con venio*"—"convene." Twice in the last month have I seen this demonstrated: once in New York at the winter convention of the AIEE; and again in a far different way at Colon, Panama, where the picturesque natives of the Isthmus dropped every regular occupation that they might fittingly celebrate the annual carnival just prior to the beginning of Lent. I am told that the term "carnival" is derived from 2 Latin words, *vale* (farewell) and *carnus* (meat). In gay, picturesque, and sometimes ludicrous costumes, by parades through colorfully decorated streets, and enlivened by bands, the throng bade a merry farewell to meat.

With the convention closing January 29, and an Institute trip through the South scheduled to begin at Miami, Fla., on February 12, Mrs. MacCutcheon and I feel that Providence must have arranged that the French liner "Lafayette" should sail at 11 p.m. on the 29th, and touch at Havana on the morning of the 12th. The Pan American Airways ship at 3 p.m. should have delivered us at Miami in ample time for the Florida Section meeting in the evening, but a storm prevented this. On the trip the ship touched at Martinique, Trinidad, Grenada, La Guayras, Caracas, and the Canal Zone. Of course, we traveled in an electrically equipped ship and at each port we found that the electrical engineer had preceded us and provided lights, railways, pumping stations, and refrigeration.

As the delightful cruise drew to a close we thought of the many Institute conventions we have been privileged to attend, the 1937 New York convention in particular; and the conventions of the future, the 1937 Milwaukee convention in particular.

The 1937 winter convention seemed one of the busiest, most stimulating, and most interesting that we have attended. Our only regret is that every member of the organization could not be there. The outstanding feature was the presentation of papers at the 14 technical sessions. There is a mental stimulus through the authors' personal presentation, which cannot be realized by reading alone; and the resulting discussion is sometimes more valuable than the paper itself. Frequently the discussions were continued outside the meeting long after it had closed. Next was the opportunity offered, through the many inspection trips, for observing the most modern electrical installations. The presentation of the Edison Medal to Doctor Alex Dow, outstanding pioneer and president of the Detroit Edison Company, was a memorable and impressive occasion fittingly climaxed by an inspiring address from Doctor John C. Parker, vice-president of the Consolidated Edison Company of New York, Inc.

During the convention an unusual number of committee meetings filled every available room at headquarters. Carefully arranged, these committee meetings appeared to stimulate rather than detract from the interest in the technical sessions. Because of the committee meetings many were present who otherwise would not have been able to attend. Some committees met on the first day, presented their recommendations to the board of directors at its meeting on Tuesday, and at a second meeting late in the week took steps to initiate the activity which had received the board's approval.

It has become customary to hold the meeting of the national nominating committee during the convention week. This plan brings to the convention a prominent, enthusiastic, and active Institute member from every District. Opportunity is also offered to each member of the nominating committee to consult many other Institute members relative to the most important work of the nominating committee.

For the first time in our history, the board of directors devoted 2 afternoons in a single week to the affairs of the Institute.

Those who attend a New York convention see our efficient headquarters' staff in operation and realize what a busy place headquarters is.

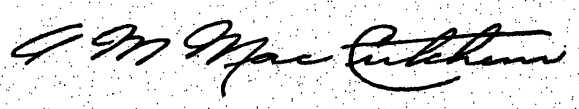
Each day I overheard or took part in discussions relative to Section activities, Section membership, Section management. Plans were discussed and final details completed as to visits by national officers to the various Sections. Ideas were exchanged and enthusiasm given and received.

Last and not least acquaintances were formed and strengthened, friendships renewed, new friendships started. The electrical engineers were meeting on a common ground and with a common purpose.

Great credit is due Chairman C. R. Beardsley, and all his committee chairmen, and the members of the committees for the excellent handling of all of the tremendous amount of planning and detail so essential to a successful convention.

The members of the AIEE enjoy and profit by convening. This year 4 invitations were received for the 1938 summer convention and one for 1939. It was indeed difficult to choose between these invitations, but Washington, D. C., was finally selected since the Section there is very active, has not previously been our host, can offer unusually adequate accommodations, and is located in a city we would all like to visit.

The next national convention will be at Milwaukee, Wis., next June, cooled by the breezes from Lake Michigan. In last December, I visited the hotel that has been selected for convention headquarters and saw one of the finest convention floors to be found in this country, with every provision for assembly and meeting rooms. The Milwaukee committee was organized over 7 months ago and has planned an unusual convention of broad general interest. In spite of a recent story in *Saturday Evening Post* I believe in conventions of the type we hold and wish the author of that story might be with us in Milwaukee and observe how a real engineering convention is carried on. I hope to meet a large number of you at Milwaukee.



# Improved Lighting in Passenger Vehicles

THE SCIENCE OF SEEING differs somewhat from the science of vision with which most of us are generally familiar. The science of vision is a relatively old subject and deals with the eyes, their functions and limitations. The science of seeing, however, treats the human being as a seeing machine, particularly as regards its behavior, efficiency, and welfare.

Years of research, from which grew this new science, definitely prove that lighting values and conditions of the past, and especially in the realm of transportation, are totally inadequate for what may be termed comfortable or easy seeing. Such ideas or beliefs as that 4, 6, or even 8 footcandles represent adequate lighting have been literally blasted.

It is obvious that of those passengers who attempt to read while patronizing transportation systems today, all but a very small percentage are 20 years of age or more. A recent survey indicates that of those at the age of 20 years 23 per cent have defective eyesight; at age 30, 39 per cent; at age 40, 48 per cent; at age 50, 71 per cent; while at 70 years of age 95 per cent have impaired eyes.

Furthermore, investigations covering several occupational groups show that in the farmer and laborer class, where work is usually carried out under daylight conditions only (500 to 8,000 footcandles), less than 20 per cent have defective eyes. In the carpenter and painter groups, a percentage of from 20 to 40 is noted; the machinist and printing occupation from 40 to 60; housewife and textile worker from 60 to 80; and in the drafting and stenographic field from 80 to 100.

The foregoing is mentioned for the purpose of bringing out the great need for more and better lighting, not only for the purpose of aiding those eyes that are already defective but also to serve to protect those millions of eyes that are as yet unimpaired.

It is encouraging to note that recently the several transportation agencies, in their earnest efforts to serve the needs of the public, have begun to give serious thought to this subject of lighting.

The modern day coach shown in figure 1 is indicative of the strides being made by the more progressive railroads. It is lighted by means of a combination indirect and direct louvered system. The indirect, which provides a low general illumination, is delivered from a single row of lamps spaced along the center line of the ceiling. Direct view of these lamps is prevented by the unique baffle which not only directs their light toward the ceiling but also serves as the duct for air conditioning.

This system is supplemented by individual seat-lighting fixtures of the direct type properly louvered, which are incorporated within the rolled edge of the continuous basket or baggage rack. Approximately 12 footcandles are obtained at the reading plane. About 5 watts per square foot of floor area are provided.

No discussion of rail transportation would be complete without presenting some of the lighting treatments which are being incorporated in the new Diesel-electric streamline trains. Figure 2 shows a portion of a truly modern observation lounge car. The lighting here is delivered from a semi-indirect open-top louvered-bottom aluminum trough containing small-wattage lamps located on approximately 7-inch centers. The general illumination is secured by light reflected from the ceiling and the reading-plane illumination derived mainly from the direct light from the lamps. The front edge of the trough and the transverse louvers in the bottom of the trough protect the eyes of those seated from direct view of the lamps. Approximately 12 footcandles of illumination are provided at the reading plane.

Another example of modern train lighting which is quite worthy of note is that of a recently built Pullman sleeping car shown in figure 3. The general illumination



**Fig. 1. Combination indirect and direct louvered lighting systems in a modern stream-lined day coach**

Indirect lighting system consists of 15-watt 60-volt lamps located above air-conditioning baffle; individual seat lighting is from 60-watt 60-volt tubular lamps located above transverse louvers in edge of bag rack

An article written especially for ELECTRICAL ENGINEERING, based upon an address by H. H. Helmbright of the incandescent lamp department of the General Electric Company, Nela Park, Cleveland, Ohio, before a meeting of the transportation group of the New York Section, April 9, 1936; recommended for publication by the AIEE committee on production and application of light.



**Fig. 2 (above). Semi-indirect louvered-trough lighting in an observation lounge car**

Each trough contains 10-watt 32-volt lamps spaced 7 inches apart

is furnished from a continuous trough of the direct lighting type, in which are also incorporated the air-conditioning outlets. The semicylindrical glass sections diffuse the light from the single row of lamps which are mounted within a reflector recessed into the ceiling. A night lighting circuit consisting of low-wattage blue-colored lamps is also included to facilitate reading the section numbers and also to insure safe passage along the aisle after berth sections are "made up" for occupancy.

A new type of berth-lighting fixture furnishing approximately 10 footcandles is installed at both ends of the section. This fixture is also equipped with the blue night-lighting feature.

Train-lighting systems of the totally indirect type, although possessing many virtues, are rapidly being abandoned, partly because of their extremely low efficiency (from 8 to 15 per cent) and the rapid depreciation of their reflecting surfaces under railroading conditions. Furthermore, a totally indirect system that would produce footcandles in keeping with modern standards would probably produce uncomfortable ceiling brightness that would be annoying to the eyes.

Strange as it may seem, the electric street-railway industry, which until recently seemed doomed to be replaced by the motor bus, has taken a "new lease on life." The industry has joined with the various manufacturers of electric railway equipment in staging a "comeback." A distinctly new type of vehicle has been developed that differs in many respects from the general conception of the street car. Lighting, consisting of a relatively large number of bare lamps studded throughout the car ceiling,

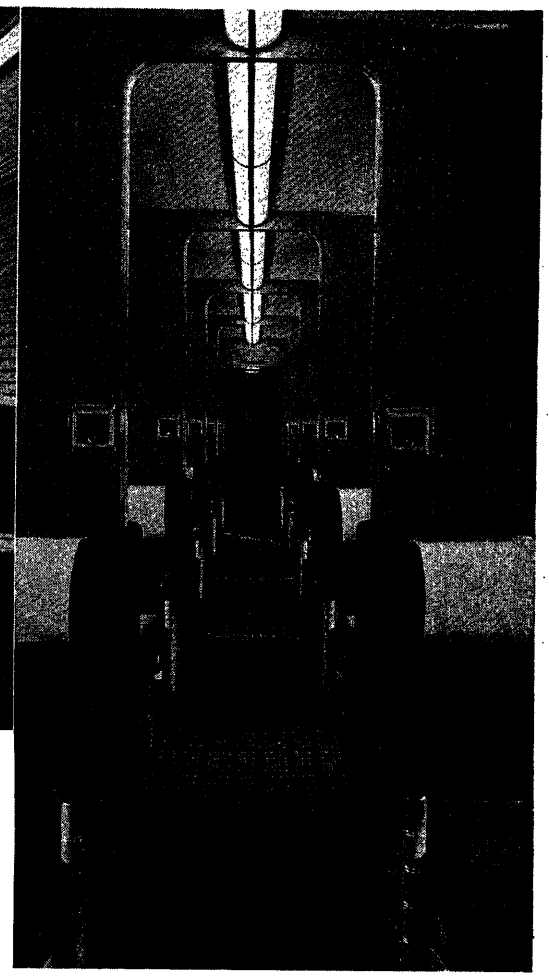


**Fig. 3. A modern Pullman sleeping car lighted by central lighting system and new berth-lighting fixtures; night-lighting circuits are incorporated within fixtures**

The ceiling fixture of the continuous direct type contains 10-watt 32-volt lamps on approximately 7-inch centers above semicylindrical flashed opal glass; small 6-watt blue-coated lamps are provided for night-lighting use

has been replaced by more efficient and less glaring systems giving the passenger from 10 to 20 footcandles of lighting. Figure 4 shows one type of street car that has been equipped with the semi-indirect louvered trough producing an average of 18 footcandles throughout the car. This replaced a direct system delivering from 8 to 10 footcandles at the reading plane.

Another continuous louvered system in which the greater portion of the light is directed toward the reading plane has been produced and installed in trolley busses (figure 5). This design also delivers approximately 18 footcandles at the reading plane, but permits a spacing of lamps 50 per cent greater than in the semi-indirect trough shown in the street car (figure 4).

Other modern and efficient types of lighting systems recently produced have fixtures of the direct type placed directly above each transverse seat. In general, the design is such that accurate control is obtained, thus preventing direct glare from reaching the reader's eyes. This control may be secured by means of lenses or by glass-



**Fig. 4 (above). Street car equipped with open-top louvered-bottom aluminum trough for lighting**

Trough contains 30-volt 1-ampere automatic-cutout lamps spaced on 10-inch centers



**Fig. 5 (right). A modern trolley coach with recessed louvered trough for lighting**

Trough contains 30-volt 1-ampere automatic-cutout lamps spaced on approximately 15-inch centers

enclosed reflectors. The lighting efficiency of these systems, in terms of footcandles at the reading plane, is slightly greater than that obtained from either the semi-indirect or direct louvered trough.

The gasoline-motor-coach field, desiring to maintain its present position in city transit and also to compete successfully with the new-type street car and the electric trolley coach, is making rapid progress in the art of lighting. Power supply has been increased from approximately 150 watts to 750 watts and in extreme instances to 1,200 and 1,500 watts. Present day practice results in one fixture containing a 21-candlepower lamp being placed above each transverse seat or its equivalent. Until recently, one fixture containing a 15-candlepower lamp and in some cases only a 6-candlepower lamp, placed above each alternate seat, was considered adequate.

Here again the lens or the reflector design is used to obtain high output efficiency and to avoid objectionable glare. By the use of the 21-candle power lamp as mentioned, it is possible to obtain approximately 10 footcandles at the reading plane. In figure 6 a good example of modern motor coach lighting is shown.

Judging from the intense interest in illumination that is being displayed by transportation officials, it is believed that the time is not far distant when transportation lighting conditions will be quite in keeping with those obtaining in other fields where usual seeing tasks are performed. Lighting still remains one of the most important tools available to the transportation field in furthering the development of passenger travel.



**Fig. 6 (below). Modern lighting in a motor coach**

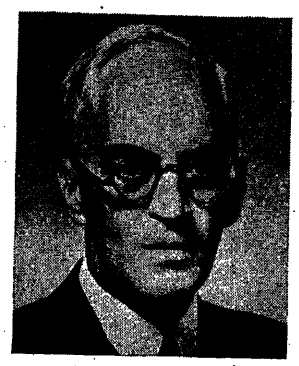
Open louvered-type fixtures are used with a 12–16-volt 21-candlepower lamp in each

# Power and People

By JOHN C. PARKER
FELLOW AIEE

**The application of technical advances to the welfare of mankind is held to be the true contribution of engineering to civilization, rather than the advances themselves; power together with tools to use it, and not power alone, led to American industrial development. More than merely the availability of large amounts of power is necessary in order that standards of living may be raised, and maintained.**

BECAUSE I know a little more about power engineering than about any of the other varied aspects of our profession, it seems suitable in large part, in attempting an inquiry into the social relations of our more mechanical performances, to use some aspects of the arts of energy production and distribution as typical rather than as the exclusive subject matter of our discussion. I suspect that we are in essential agreement as to all that will be said here this evening. Certainly I do not believe that I shall be bringing any new ideas to you, nor is what I have to say any recently inspired product of the vigorous or violent sequence of events in this decade. I hope to suggest for your reconsideration things already well known to you, but which, under the pressure of necessity in material things, all of us are likely to get into a wrong perspective or even entirely to forget.



Doctor Parker

I approach a discussion of the relation of technology to humanity with a greater hesitation because today it seems increasingly convenient to seek implications behind explicit terms. Will you accept my assurance that no suggestions are intended beyond the things actually discussed? Whatever applications to engineering conduct may be suggested, it would be most improper before a society of professional engineers to attempt to preach at other elements in society. I think it may fairly be said that however vivid our professional imagination and however sound our social conduct, we engineers are not characteristically possessed of an extraordinary degree of social imagination.

This comes about through the very nature of our training and more particularly of our engagements. Probably there is no calling more definitely social in its character than is that of the engineer. The engineer does not live a life of isolation but on the contrary works with and through other men. His work, whether it be in research or design or construction or production or commercial distribution, involves understanding of, and adjustment to and co-operation with other men. A community of effort is necessary to the complete realization of his undertakings. He has then a high reality of contact within a closely articulated social unit. In this his work is definitely more social than that of the physician or of the lawyer or of the minister of souls or of the exponent of the creative arts, each of whom, in a large degree, works as an individual. In that very fact, however, the engineer has at once a satisfaction and a limitation of his social contacts. With other men, largely of identical or at least of closely related interests and limitations, he finds satisfaction for his desires for human contact and such satisfaction easily enough so preoccupies his time that he can easily fail of social understanding of the people whom his profession serves or of the social significances of his own works.

The profession perhaps is not unlike the cloistered monastic orders, living their intensely intimate and interrelated lives, out of touch with the world immediately about them. The physician or the lawyer, on the other hand, carrying on an individual practice even with people in their less normal temper or physical state, does have of necessity a vividness and reality of contact with people other than his coprofessors, and properly to do his work must have the imagination broadly to interpret their lives, their needs, and the significance of his professional efforts in their behalf.

These individual service professions do come closer to the people served than do we.

In consequence of engineering remoteness, we perhaps become obsessed with the technical beauties and interests of our work and with the human problem of co-ordination with our fellows in creation and miss some perspective of how our works touch on the larger interests of society. Not infrequently, it seems to me, we have missed entirely the large significances of engineering and perhaps as frequently, in the fashion so common among self-deprecatory people, we have put up a certain defensive insistence on importances which simply do not exist.

If at both extremes the world has taken us at our own depreciated valuation, there can be little complaint on our part, nor can there be any great surprise if the less ponderable and less obvious values in us and in our works are not spontaneously accepted. Of course, it hurts our finer professional sense if people think of us as mere technicians of unimportant arts, whether the niceties of sound engineering analysis are appraised merely as necessary contributions to a socially unimportant technique, or, as might be inferred from lay references in the news columns

An address presented January 27, 1937, upon the occasion of the presentation of the Edison Medal, during the AIEE winter convention, New York, N. Y.

JOHN C. PARKER is vice-president of the Consolidated Edison Company of New York, Inc.

and in the advertising space, the engineer is esteemed as only a slightly sublimated form of mechanical handyman.

On the other hand, when laymen, editorial writers, and public officials agree with us in adulation of our works and hail engineering achievement as the be-all and the end-all of social progress, it is easy for us smugly to agree with what is at once too narrow a conception of the value of our work and too great an emphasis on its place in a world of human beings. When such a philosophy becomes characteristic of a nation or of a period, we may well be in desperate danger.

There is not exaggeration in the belief that a disproportionate acclaim is given to mere mechanical achievement.

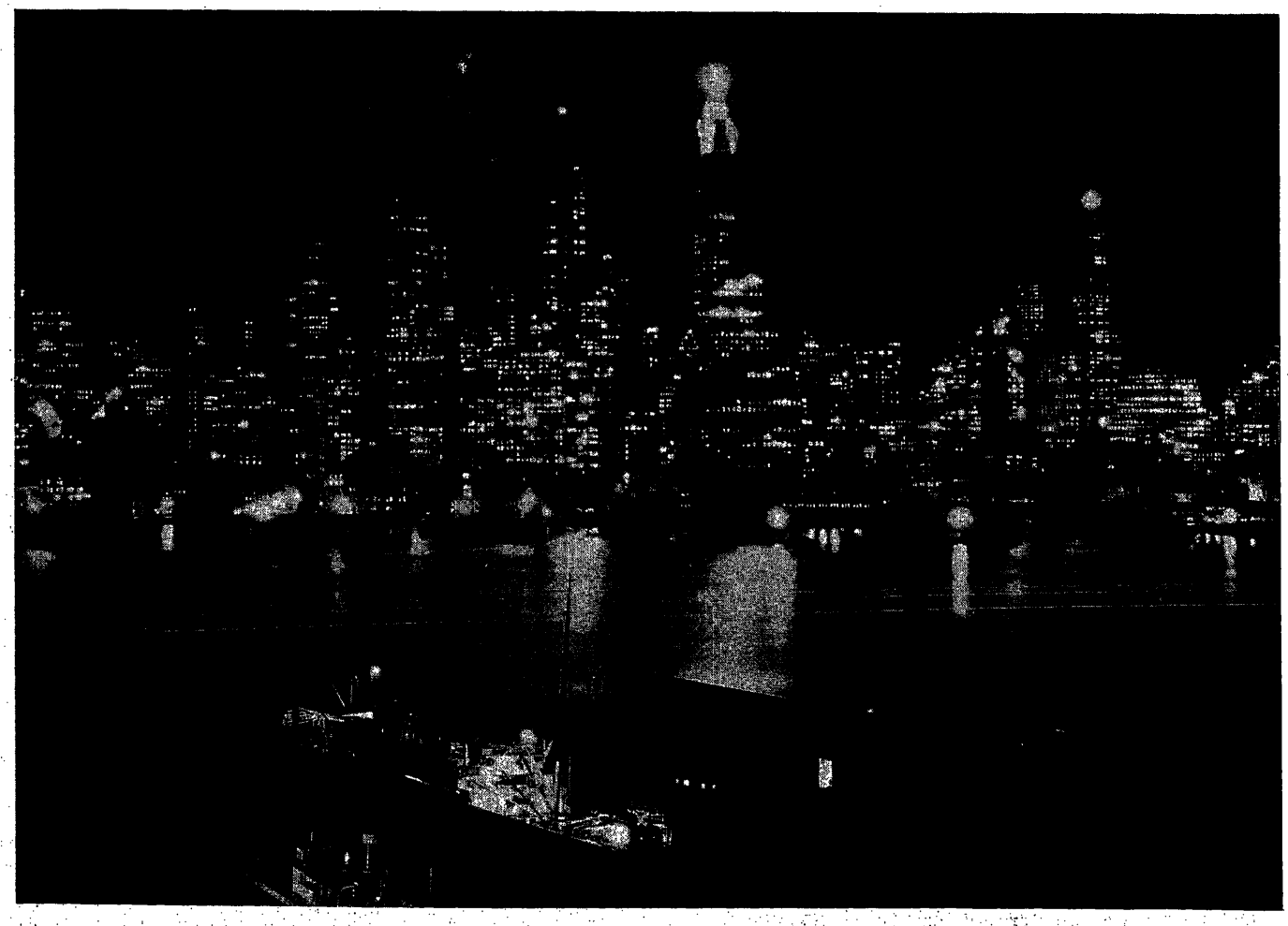
A few days ago an eminent traveler expressed his belief that the hazards of life were great in this country because we were the most highly civilized, the cause or the evidence of our civilization being, in his mind, the fact that we have so many machines. The extraordinary thing is that that remark did not produce any comment in disclaimer of mechanisms as either an origin or an evidence of civilization, though in all truth an essentially barbaric people might produce as great engineering works as did the uncivilized Romans in their crudest period of material well-being.

The truth is that our engineering activities are not necessarily evidences of civilization, nor, although they are almost essential, are they by themselves the means to civilization. On the contrary, when pursued too narrowly they can be destructive of the real values in living.

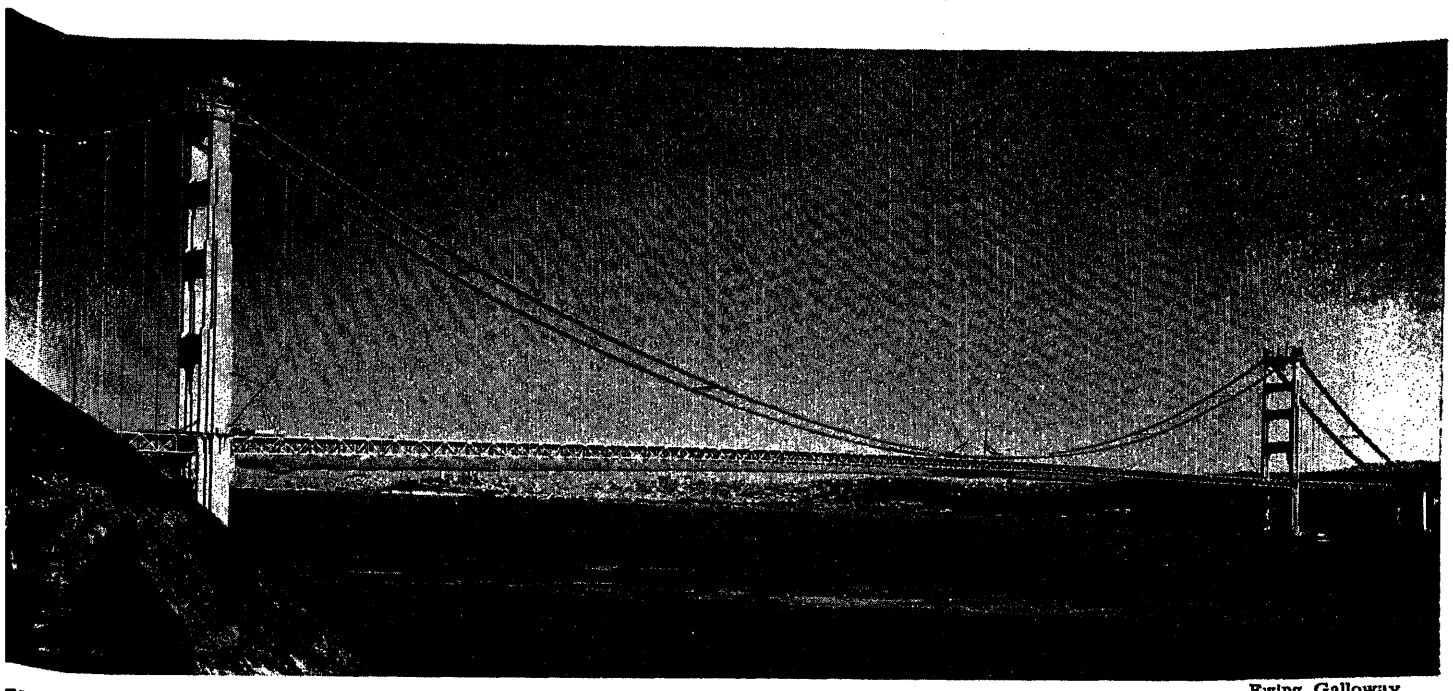
The engineer does not need to arrogate to his works an undue or an undeserved importance in order to find a splendid justification for his calling. Reasonable social awareness will disclose paramount reasons for a fine professional pride.

These lie in 2 categories, of which the first, and the one which can be a most extraordinary contribution to the welfare of the race and to the progress of our times, lies in the engineer himself. I need not develop at great length all those characteristics which most mark the men who have been the pride of our profession.

The engineer who is an engineer approaches his work without bias and with a mind freely open to conviction. He cannot be a special advocate and remain in any professional sense an engineer. Whatever may be the limits of his vision, he does at least possess a fine objectivity in his imagining. For him no sentimentality or wishful thinking will conjure up visions different from the world of things as they are. His creative thinking is the finer ability to project the observed facts of today into principles and rules of conduct and a clear picture of possibilities that are certainties because their origins are actual.



"Extra hours redeemed from darkness"



Ewing Galloway

**The pure lines of the catenaries spanning the Golden Gate and the rhythmic proportions of their supporting towers are a glorious outward expression symbolic of the courage and dignity of the conception and of the long period of painstaking and anxious preparation"**

Because of his freedom from bias and the objectivity of s thinking, he must of necessity be possessed of integrity, id because he is intellectually honest and open-minded e is tolerant of judgments that do not conform with his vn, while courageous and firm when he gets out of the ld of opinion and into that of fact.

If as a profession we can gain acceptance by the world the personal qualities of the engineer as freely as it has en willing to accept his works, society's debt to us will enormously greater.

Secondly, the works as well as the character of the gineer give him a right to claim a great place in the teem of mankind, not for the things themselves but r these things in their relation to civilized living and inking. There is a profound and important difference re and one which in practical effect needs the most pains- king care to avoid damaging, if not fatal, error. The stinction is that between sterile virtuosity and a vital tistry which reaches into the very fibers of men, or again is not much different from the contrast which exists tween a flippant self-indulgence in metaphysical acro- tics and the beneficent philosophy which gives us God, edom, and immortality.

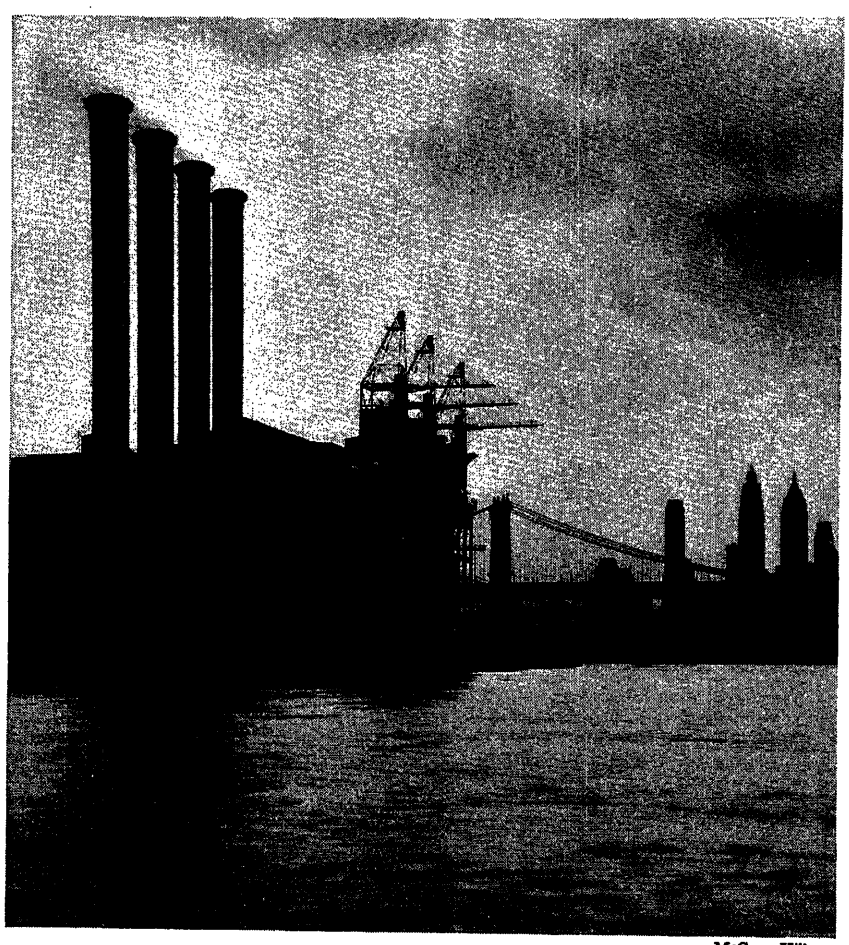
To get down to cases, the production of the electric ht or the development of an industry about it means thing or less than nothing except as it may be related an over-all improvement in the welfare of mankind. uly this art has enabled men of good purpose to live eir lives in greater security and nobly to employ extra urs redeemed from darkness. I think it is not at all reasonable to claim that the writing and the wide blication of fine literature have tremendously been mulated by the possibilities created by this one art of e engineer.

The important thing to recognize, however, is that the technical achievement has gained much of its significance as an adjunct to the arts. The production of a minute lighting unit is only a slightly more advanced form of achievement than that of the man who writes the Lord's Prayer within the space of a postage stamp, but the production and adaptation of such a luminant for the nicety of a surgical operation becomes a service very real indeed.

What is important here is, of course, how people use the power that we place in their hands. Quite as easily, if humanness of feeling and cultivation of mind do not go along with our technical possibilities, these can become curses rather than beneficences.

So, if we please, the telephone and the telegraph, interesting inventions, marvelous expressions of research and energy and co-operation and faith, still remain things of little importance except as they bring people into more familiar intercourse and closer understanding one of another, except as they remove the narrowness of isolation and contribute to the genuine happiness and welfare of men.

Our great railroad systems would not be worthy of the sacrifices that have gone into creating them were it not for what they have done in enabling men to push out into freer and more intelligent lives and to grow, and themselves, through the agencies of transportation, to be of service to other men in distant parts of the world. The automobile merely as a device for speed and restlessness would be a wonderful mechanical achievement and a curse to the race, but men have been able to relate themselves to, and to appropriate, these engineering achievements for a more decent living and as aids to something more than merely material happiness. In all these real values our engineering works have gained their significance be-



McGraw-Hill

"The power engineers of this country have done, as the engineers have done in practically every field of American endeavor, a glorious job"

cause of uses ancillary to other functions of living, and doing so have become vastly greater even than the engineers conceived.

I would not be thought for one moment to be deprecatory of the intrinsic romance of engineering achievement, nor would I concede that engineering structures are deficient in beauty and in nobility. The pure lines of the catenaries spanning the Golden Gate and the rhythmic proportions of their supporting towers are a glorious outward expression symbolic of the courage and dignity of the conception and of the long period of painstaking and anxious preparation. The spiritual qualities of such an engineering work may be different from those appearing in a work of poetry, art, or music, but because of difference they are no less present. All one would say is that in both the engineering and the less rigorously scientific fields of the other arts the real beauty, the real romance, the real nobility come from interrelation with life.

Indeed such things as we have spoken of—the service which engineering works render to life, and the spirit and the character with which the engineer approaches his profession—are the stuff of which the arts and philosophy are made.

Even in the narrowly technical sense, our portions of the arts are portions and not the whole, and a great deal of disappointment and some social disturbance can be avoided by recognition of that. A specific instance may illustrate the way in which absence of realistic social awareness may lead to dangerous implications.

There is a general public interest in the problems of power production and distribution that is way out of proportion to any significance even so important an art has in the affairs of men. This would be puzzling if it were only a recent phenomenon. It is not the less disturbing because of the fact that it has been developed over a period of years by an ill-considered but perfectly honest enthusiasm which has mistaken simultaneity of occurrence for a relation of cause and effect.

When in the middle and late '20's the rest of the world was suffering the economic aftermaths of war and we in this country were riding on the full tide of what we believed to be prosperity, we explained to ourselves that we had so many horsepower back of the elbow of every American working man. The *Daily Mail* sent an English commission to discover that mechanically developed power was the great secret of American prosperity; the Soviet Union initiated its series of 5-year plans with an emulation of the great American electrical industry, while Fascist Italy sought to develop the backbone of the peninsula through a superpower system. I have no quarrel with these things, but I had then and have today a profound disagreement with a wrong emphasis.

The power engineers of this country have done, as the engineers have done in practically every field of American endeavor, a glorious job and they continue to do so. We have produced and distributed a superlative quality of service at extraordinarily low prices. It has been made available to the largest feasible percentage of the population and is used in a degree almost unrivaled throughout the world. Yet this much vaunted power use did not suffice to keep us from plunging headlong and with characteristic American vigor into the world depression. There is no reasonable basis for believing that power development on an even greater scale in this country is going to pull us into the prosperity which the secret of American well-being a dozen years ago was not able to preserve for us. Claiming all the territory in sight at that time was a result of rather superficial thinking. Power engineers today would be foolish if they accepted the responsibility implied in the theory that dynamic development is a thing precedent to social or economic uplift. Acceptance of any such idea will simply find the power people again discredited.

Let us see what the actual fact is in regard to the place of power development in the American industrial picture of the predepression days. There was more power at the

command of the worker in industry than existed anywhere else in the world. It is so rudimentary as to be almost trite to say that the factory worker did not take $x$ kilowatts into his hands and apply them directly to a bunch of steel ingots and have a freight car emerge from the process. Not only that, but American industry did not set out with the idea of trying to apply power to industrial production and thereafter discover the means for utilizing power. Ingenuity, energy, and the courage of conviction produced the machine tool, the turret-lathe, the automatic screw machine, punch presses, and drop hammers. These called for power and for power in ever increasing quantities. Without an ample supply of dependable power at modest prices we should have had carefully to restrict the use of power in manufacture and the hand processes would have persisted here as they have elsewhere.

The power industry saw a commercial opportunity and observed a social responsibility. Its place in the picture is sufficiently great in that it did supply that which was necessary to the operation of the machine tool.

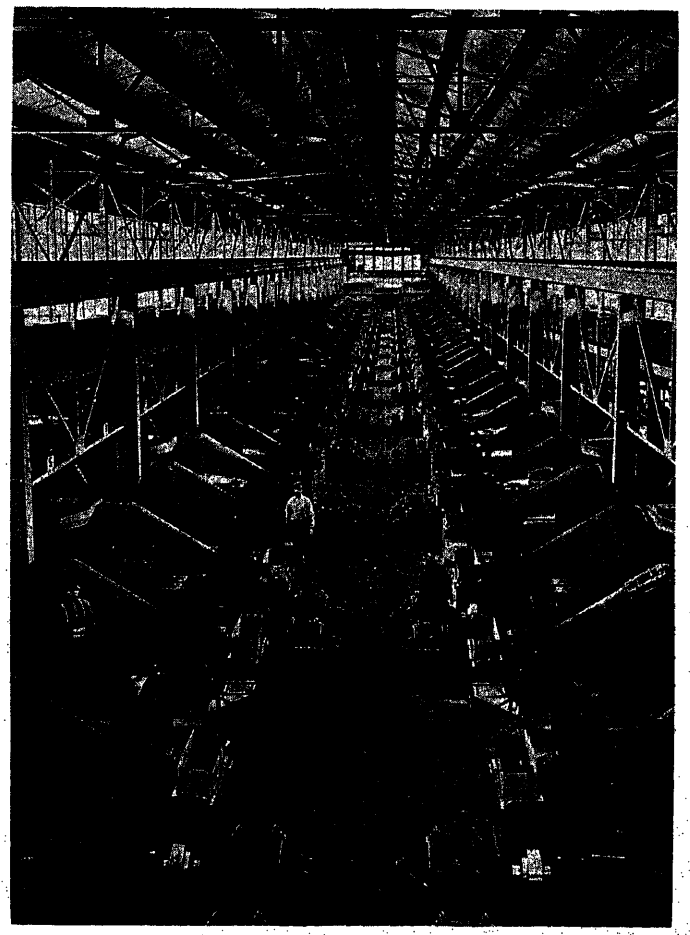
Neither power nor the machine tool without the other could have established the American methods in industry, nor could both of them together have done very much without the development of elemental metals and of alloys and plastics which should lend themselves to the processes of quantity production. These again would have been of little use had it not been for the development of design directed quite as much to the working of modern materials through the power driven machine tool as to the functioning of the product after it was made. An entirely new technique of design was called for, a technique superb in its philosophic simplicity, in its intellectual straightforwardness, in its impatience with artifice or dissimulation. But neither design for production, nor modern materials, nor machine tools, nor the power to drive them, or any of them in combination would have been of the slightest use without one of the greatest contributions that America has made to industrial progress. That contribution may be described in any one of its aspects as the use of tolerance limits, interchangeability of parts, standardization, the use of limit gauges. Again there is a whole philosophy of moral conduct suggested in the conception of units interchangeably and excellently adapted to correlation with other units for the production of a whole, no one being required to be perfect but each one being limited to a tolerable excess or deficiency from a working ideal.

When all of this is said and done we have not yet quite approached the full story of the place of power in the business of satisfying the needs of the people. Engineers well understand that the process of industrial production, whether it be in machines or textiles, in meats or magazines, is a function of quantity. Below a rather large minimum an enterprise cannot develop the methods of interchangeability which make the machine tool tolerable or which bring power into the service of the workman. Enterprise and courage and a reasonable assurance of success are necessary as inducements to the people who risk their savings in enterprises which may become obsolete on a whimsical turn of fashion or impotent through a major economic disturbance. This is the part of the entrepreneur who, in a very real sense and working outside the fields of power development, has been necessary to the development of the industrial uses of power in this country.

All these elements put together might have accomplished nothing had it not been for the superb achievements in distribution which have brought the end results of industry to the final user.

Some engineers and a certain sentimental type of social scientist occasionally deprecate the function of commercial distribution and find it quite without use. I am not at all sure that advertisers and merchants are perfect or even intelligent in their processes, but I do know that it is something to have persuaded several millions of people to want a new agency of transportation and to promote such construction of roads as would make it possible for those millions to reorganize their living about an automobile, and to persuade those same millions to accept an at least currently standard type of machine rather than individualistically to insist on going without through devotion to the fetish of tailor-made cars.

I am not permitting my enthusiasm to enlarge the importance of the nonengineer in this whole sequence of development. I know perfectly well that salesmen and capitalists did not in the first instance plan all that they have produced any more than the power engineer, when



Ewing Galloway

**"Power at the command of the worker in industry"**

he developed his induction motor, had any idea of applying it to the gargantuan rolls of a steel mill. I am simply saying that these people, like ourselves, recognized facts as they came along and had imagination to build from them a little at a time until from gradual progress there developed a philosophy of commercial existence. Indeed, had they tried to devise an economic or industrial system out of their own imaginings they would probably have come off very badly.

The machine tool itself was a product of necessity. It probably never would have come into at all substantial use had it not been that the cost of supporting the typical American workman made necessary some means tremendously of increasing his productivity.

Note well that every one of these elements which we have sketched has been essential to modern industrial life as we know it; even more than that, has been essential to modern nonindustrial living. Our enthusiasm for one of these elements in which we may happen to be particularly interested—let us say power—should not run away with our sense of proportion. On the contrary, it seems to me that our pride in our own service becomes greater if we have an adequate picture of where it fits in as an essential and considerable element of something enormously bigger than itself.

We need not be at all deprecatory of the importance of our power developments as service to the home or to the farm merely because we may be realistic in our apprehension of the fact that many other things enter into life and that the life is more than meat and the body more than raiment. It is understandable, though not by virtue of that at all defensible, that the specialist should develop an unrestrained enthusiasm for his particular field of human endeavor and that his extreme loyalty might communicate his zeal to others. What is not perhaps quite so clear is that economic, social, and political injuries may result from these widespread and exaggerated enthusiasms. Not alone as a matter of humane consideration, but in self-defense against the reactions of disappointed hope, we must be at pains not to arouse desires that we cannot gratify or which, gratified, will be found not all that the body or the soul can crave.

Energy available as a contribution to carrying on the amenities of domestic life is, beyond question, almost, but not quite, indispensible and a long, long way from being all-sufficient. Let me qualify this a bit. Energy in some form or other is, of course, completely necessary to human existence. For all of the necessities of life there are substitutes for those forms of energy with which you and I, as electrical engineers, are most concerned, and in some applications these other and more ancient forms may come very close to the excellences that we can offer, if indeed in some respects they may not offer facility or charm rather greater than can be developed by electric power. With this qualification, may I return to the statement that our special form of power is almost indispensible to the convenience of modern living.

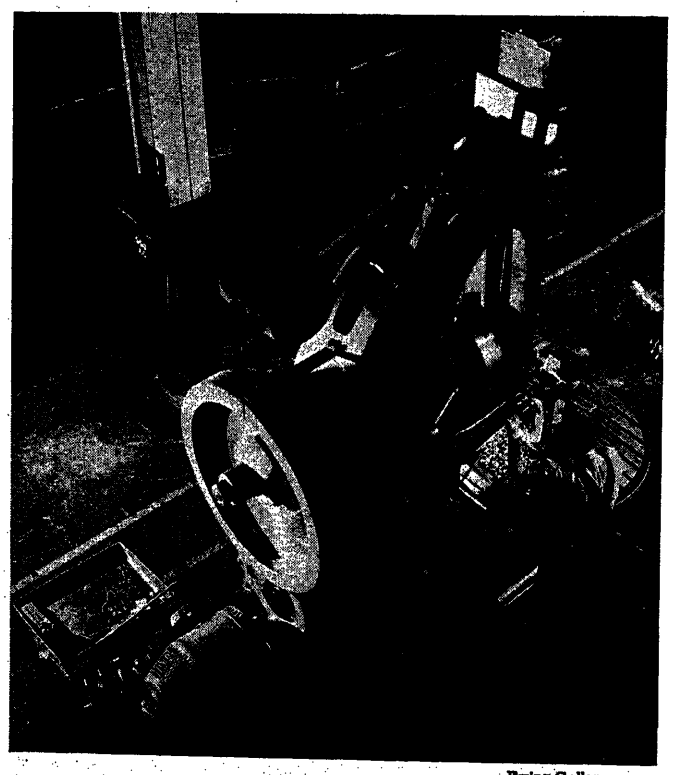
Unfortunately the ultraenthusiast paints so vivid a picture of the domestic comfort created through the power agency that people in all simplicity but in no less great sincerity come to believe that electric power is at once necessary to living and a solution of all the mechanical problems of the home. I have even read claims not dissimilar to those on behalf of the $x$ horsepower at the worker's elbow—namely, that electricity can take all the guess work out of cooking and the drudgery out of domestic life.

It is perhaps reasonable to suspect that a good deal of the current abnormal interest of the people in power problems may be due to their persuasion that this, that, or the other overly exploited device is essential to civilized living if not a sure cure for all of the difficulties thereof, instead of being, as in many cases it is, a most remarkably adept contribution thereto.

So, if you please, a profound conviction of the value of extending to the farm the power use which has been so common in industry may run away with itself.

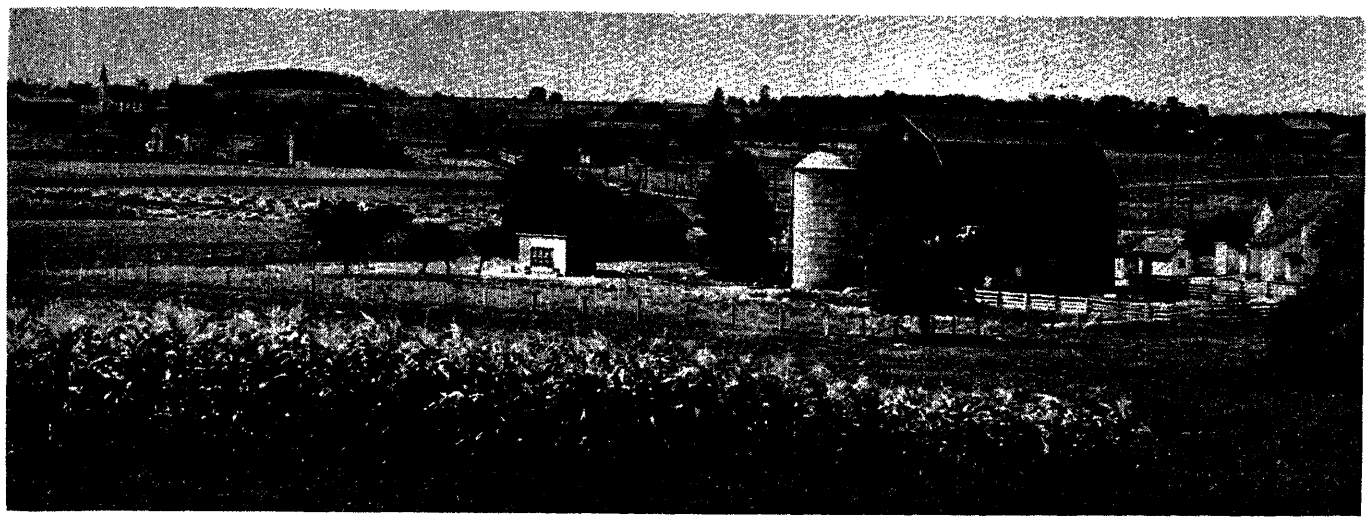
More than 25 years ago, as chairman of the committee on electricity on the farm of the association of the industry with which I was identified, I had occasion to know those early efforts at a broadened use for power. My own company in the rich farm country of western New York discovered at once the values, the difficulties, and the limitations of farm supply from contiguous distribution circuits. From such a realistic background, I have observed with much satisfaction the various well-planned efforts which, in this country of vast subeconomic areas, have saturated every section whose intrinsic economy at all approaches the productivity or the population density of western Europe.

On the other hand, I note a marked parallel between



Ewing Galloway

**"Neither power nor the machine tool without the other could have established American methods in industry"**



Ewing Galloway

**Here "rural electrification is feasible and highly developed"**

power use and the human relations. Farm use is least in those states where farm tenancy is common and progressively greater until we reach an extraordinary saturation in the lean, rock-ribbed, stubborn, but user-owned farm country of New Hampshire.

This and similar human factors make it important that we note certain limitations in this as in other desirable fields of power development.

In the first instance, the farm is not a quantity-production factory. Its functions are biologic and not mechanical, and the conditions are not repetitive nor even precisely cyclic. The economic contribution which power makes in industry cannot reasonably be expected to have any parallel in farming. The economic welfare of the rural regions is much more intimately concerned with soil quality and selection of strains and with plant and animal pathology and with market problems and transportation than with the application of mechanical power.

Success of our endeavors in industry does not necessarily indicate that we can contribute equally richly to agriculture.

Rural electricity, of course, can contribute markedly to ameliorating the conditions of rural life, but here, as in claiming too much for the economic values of farm electrification, we must be reasonably careful that we do not arouse hopes that can only result in frustration. Strangely enough, it seems not to be popularly recognized, nor even to be realized by those better informed technically, that the refinement of running water in the home is not, excepting in the least degree, related to electric wires along the highway. Yet a thumbing of the pages of any mail-order catalog will bring vivid conviction of the fact that pumps, piping, and fixtures not only are the essence of that particular evidence of civilization but that they are somewhat easily to be had. Until the essentials of sound sanitation are sought by the rural population one wonders at times about the value of the electric circuits.

The most distressingly backward of our rural communities do not in all conscience need electric power, either economically or as adjuncts to living, one-tenth as much as they need many other things closely at hand but still frightfully difficult of attainment within a farm income restricted so narrowly as to make impossible many of the mere decencies of life. I even have a suspicion that when a good job has been done in the way of aiding and advising in an improved agricultural technique and when the intimacy of human understanding offered by education and the means of communication and the means of transportation has itself ameliorated farm living as a result of the economic and social improvements, power lines will almost automatically have become extended to every part of the farm community intrinsically capable of supporting the purchase of the devices necessary to the utilization of power.

Failing of these things, which seem to me to be fundamental, there is grave danger than when experience shows electric service to be unattainable in vast stretches of this country, as it must for a long time continue to be, or when the farmer along the electric right-of-way finds his economic lot and his social outlook not essentially different than formerly, disappointed hopes will vent themselves at the expense of those who encouraged them.

A too-great desire to electrify a type of countryside unknown in those sections where rural electrification is feasible and highly developed has painted a picture of blessings enjoyed by the city dweller and believed by one all too aware of his hard lot to be denied him as a result of deliberate mischief. Thus group suspicion and aloofness have unnecessarily and unjustifiably been strengthened.

What I have been trying to say is that important as is power as an adjunct to factory, farm, and home, it, in and of itself, will not revolutionize life. We are, in our most profound relations, biologic creatures and all the conscious mechanical and technical efforts in the world are small factors in determining the essential well-being of our lives. To the extent that we have made our lives in their superficial details depart from our biologic origins, we find the mechanisms of living important. They will be the more important if our perspective keeps them in the proper relation to the other elements of living and to life itself.

# Revision of Standards for Railway Motors

By NORMAN W. STORER
FELLOW AIEE

**Higher armature peripheral speeds, better insulation, and improved ventilation of railway motors, together with the rapid development of Diesel-electric equipment for railroads, have made necessary a revision of the AIEE Standards for Railway Motors. The new standards have been adopted as "American Tentative Standards" pending further experience with the new types of machinery covered by them.**

THE STANDARDS of the AIEE for railway motors, which for many years have been accepted in the United States as the "last word" and have had an enviable reputation in all other parts of the civilized world, have been completely revised and have advanced to the status of a tentative American Standard. They will be published shortly by the AIEE as "Rotating Electrical Equipment for Rail Cars and Locomotives." Approval of this further revision was given by the AIEE board of directors at a meeting held at Pasadena, Calif., on June 24, 1936, upon recommendation of the AIEE standards committee.

Compiled by sectional committee *C*-35 of the American Standards Association under the sponsorship of the AIEE, these standards are based on many years of experience in the design and operation of railway motors and generators. They are necessary at this time not only to bring the AIEE standards for railway motors up to date, but especially to develop standards for gas and Diesel-electric equipments, the manufacture of which has grown to large proportions.

These new standards have been adopted as "American *Tentative* Standards" because the new types of machinery covered by them have heretofore had no definite standards, and such standards must therefore be developed. It is also important to leave the door open for changes if any are necessary in order to come to an agreement with the International Electrotechnical Commission.

The necessity for bringing the railway motor standards up to date will be apparent when the developments of the last few years are considered. The motor designers have been very active, and have wrought wonderful results. The problem has had the most intensive study, and advantage has been taken of every improvement in materials, processes, new discoveries, and operating experience, with the result that there has been a gradual shrinkage in the dimensions and weight of the motor that is truly remarkable.

## Reduction in Weight of Motors

Twenty years ago, the street-car motor weighed in the order of from 40 to 50 pounds per horsepower at the one-hour rating. Today street-car motors are being built weighing from 8 to 12 pounds per horsepower at the continuous rating.

Until very recently, the almost universal practice was to mount one side of the street-car motor on the axle, support the other side on the truck, and gear the armature to the axle through a single train of gears. That practice has been practically superseded for street-car motors by removing the motor entirely from the axle, carrying it on separate springs, or mounting it rigidly on the truck, and driving either through a double-reduction gear unit carried on the axle, or through a "right-angle drive" and a hypoid gear. In either case, the motor is relieved of the pounding of the track, and the track and special work are relieved of the pounding caused by the dead weight of motor on the axle, both results being very desirable.

These light-weight motors together with the light-weight car construction recently developed have given the street railway a new lease of life and made possible the high-speed stream-lined Diesel-electric trains that have recently been so much in the public eye. In the Diesel-electric trains, the weight of the power plant and motors, with the car to carry them, forms a considerable part of the total weight of the train, so that, because the weight reductions outlined apply to both motors and generators, the total reduction is a very important amount.

The question arises as to how this great reduction has been accomplished. There are 3 important factors that are directly responsible:

1. Higher armature peripheral speeds
2. Higher permissible temperatures
3. Better and more ventilation

The output of a given size of motor with a given current capacity increases as the rated voltage and speed increase, to a certain point, then more slowly as the torque begins to fall as the result of core loss and windage until maximum voltage or maximum speed is reached. Hence, other things being satisfactory, it is desirable to operate at as high a speed as is feasible with the gearing available. Higher speeds now used were made possible by refinements in the construction of armatures and commutators, perfect balance, roller bearings, and improved gears.

The rise in the temperature of a railway motor has always been one of the most important, if not the most important, limits. Of course, the motor must be strong enough mechanically and must commutate satisfactorily.

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Essentially full text of "Revised Railroad Standard Recognizes Light-Weight Motors, New Designs," published by the American Standards Association in the February 1937 issue of *Industrial Standardization*.

NORMAN W. STORER, retired, Pittsburgh, Pa., is former consulting railway engineer of the Westinghouse Electric & Manufacturing Company, East Pittsburgh, Pa. He has had many years of experience in railway work, and served on the AIEE committee on transportation almost continuously from 1914 to 1936. A biographical sketch of Mr. Storer appeared on page 1405 of the December 1936 issue of ELECTRICAL ENGINEERING.

After these features are secured, the rise in temperature fixes the rating. Hence, any increase in the permissible temperature rise will permit an increased rating. There has been a great deal of experience in the last 20 or more years with insulation made of incombustible materials such as mica and asbestos, known as class *B* insulation, which has convinced the committee that the temperature rises given in the AIEE rules can safely be raised for class *B* insulation. It has, therefore, been increased from 105 up to 120 degrees centigrade rise at the continuous rating, measured by the resistance method. This is a conservative increase based on the large number of motors which have been operating for years at such temperature rises.

Twenty-five years ago, it was the general practice to operate with street-car motors completely enclosed. Locomotive motors were in some cases cooled by forcing a stream of air through them by motor-driven blowers. The use of fans on the armature shafts, inside of the motor frames, was just beginning. Both of these methods of cooling railway motors have been carried to what appears at the moment to be the ultimate limit and have made tremendous increases in motor capacity.

## Increase in Peripheral Speeds

In no class of railway motors have speed and ventilation been carried to greater extremes than in the single-phase motors for the Pennsylvania Railroad for multiple-unit trains and stream-lined passenger locomotives. There, peripheral speeds of armature and commutator are approximately 12,000 and 9,000 feet per minute, respectively, which are about 70 per cent above the speeds of a few years ago. A veritable hurricane is blown through the motors. The weight per horsepower was brought down below that of d-c motors designed only a few years ago, which made it entirely practicable to equip a single-phase passenger locomotive with motive power capable of slipping the wheels with the maximum permissible weight on the drivers and still be able to develop the full motor rating at 90 miles per hour.

With such motors as these, the old methods of rating fall short of the requirements. The continuous rating becomes practically the same as the one-hour rating because of the rapid ventilation. The one-hour rating is of little, if any, value as a measure of the thermal capacity of the motor, and many engineers have advocated dropping it, but while admitting its small value, the committee feels that it should be continued until a better measure of thermal capacity is agreed upon.

For these reasons, the committee offers a "thermal capacity rating" in the appendix. A number of schemes have been suggested but none has yet had any extensive test. The method proposed will add very little to the cost of the usual tests and should, if properly used, give a good measure of thermal capacity, which is practically the same as overload capacity. The committee asks for a fair trial of it and the results obtained.

Altogether these rules represent the best thought of the committee that compiled them. The committee consists of 2 members each from 4 national organizations which are vitally interested. They are as follows:

AMERICAN TRANSIT ASSOCIATION

H. H. Adams (M'19) superintendent of shops and equipment, Chicago Surface Lines, Chicago, Ill.

R. H. Dalgleish (A'11) chief engineer, Capital Transit Company, Washington, D. C.

NATIONAL ELECTRICAL MANUFACTURERS ASSOCIATION

S. B. Cooper, railway sales department, Westinghouse Electric & Manufacturing Company, East Pittsburgh, Pa.

M. R. Hanna (A'03) engineer, motor division, transportation department, General Electric Company, Erie, Pa.

AMERICAN RAILWAY ASSOCIATION

J. E. Sharpley, electrical engineer, The Virginian Railroad, Princeton, W. Va.

Sidney Withington (M'20, F'24) electrical engineer, New York, New Haven and Hartford Railroad, New Haven, Conn.

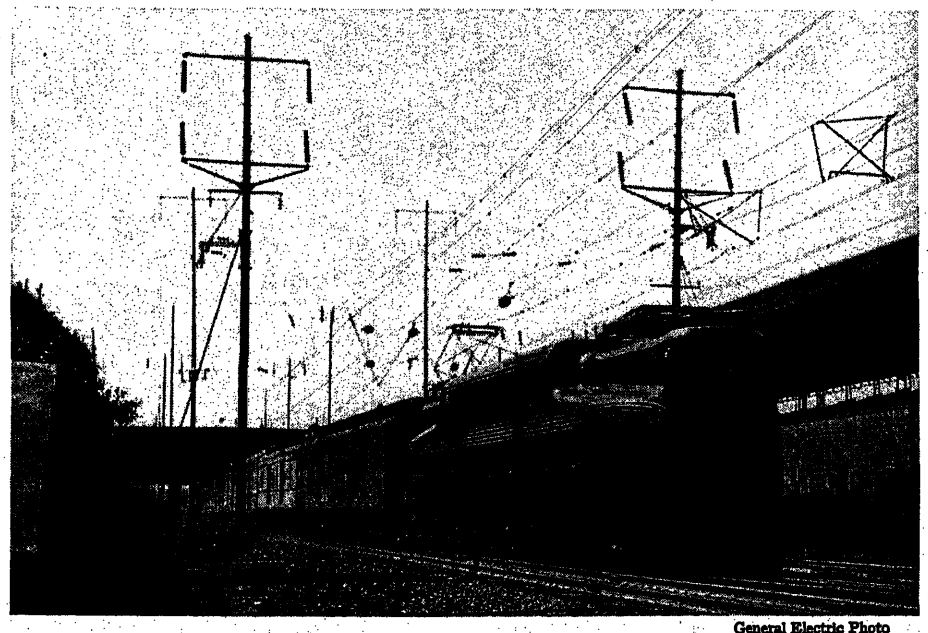
J. V. B. Duer (A'15, F'29) *alternate*, chief electrical engineer, Pennsylvania Railroad, Philadelphia, Pa.

W. S. H. Hamilton (A'19, M'26) *alternate*, equipment electrical engineer, New York Central Railroad, New York, N. Y.

AMERICAN INSTITUTE OF ELECTRICAL ENGINEERS

E. L. Moreland (A'11, F'21) consulting engineer, Jackson & Moreland; also head of department of electrical engineering, Massachusetts Institute of Technology, Cambridge.

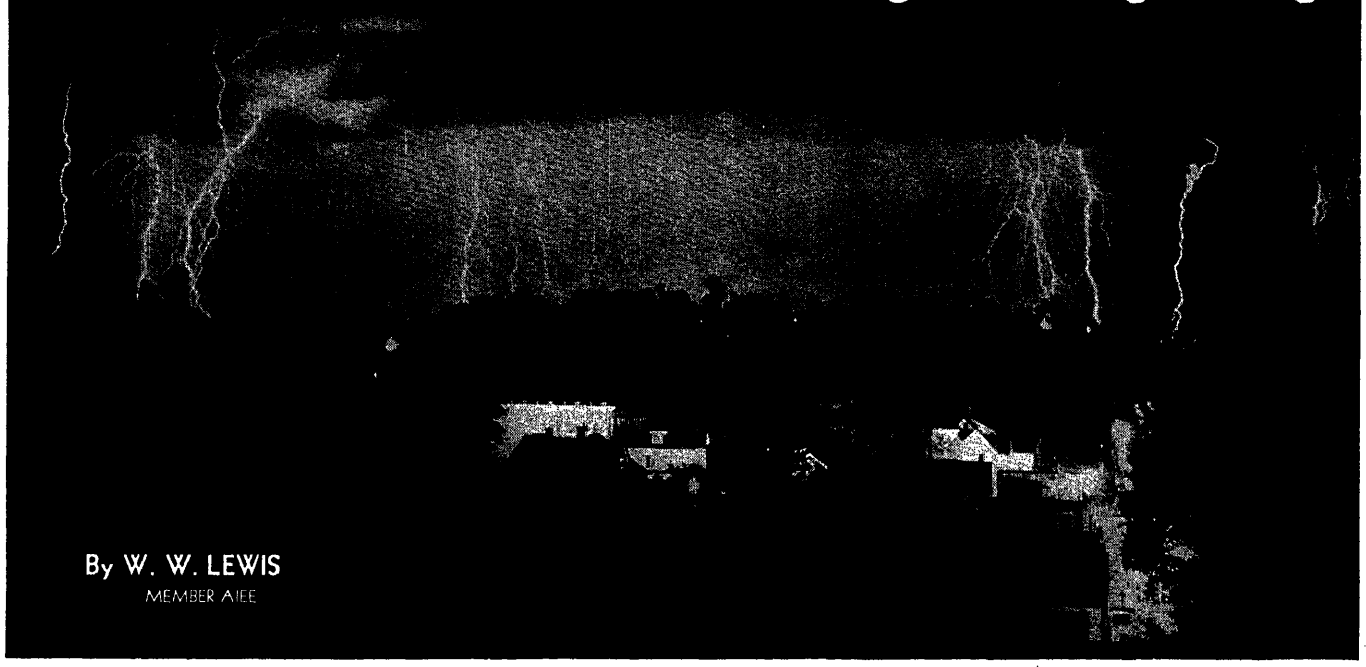
N. W. Storer (A'95, F'13, member for life, past vice-president) *chairman*, retired, Pittsburgh, Pa., formerly consulting railway engineer, Westinghouse Electric & Manufacturing Company.



General Electric Photo

**A passenger train of the Pennsylvania Railroad entering Philadelphia, because of their advanced design the single-phase motors with which the streamlined locomotive is equipped require new standards for rating**

# Protection of Power Lines Against Lightning



By W. W. LEWIS
MEMBER AIEE

**A brief review of the fundamentals of the lightning protection problem, and of the various common methods of protecting power transmission lines against lightning, their comparative merits, and their relative costs.**

IN THESE DAYS of intense public interest in electricity, the public utilities are making every effort to provide as continuous and dependable service as possible. They are interested therefore in those types of construction and auxiliary devices that will help them maintain a high standard of service.

It is probable that lightning can be held responsible for at least 75 per cent of all interruptions on bare-wire transmission circuits, at least in the eastern part of the United States. The other 25 per cent is caused by such things as wind, sleet, trees, failure of line insulation or structure, failure of apparatus, and mistakes in operation.

The lightning discharge from cloud-to-ground may cause induced or direct potentials to appear between conductors and ground. If such potential is sufficiently high, flashover may result; and if the lightning flashover is followed by dynamic current, tripout may follow.

There are several ways in which the effect of lightning upon transmission lines may be minimized: by the use of (1) overhead ground wires, (2) expulsion protective gaps, (3) Petersen coils, or (4) immediate initial reclosure. In the following paragraphs these methods are discussed in detail.

## Line Without Overhead Ground Wires

When lightning strikes a conductor on a line not equipped with overhead ground wires, the current divides and flows in both directions toward the towers. Only a small amount of current passing through the surge impedance of the conductor is necessary to built up sufficient potential to flash over the insulator string.

When lightning strikes a tower, the total current passes down or up the tower, encounters the tower-footing resistance, and raises the potential of the tower above ground potential. This potential is roughly the product of the current and the tower-footing resistance. If this product is high enough, an insulator string or strings will flash over. In some instances the normal-frequency voltage added to or subtracted from the transient voltage may determine which strings flash over. Flashover of an insulator string places the impedance of the conductor in multiple with that of the tower and tends to relieve the potential of the tower and thus may prevent other strings from flashing over.

Where wood poles are used, the resistance to ground is so high that flashover between conductors may take place instead of flashover to ground.

## Line With Overhead Ground Wires

One ground wire is usually not sufficient to shield the conductors effectively from direct strokes, either on single-circuit horizontal arrangements or double-circuit vertical arrangements. Two ground wires placed above and mid-

Essential substance of a paper presented at a meeting of the AIEE Philadelphia (Pa.) Section, January 11, 1937.

W. W. LEWIS is electrical engineer in the central station engineering department of the General Electric Company, Schenectady, N. Y. He is the author or co-author of several Institute papers on lightning protection, and is serving on 4 Institute technical committees.

way between the conductors on horizontal arrangement or over the outermost conductors on vertical arrangement have proved adequate in practice to shield the conductors.

When the conductors are properly shielded, a direct stroke will strike either the ground wires or the tower. If it strikes the ground wires, the current will divide and flow toward the towers at the ends of the span. At the tower the current will divide again, part passing down the tower and part continuing on the ground wire. The part passing down the tower will encounter the footing resistance, the tower will be raised in potential by the product of current and resistance, and flashover will result if this product exceeds the strength of the insulation. Coupling between the ground wires and conductors and the normal-frequency voltage may sometimes determine which insulator strings flash over.

When lightning strikes the top of a tower, the current divides, part going down the tower and part going out on the ground wires in both directions. Again, the part going down the tower encounters the footing resistance, raises the potential of the tower above that of the conductor, and may cause flashover if the potential is sufficiently high.

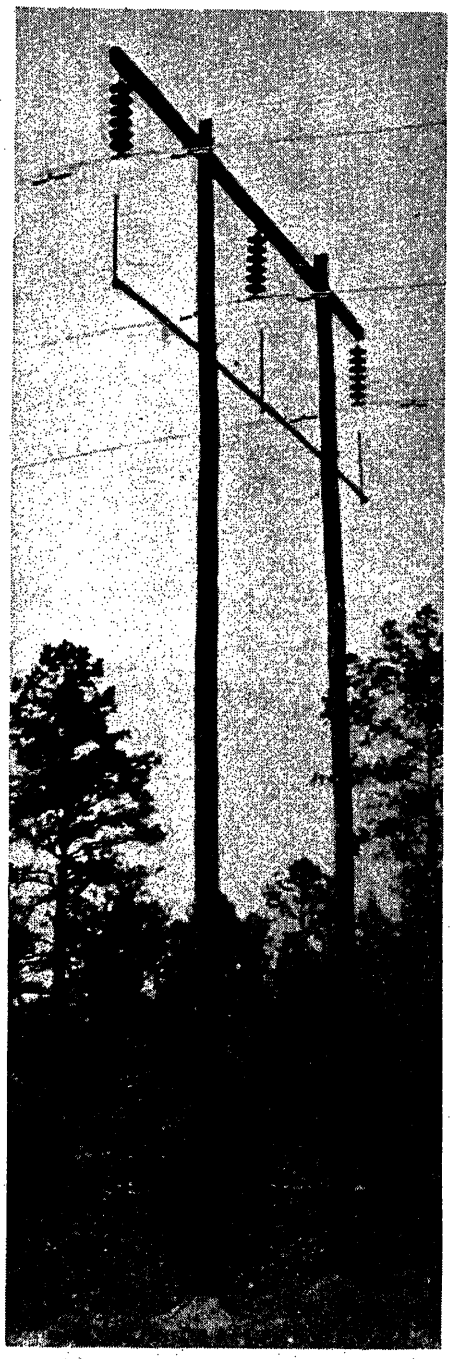
Where wood poles are used with overhead ground wires and down leads, the action is exactly the same as for steel-tower lines, except that the wood crossarm may add extra insulation and allow the potential to rise somewhat higher before flashover. Where the insulator hardware is bonded and grounded, the action of wood-pole lines is identical with that of steel-tower lines.

## Tower-Footing Resistance

From the previous discussion it is apparent that the prevention of flashover resulting from direct strokes to overhead ground wires or towers, depends largely on the tower-footing resistance. Assuming a knowledge of the magnitude of current in towers due to direct strokes and of the strength of the line insulation, then it is possible to arrive at a limiting value of tower-footing resistance for a given line. For example, if the highest current expected is 100,000 amperes and the line insulation is 1,000 kv, then the highest permissible footing resistance is 10 ohms.

Several devices have been used to reduce tower-footing resistance, among which are driven rods, driven wells, ground plates, and buried conductors or counterpoises. Among the questions still to be answered are: the relative effectiveness of a given resistance obtained by 2 different methods, such as driven rods or counterpoise wires; the relation between resistance measured by Megger at low current and voltage and that encountered by lightning current of high intensity and at high voltage; also the most effective length of counterpoise.

Evidence gathered during the past few years attests to the great effectiveness of the continuous tower-to-tower counterpoise wire. A section of line 2.6 miles long equipped with tower-to-tower counterpoise has operated 8 years without flashover, as against an average of 10 flashovers per year in the 3 years previous to the installation of the counterpoise wire.



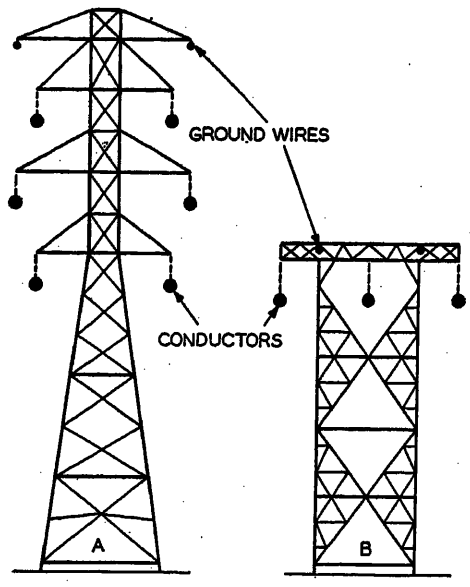
**Installation of expulsion protective gaps on 115-kv H-frame line**

A continuous counterpoise is, of course, a conductor or conductors buried under the transmission line from end to end of the line or certain sections of the line and connected to all tower feet. Some engineers believe that if the same amount of conductor were used as a radial or crowsfoot counterpoise, where several conductors merely radiate outward from the foot of each tower with no connection between towers, it will give more effective protection.

Short radial counterpoise wires also have improved the operation of lines. On the Glenlyn-Roanoke (Va.) line of the Appalachian Electric Power Company certain towers are equipped with 150-foot counterpoise wires running parallel with the line and from diagonally opposite legs of the towers, with 40-foot wires running at right angles to the line from the other 2 legs. A number of records obtained in 1935 showed the sum of the current readings in the long wires to have a ratio of 4.3 times the current in the short wires; the ratio of the lengths is 3.75. In 1936, a large number of readings on this line showed the sum of the current readings in the long wires to have a ratio of 2.9 times the current in the short wires.

On the Wallenpaupack-Siegfried line of the Pennsylvania Power and Light Company, certain towers were equipped, in 1936, with one 250-foot and 3 50-foot radial counterpoise wires. The summation of readings of currents in the long and one short wire gave a ratio of 7.5, as

compared with a ratio of lengths of 5. Simultaneous readings of current at several different points along the 150- and 250-foot counterpoise wires indicated an almost uniform current distribution along the wires, but with different rates of current connection or dissipation at different current levels. It has been suggested that figures




**Arrangement of overhead ground wires to give good shielding against direct strokes, for vertical and horizontal configuration of conductors**

of this sort for several different lengths and ratios of length might give some indication of the effective minimum length of counterpoise wires.

## Expulsion Protective Gaps

Another way of attacking the problem of continuity of service is to direct the flashover through gaps or tubes set for a slightly lower flashover potential than the insulators, not attempting as in the previously discussed solution to prevent flashover altogether.

The expulsion protective gap is a tube with an internal gap, connected to the line through an external gap, the whole having a flashover potential lower than that of the insulator string. The tubes are selected for the range of short-circuit currents expected. The short-circuit current that follows the lightning flashover produces a pressure within the tube and the arc is extinguished within a half cycle.

For continuity of service, it has been customary to build double-circuit lines. However, even with 2 circuits a large proportion of the faults may involve both circuits, because when lightning current passes down a tower, the tower potential may be raised above that of all 6 conductors, and the probability is that more than one conductor will flash over at a time. On wood-pole lines, faults frequently spread between circuits because of the high resistance of the pole, which does not relieve the potential due to a direct stroke.

For the foregoing reason some power companies now are building single-circuit lines equipped with expulsion protective gaps, instead of double-circuit lines. Among these may be mentioned the Pennsylvania Power and Light Company's 66-kv wood-pole lines, the Carolina Power and Light Company's 115-kv wood-pole lines, and the American Gas and Electric Company's 132-kv steel-tower lines. In the limited time they have been in operation, such lines have had very good service records.

Expulsion protective gaps were placed on one circuit of the Glenlyn-Roanoke double-circuit line in 1933, and on the Roanoke-Danville single-circuit line in 1934. In the 3 years, 1933, 1934, and 1935, a total of 339 gap operations occurred, with 30 cases of incorrect operation. The outages on the 2 circuits of the Glenlyn-Roanoke line averaged 10 per year during the 3 years of expulsion-gap operation, against an average of 18 per year during the previous 7 years. On the Roanoke-Danville line the outages for the 2 years of gap operation averaged 4.5 per year against an average of 19.5 per year for the 7 previous years.

The Pennsylvania Power and Light Company and the Pennsylvania Water and Power Company installed, in 1935, expulsion protective gaps and Deion gaps on about 98 miles of 66-kv line, consisting of 81 miles of single-circuit wood H-frame line and 17 miles of double-circuit steel-tower line. Out of a total of 944 structures, 543 were equipped with gaps. During the 1935 season there were 374 tube operations, with 8 tube flashovers or failures. There were 18 tripouts on these lines during this period.

Data given for the lines of the Appalachian Electric Power Company indicate that for the Glenlyn-Roanoke line the outages on the double-circuit were reduced about 45 per cent after the installation of expulsion protective gaps on one circuit. On the Roanoke-Danville single-circuit line the outages were reduced about 75 per cent after the installation of the expulsion protective gaps. Approximately 9 per cent of the gap operations on both lines were incorrect.

Data at hand for the 66-kv Pennsylvania lines do not permit of an evaluation of the improvement in operation due to the gaps, except perhaps in case of 2 of the lines. On these 2 lines gaps were installed to guyed structures only, which comprise about 25 per cent of the structures on the Northumberland-Williamsport line and about 14 per cent on the Berwick-Bloomsburg line. The operating record of these lines showed 1 tripout on each line in 1935 as compared with a yearly average of 7 tripouts on the Northumberland-Williamsport line and 5 on the Berwick-Bloomsburg line during the previous 4 years. There were many correct gap operations (the incorrect gap operations were slightly over 2 per cent on these lines).

It cannot be said that each correct gap operation saves a tripout. It must be remembered that the flashover potential of the expulsion-gap assembly is considerably less than that of the insulation assembly which it is designed to protect (10 to 15 per cent less for the 132-kv steel-tower lines and about 40 per cent less for the 66-kv wood-pole lines considered in this discussion). It is obvious therefore that the number of expulsion-gap operations will be greater than the number of insulator flashovers that would have occurred if the gaps had not been installed. Nevertheless, it is probably true that the

gaps saved a large number of tripouts on these lines during the period of their operation.

## Petersen Coils

Briefly, the Petersen coil is a reactance coil connected between the system neutral and ground and specially proportioned in relation to the capacitance of the system. Upon the occurrence of a line-to-ground fault on one conductor, a lagging current will flow through the coil which is equal in magnitude and opposite in phase to the charging current at the fault. Under this condition the resultant current at the fault becomes zero and the fault is cleared.

In some instances there is a residual in-phase component of current at the fault, which cannot be neutralized by the Petersen coil. This current is due to corona on the line conductors, leakage over insulators, and other factors. If large enough to be important, the in-phase component may be neutralized by special auxiliary means. It is obvious that the Petersen coil cannot neutralize a line-to-line fault.

The use of the Petersen coil in Germany and other European countries has been very extensive. Approximately 1,000 coils have been installed on systems varying in voltage from 5 to 220 kv. In the United States the solidly grounded neutral system has been very popular, and therefore Petersen coils and other grounding devices have not received wide acceptance.

At the present time there are 5 coils in operation in the United States as follows: an 800-kva continuous-rated coil on the 44-kv system of the Georgia Power Company; 2 10,000-kva 10-minute-rated coils on the 140-kv system of the Consumers Power Company, Mich.; a 3,000-kva 30-minute-rated coil on the 33-kv system of the Central Maine Power Company; and a coil rated 800 kva for 30 minutes on the 33-kv system of the Public Service Company of Indiana. A 10,000-kva 10-minute coil will be installed during the spring of 1937 on the 100-kv system of the Public Service Company of Colorado.

The first Petersen coil in the country was an 800-kva continuous-rated coil installed on the Lock 12-Vida-Selma-Montgomery section of the Alabama Power Company's 44-kv system in 1921. This coil operated successfully until early in 1924 when it was removed because the system mileage had practically doubled and greatly outgrown the capacity of the coil. The coil was moved to the Georgia Power Company's system and installed on the 130-mile Marietta section of the 44-kv system, where it has been in successful operation for about 6 years.

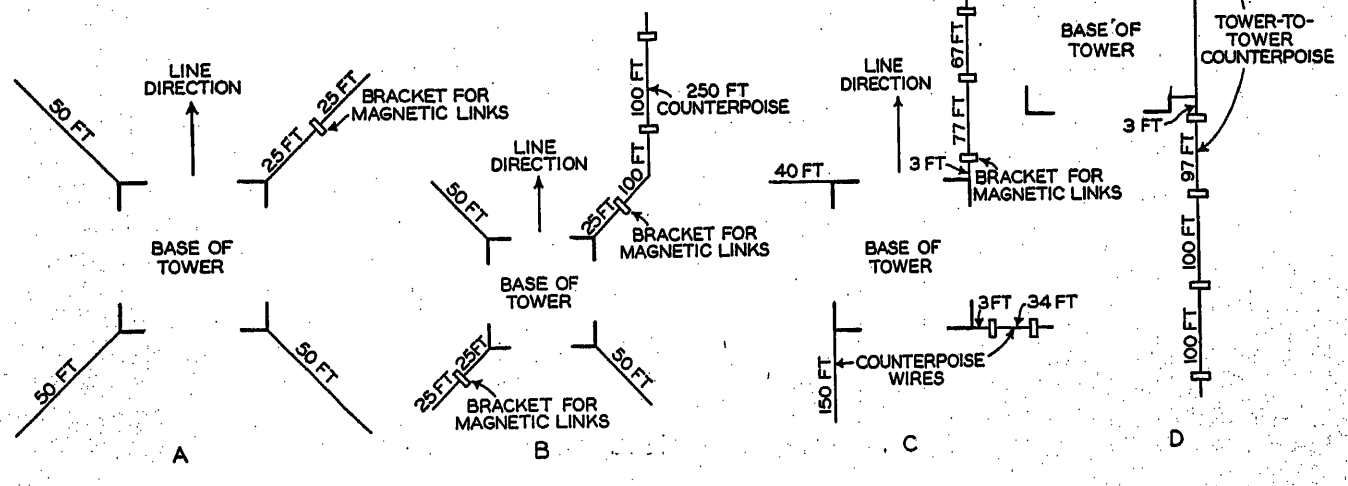
The Consumers Power Company's coils were installed late in 1931. The system consists of 275 miles of line on steel towers, all but about 40 miles of which is single circuit. There are no overhead ground wires on this line. The coils are rated 10,000 kva for 10 minutes and are installed one at Saginaw and one at Alcona. Operation on this system shows approximately 70 per cent of all faults in about 5 years' service cleared without oil circuit-breaker operation.

The Central Maine system consists of 560 miles of 33-kv line on wood poles with pin insulators and no overhead ground wires. The Petersen coil was installed in the fall of 1935. In the 14 months from August 1, 1935 to October 1, 1936 the Maine coil operated 54 times and cleared all faults that were not permanent, without a service interruption. In the Gulf Island Station in the 6 years before the coil was installed, there were 27 insulator or bushing flashovers associated with faults at other points on the system. Since the coil has been in service flashovers of this type have not occurred.

It is probable that the majority of faults start as single-phase-to-ground disturbances and that later other phases may become involved. It is also probable that high tower-footing resistance, by allowing the tower potential to rise above that of the conductors, is responsible for the other phases becoming involved. Consequently, a reduction in tower-footing resistance will decrease the number of phase-to-phase faults, and allow the single-phase faults to be cleared by Petersen-coil operation.

**Various counterpoise arrangements now in use**

(*A*) Symmetrical radial
(*B*) Unsymmetrical radial
(*C*) Unsymmetrical radial
(*D*) Continuous tower-to-tower



## Immediate Initial Reclosure

During the last few years an operating procedure has been developed to improve continuity of service on feeders and tie lines: The practice of immediate initial reclosure of a circuit-breaker that has been tripped automatically. Many of the causes of short circuits have disappeared by the time the controlling breaker can be reclosed. Experience has demonstrated that immediately returning voltage to a circuit not only does no harm, but completely neutralizes the effects of interruption on most types of load.

All motors connected to an immediately reclosed circuit must have time delay on their undervoltage releases, if full benefit is to be derived from this procedure. Otherwise the motors having an instantaneous under-voltage device will be disconnected during the period of no voltage, and it then makes no difference whether the voltage is reestablished immediately or later. Provided under-voltage devices, when used, have time-delay features, it is possible to open the circuit-breaker and immediately reclose it with no detrimental effect on many kinds of load. The value of this procedure increases with the prevalence of lightning on a system, for then a smaller proportion of faults arises from causes that are permanent.

Some companies, especially in the Southeast, have applied immediate reclosure to their systems with significant improvement in their service. On one system it has been found that a circuit can be returned immediately to service after nearly 90 per cent of the tripouts, and remain closed with no loss of load and no detriment to service.

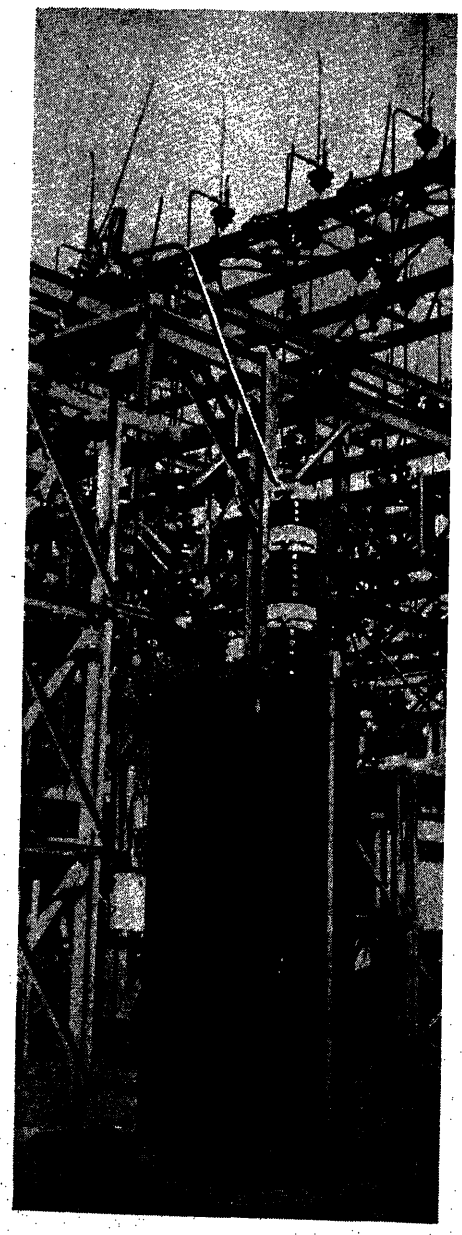
Immediate reclosure does not benefit all types of loads. Where it is applicable, and where many of the outages result from transitory causes, such as lightning, immediate reclosure is usually a simple, inexpensive, and very effective means of improving the service. In addition, immediate reclosure reduces service interruptions from certain causes from which the other protective means may not. These include temporary conductor contact from wind, sleet, or foreign materials on the line, such as kite strings, tree branches, and birds, which often leave the line clear after the first tripout.

## Summary

None of the means of lightning protection considered here has shown a perfect record. In some instances, however, overhead ground wires, when properly installed to shield the conductors from direct strokes and when accompanied by adequate insulation and low tower-footing resistance, have shown an almost perfect record.

The expulsion protective gap has shown good performance, especially on wood-pole H-frame lines. Improvements in the tubes may be expected as a result of past operating experience. This will tend further to improve the performance of these gaps. There is some evidence that equipping one circuit of a double-circuit line is beneficial, and on the Pennsylvania systems equipping only the guyed structures was apparently beneficial.

In the limited experience with Petersen coils in the United States, this equipment has shown a record of suppression of faults of the order of 70 to 80 per cent. Low tower footing resistance is of importance here in limiting the number of phase-to-phase flashovers, thus giving the Petersen coil full opportunity of taking care of the line-to-ground flashovers for which it is adapted.



**Petersen coil installed on a 33-kv system**

Immediate initial reclosure has been applied mainly to radial feeders and tie lines of medium voltages (up to 66 kv), although trial installations have been made on higher-voltage lines (up to 132 kv). A certain amount of maintenance is involved in the oil circuit-breakers, relays, and other equipment.

It is difficult to evaluate in general terms the cost of applying the various methods mentioned, so that the following figures should be considered as only very rough: For a 115- or 138-kv double-circuit steel-tower line, the cost of 2 overhead ground wires plus a continuous tower-to-tower counterpoise wire would be roughly $1,500 or $1,600 per mile. The cost of expulsion protective gaps plus installation would be roughly $1,200 to $1,400 per mile for both circuits or $600 to $700 if only one circuit is equipped. The cost of a Petersen coil for a 100-mile line plus installation would be roughly $10,000, or $100 per mile. Immediate initial reclosure is probably the least expensive of any of the methods mentioned, assuming that suitable breakers and relays are already available and that only the automatic reclosing device is required.

Each method has its advantages and disadvantages, and the best method for a particular case can be selected only after a study of all the circumstances.

# Further Characteristics of the Carbon Arc

By W. C. KALB
MEMBER AIEE

*In this paper the carbon arc is considered in its 3 characteristic forms, the low intensity arc, the high intensity arc, and the flame arc. The influence of arc current on the energy emission is discussed in relation to each of the 3 types, as well as the effects of variation in arc voltage.*

*The discussion covers characteristics which should be given consideration in order to make most effective application of the various types of arcs.*

IN THE course of a previous paper, which discussed the general characteristics of the carbon arc, it was pointed out that there are 3 distinct types of carbon arcs, the low-intensity neutral-core arc, the flame arc, and the high-intensity arc. The characteristic features distinguishing these 3 types of arcs were also described. Each of these types has its own peculiar characteristics and is affected in different manner or degree by variations in arc conditions. It is the purpose of the present paper to present further data on the characteristics of these arcs and to consider the effect of certain variables on the character and intensity of the light emitted.

## Distribution of Radiant Energy

The quality of light from the high-intensity arc is inherently whiter than that from the low-intensity neutral-core arc. This might be anticipated from the much higher intrinsic brilliancy of the crater. Spectral energy distribution curves for all carbon arcs show 2 characteristic peaks, one of moderate intensity at about 2,500 Angstrom units and a dominant band of emission, commonly called the "cyanogen peak," at about 3,800-3,900 Angstrom units. Except for the influence of this cyanogen peak, the energy emission from the d-c low-intensity neutral-core arc at full brilliancy tends to follow the theoretical black-body radiation curve for 3,810 degrees Kelvin, the brightness temperature of carbon at the point of vaporization. The emission from the d-c high-intensity arc, on the other hand, comes nearer to the black-body curve for 5,600 degrees Kelvin. This difference is illustrated in figure 1, in which all curves have been adjusted to a maximum value of 100 (exclusive of cyanogen peak) on an arbitrary scale of intensity. It is obvious from the energy distribution shown by these curves that the light from the high-intensity arc has a substantially even balance of all colors and comes close to our conception of a pure white light. It is equally obvious that the light from the low-intensity arc has a yellowish tint resulting from the higher intensity of the longer wave lengths within the visible range.

The distribution of radiant energy from the flame arc is dependent largely on the composition of the core. This is illustrated, for the visible range, by figure 2 where the output from a 30-ampere 50-volt a-c arc between neutral-core carbons is compared with that from carbons burned under the same conditions and having identical outer shells but whose cores contain, respectively, cerium, calcium, and strontium. Figure 3 shows the effect of variation in core composition on the ultraviolet emission. The respective core compositions in this case contain the elements listed below the curves. Many elements, other than those whose effects are illustrated in figures 2 and 3, have pronounced influence on the quality of emission in both the ultraviolet and the visible portions of the spectrum. This fact makes the flame arc a highly flexible source of radiation, capable of adaptation to a wide range of requirements in radiation characteristics.

## Effects of Increasing Arc Current

In all types of arcs, one effect of increasing arc current is to increase the light output. This result, however, is subject to certain practical limitations characteristic of the various types. For a given type and size of trim there is a certain range of current within which best results are obtained. Operation at lower currents allows the arc to wander over the face of the carbon with resulting unsteadiness of light. Currents above this optimum range likewise produce an unsteady arc due to the effects of overloading the carbons. Carbon manufacturers have carefully determined the optimum range of current for the several types and sizes of carbons, and their instructions should be followed. As long as proper arc conditions are maintained, operation within the recommended range of current can be depended on to produce satisfactory arc performance.

In the d-c low-intensity arc the light produced is largely dependent on the area and intrinsic brilliancy of the positive crater. Only a small percentage of the total light comes from the arc stream and the less brilliant tip of the negative carbon. Mott and Kunzmann (reference 2) have shown that the relation between arc current and crater area may be expressed by an equation of the form

$$A = 7 + 0.47 I^e$$

where

$A$ = crater area in square millimeters
$I$ = arc current in amperes
$e$ = 1.4 for carbons of large diameter
= 1.35 for carbons of small diameter

More recent observations (reference 3) on positive carbons of 10 to 13 millimeters diameter, designed for use in low-intensity d-c projection lamps of the reflecting type,

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**Table I—Influence of Arc Current on Low-Intensity D-C Arc at 55 Volts, SRA Trim**

| Diameter Positive Carbon, Millimeters | Arc Current, Amperes | Crater Area Square Millimeters | Maximum Intrinsic Brilliancy, Candle Power per Square Millimeter | Candle Power Directly in Front of Crater | Candle Power per Arc Watt |
|---|---|---|---|---|---|
| 10 | 21 | 34.8 | 174 | 5,720 | 4.95 |
| 10 | 24 | 39.2 | 175 | 6,650 | 5.04 |
| 12 | 28 | 49.0 | 171 | 7,900 | 5.12 |
| 12 | 34 | 60.0 | 175 | 9,800 | 5.24 |
| 13 | 32 | 61.0 | 171 | 9,100 | 5.16 |
| 13 | 44 | 77.9 | 172 | 13,200 | 5.45 |

**Table II—Influence of Arc Current on High-Intensity D-C Arc With Rotating Positive**

| Diameter of Positive Carbon, Millimeters | Arc Current, Amperes | Average Arc Voltage | Crater Area, Square Millimeters | Intrinsic Brilliancy, Candle Power per Square Millimeter | Candle Power of Crater Light | Candle Power per Arc Watt |
|---|---|---|---|---|---|---|
| 9 | 50 | 44 | 29.3 | 430 | 12,500 | 5.68 |
| 9 | 75 | 54 | 35.4 | 705 | 25,000 | 6.17 |
| 11 | 90 | 60 | 56.0 | 750 | 42,000 | 7.78 |
| 13.6 | 100 | 63 | 73.3 | 535 | 39,000 | 6.20 |
| 13.6 | 125 | 68 | 92.0 | 815 | 75,000 | 8.82 |
| 16 | 135 | 70 | 132.0 | 570 | 75,000 | 7.94 |
| 16 | 155 | 72 | 145.7 | 695 | 101,000 | 9.05 |

support the substantial accuracy of this formula. The measured values of crater area represent values of $e$ ranging from 1.32 to 1.35.

The vaporizing temperature of carbon having been approached in the low-intensity arc, further increase in arc current results in little increase in intrinsic brilliancy of the positive crater. The increase in crater area, however, does result in an increase of total light emission. The optical systems used in most projection lamps and projectors place limitations on the area of the positive crater face from which the light can be effectively focused within the dimensions of the aperture plate and projected onto the screen. For this reason, when a projector carbon has been raised to its maximum intrinsic brilliancy, further increase in current produces little, if any, increase in screen illumination. Table I shows the influence of arc current on the crater characteristics and light output of the d-c low-intensity arc with the type of carbons now extensively used in reflecting type projection lamps.

Mott and Kunzmann (2) found that the candle power of low-intensity searchlight carbons, within the range of 20 to 150 amperes, followed substantial y the curve expressed by the equation,

$$CP = 51.4\ I^{1.4}$$

The carbons now used in the d-c low-intensity reflector arc show higher efficiency in light production. The candle power measurements given in table I are closely approximated by the equation $CP = 164.0\ I^{1.165}$.

In the d-c high-intensity arc, increase of current increases both the area and the depth of the positive crater. The increase in crater area with increasing current is shown by the curves in figure 4. It is apparent from these curves that, at the same current, 2 carbons of different diameters will show a substantially larger crater on the larger carbon. The influence of arc current on the intrinsic brilliancy of the positive crater is shown by the curves in figure 5. Here it is apparent that, of 2 carbons of different diameters operated at the same current, the

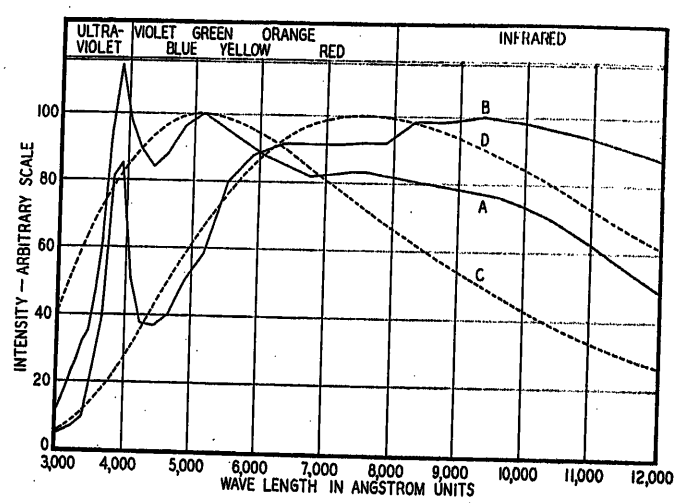



**Fig. 1. Spectral energy distribution curves**

*A*—13.6-millimeter d-c high-intensity arc, 125 amperes, 63 volts
*B*—12-millimeter d-c low-intensity arc, 30 amperes, 55 volts
*C*—Theoretical black-body radiation at 5,600 degrees Kelvin
*D*—Theoretical black-body radiation at 3,810 degrees Kelvin

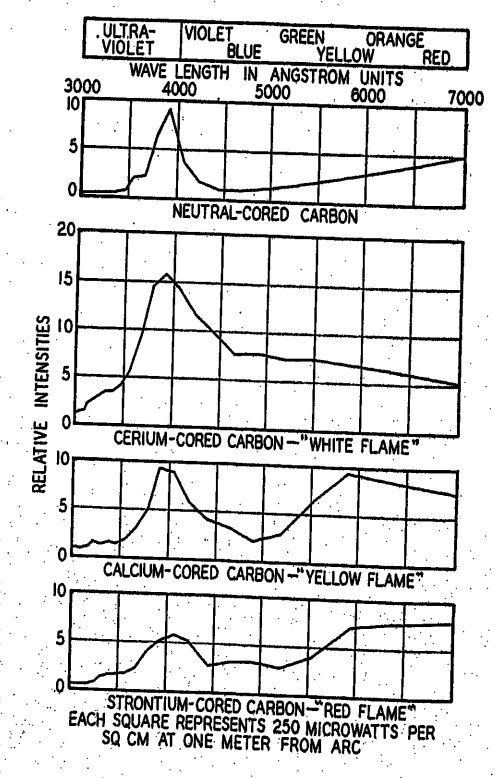



**Fig. 2. Effects of core composition on near ultraviolet and visible radiation—30 amperes, 50 volts, a-c**

smaller will have the higher intrinsic brilliancy. This is the natural result of concentrating the energy of the arc within a smaller area. It is evident, from a comparison of these curves with the data given in table I, that much higher intrinsic brilliancies are available from the high-intensity arc than are possible to obtain from the low-intensity arc.

Table II shows the effect of arc current on the crater light from the d-c high-intensity arc with rotating positive electrode and also shows the arc-voltage representative of average operating conditions at the specified arc currents. The figures in this table do not include the light from the tail flame of the arc, which represents about 32 per cent of the total light output but cannot be properly

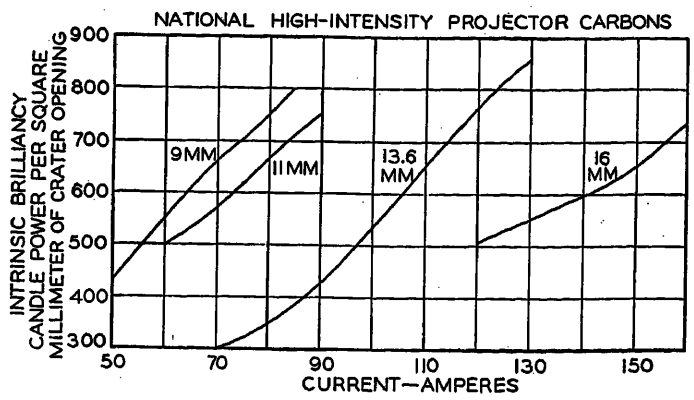



**Fig. 5. Intrinsic brilliancy versus arc current—d-c high-intensity arc**

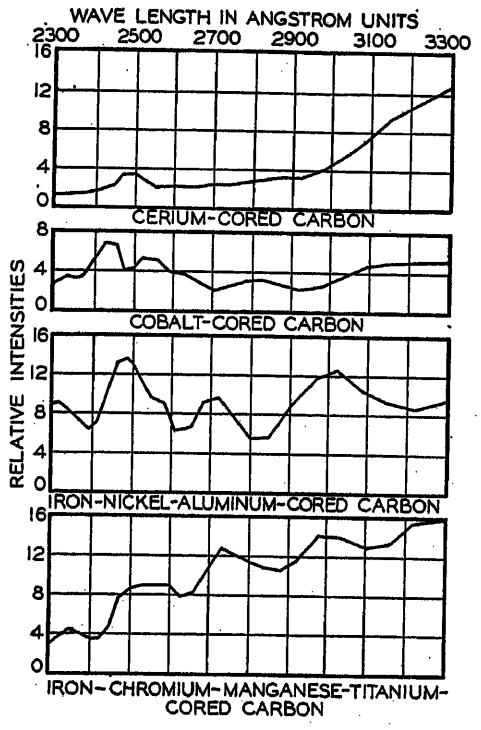



**Fig. 3. Effects of core composition on short ultraviolet radiation—60 amperes, 50 volts, a-c**

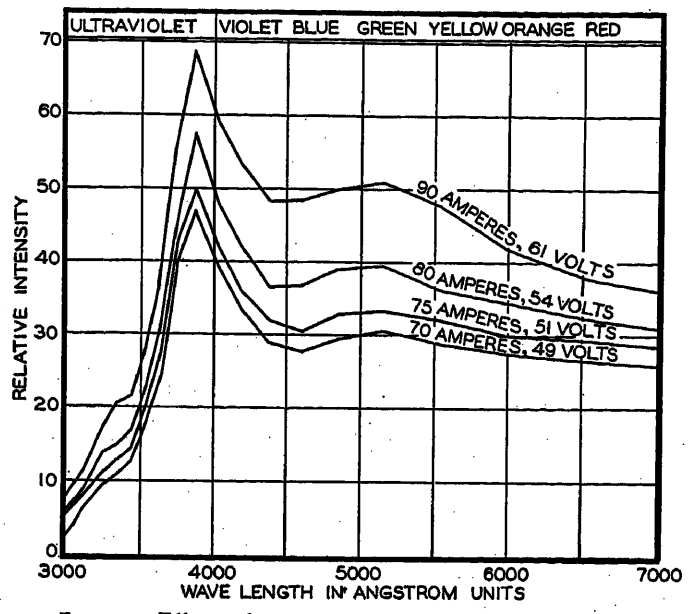



**Fig. 6. Effect of arc current on energy distribution d-c high-intensity arc—9-millimeter positive**

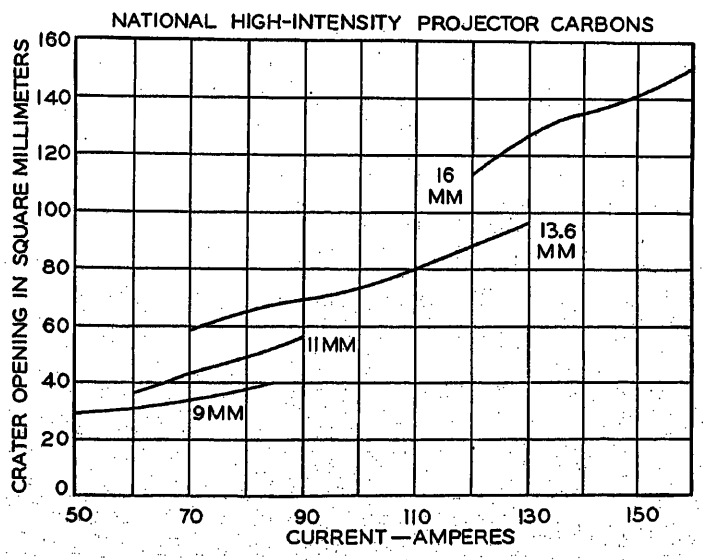



**Fig. 4. Crater area versus arc current—d-c high-intensity arc**

focused by the optical system of projection lamps and therefore does not add to the screen illumination.

Increasing current does not greatly affect the quality of light emitted by the high-intensity arc. This is shown in figure 6 by the energy-distribution curves for a high-intensity arc with 9-millimeter positive operated in a reflecting type projection lamp at arc currents of 70, 75, 80, and 90 amperes. Over this range of current the increase in arc watts and the increase in radiant energy are in approximately the same ratio, the effect of increasing current being slightly more pronounced in the blue and green bands of the spectrum than in other portions.

With flame arcs the effects of increasing arc current are decidedly complex. They vary with the composition of the flame supporting core, with the range of current in which comparison is made and with the portion of the spectrum in which intensity of radiation is observed. A few examples are cited to illustrate the effects of arc current under specific conditions.

The increase in intensity of ultraviolet radiation, between the limits of 2,900–3,100 Angstrom units, which

results from increasing arc current, with voltage constant, is shown by the curves in figure 7. The upper curve shows the effect on a carbon having iron, nickel, and aluminum in the core and the lower curve the effect on one containing cerium. The curves in figure 8 show the corresponding effects on total radiation over a broad band of the spectrum, from 1,700 to 6,500 Angstrom units. This includes practically all ultraviolet emission from the arc and a major portion of the visible light. In this case, the upper curve represents the cerium-cored carbon and the lower curve the carbon containing iron, nickel, and aluminum.

The effect of current increase at different wave lengths can be illustrated by curves showing the variation in mean exponential relation between changes in arc current and resulting changes in intensity of radiation. These curves, presented in figure 9, are based on the equation

$$\frac{W_2}{W_1} = \left(\frac{I_2}{I_1}\right)^e$$

where

$W$ = intensity of radiant energy
$I$ = arc current in amperes
$e$ = exponential relation between current and intensity

Curves are drawn for 2 ranges of arc current, 30–60 and 60–90 amperes, and for the 2 types of carbons shown in figures 7 and 8. The complexity of the relationship between arc current and resulting energy emission at different wave lengths is evident from these curves.

A series of observations of more practical application, relating to the light output of the flame arc under varied conditions of operation is given in table III. These observations were made with white flame (cerium cored) photographic carbons in the lamp mechanism of a photo-engraving lamp of standard make.

The data in table III disclose that, under the same conditions of arc voltage and current, the d-c arc between flame carbons gives higher light output than the a-c arc; the d-c arc with upper carbon positive gives higher light output than with upper carbon negative; and, the d-c arc with cerium-cored negative gives higher light output than with neutral-cored negative.

While the foregoing figures show a decided advantage for the d-c arc over the a-c arc on the basis of candle power per arc watt, this advantage is more than offset when the comparison is made on a basis of candle power per line watt between a single d-c arc on a 115-volt circuit and a transformer-operated a-c arc. It is common practice, however, particularly in twin-arc lamps, to operate 2 d-c arcs in series from the standard-voltage d-c circuit at a somewhat lower arc voltage than that used in obtaining the data given in table III. Under these conditions comparison on the basis of candle power per line watt favors the d-c arc when no reflectors are used. This was the condition under which data was obtained for the comparison given in table IV.

The use of reflectors may and, in most designs, does more than offset the primary advantage of the d-c twin arc over the single, transformer-operated a-c arc. This is because higher efficiency in reflector design is possible with the single arc which can be centered in a reflector of symmetrical form.

## Effects of Arc Voltage

The d-c low-intensity arc with neutral-cored carbons gives optimum performance over a rather limited range of arc length and arc voltage. For this reason it is customary to maintain approximately constant arc voltage and to vary the light output by adjustment of arc current. The d-c low-intensity reflecting arc is usually operated with 54–57 volts at arc. Curve *A* in figure 10 is representative of the average relationship between arc voltage and current in other types of lamps using the d-c low-intensity arc.

The d-c high-intensity arc, under given conditions of trim and arc current, should also be operated at essentially constant arc voltage. In fact, arc voltage is often used as the control factor for operating the carbon-feeding

Table III—Light Output of Cerium-Cored Flame Arc at 55 Volts

| Upper Carbon | Lower Carbon | Power | Arc Current, Amperes | Mean Spherical Candle Power | Mean Spherical Candle Power per Arc Watt |
|---|---|---|---|---|---|
| 1/8- by 12-inch cerium cored | 1/8- by 12-inch cerium cored | A-C | 30 | 6,985 | 4.23 |
| 5/8- by 12-inch cerium cored | 1/8- by 12-inch cerium cored | A-C | 45 | 9,800 | 3.96 |
| 5/8- by 12-inch copper coated, cerium cored | 5/8- by 12-inch copper coated, cerium cored | A-C | 60 | 13,500 | 4.09 |
| **Upper Carbon Positive** | **Lower Carbon Negative** | | | | |
| 1/8- by 12-inch cerium cored | 1/8- by 12-inch cerium cored | D-C | 30 | 10,110 | 6.13 |
| 5/8- by 12-inch cerium cored | 1/8- by 12-inch cerium cored | D-C | 45 | 13,520 | 5.46 |
| 5/8- by 12-inch copper coated, cerium cored | 5/8- by 12-inch copper coated, cerium cored | D-C | 60 | 21,120 | 6.40 |
| **Upper Carbon Negative** | **Lower Carbon Positive** | | | | |
| 1/8- by 12-inch cerium cored | 1/8- by 12-inch cerium cored | D-C | 30 | 7,540 | 4.57 |
| 5/8- by 12-inch cerium cored | 1/8- by 12-inch cerium cored | D-C | 45 | 11,840 | 4.78 |
| 5/8- by 12-inch copper coated, cerium cored | 5/8- by 12-inch copper coated, cerium cored | D-C | 60 | 15,970 | 4.84 |
| 1/8- by 12-inch neutral cored | 1/8- by 12-inch cerium cored | D-C | 30 | 6,985 | 4.23 |
| 5/8- by 12-inch neutral cored | 1/8- by 12-inch cerium cored | D-C | 45 | 8,710 | 3.52 |
| 5/8- by 12-inch copper coated, neutral cored | 5/8- by 12-inch copper coated | D-C | 60 | 11,410 | 3.46 |

mechanism. Nevertheless, arc voltage alone does not afford a sufficient basis for adjustment of the carbons in the high-intensity arc. Joy and Downes (reference 4) have published the results of a thorough investigation of this subject. They have shown that it is possible to operate a high-intensity arc at 120 amperes with 70 volts drop across the arc at arc lengths ranging from $^5/_8$ inch to $1^1/_8$ inches. However, widely divergent results as to steadiness and quantity of crater light are encountered over this range of arc lengths. Relative position of positive and negative carbons is probably a factor of greater importance than arc voltage in maintaining correct arc conditions. Without discussing theories of the action taking place within the crater of the high intensity arc, it will here suffice to say that steady burning, uniform light output and characteristic extreme brilliancy are dependent on the maintenance of uniform crater depth and form and uniform conditions within the crater. It is obvious that these factors will be influenced to a marked degree by the manner in which the negative arc stream impinges on the positive crater. Detailed instructions for obtaining optimum performance are contained in a handbook which has been made available to projectionists and other users of high-intensity arcs. Values representing average arc voltage for the d-c high-intensity arc with rotating positive, under correct operating conditions, are indicated by curve *B* in figure 10.

There has recently come into extensive use in motion picture projection a carbon arc which our present knowledge indicates to be a true high-intensity arc but which is operated at much lower arc voltage than the older types of high-intensity arcs. This arc is known in the motion picture industry as the Suprex type arc. Among several points of difference from the older types is the fact that it is operated at a relatively short arc length with a drop of 31 to 40 volts across the arc. Due to this low arc voltage, it is desirable that the Suprex arc should be operated from a low-voltage source of power. This is necessary to obtain best performance as well as good power economy.

It has been demonstrated that the crater depth of the high-intensity positive increases with increase of arc current; that the voltage drop in the arc stream is com-

**Table IV—Comparison Between D-C Twin-Arc and Transformer-Operated A-C Arc, All Carbons Cerium Cored**

| | 2 45-Volt, D-C Arcs in Series on 115-Volt Line, Upper Positive | | 55-Volt A-C Arc, Transformer Operated; 3 Per Cent Loss Allowance | |
|---|---|---|---|---|
| Arc Current, Amperes | Mean Spherical Candle Power | Mean Spherical Candle Power per Line Watt | Mean Spherical Candle Power | Mean Spherical Candle Power per Line Watt |
| 30 | 16,540 | 4.80 | 6,985 | 4.10 |
| 45 | 22,140 | 4.28 | 9,800 | 3.84 |
| 60 | 34,600 | 5.01 | 13,500 | 3.97 |

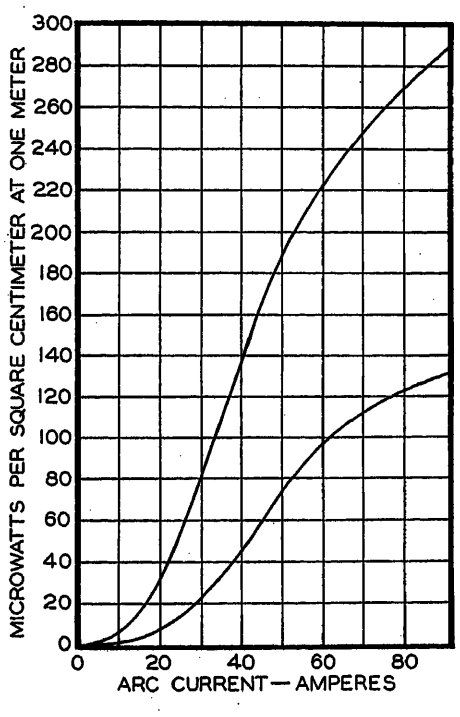



**Fig. 7. Variation of ultraviolet (2,900–3,100 Angstrom units) with current-flame arc at 50 volts, a-c**

Upper curve—Iron-nickel - aluminum core

Lower curve—Cerium core

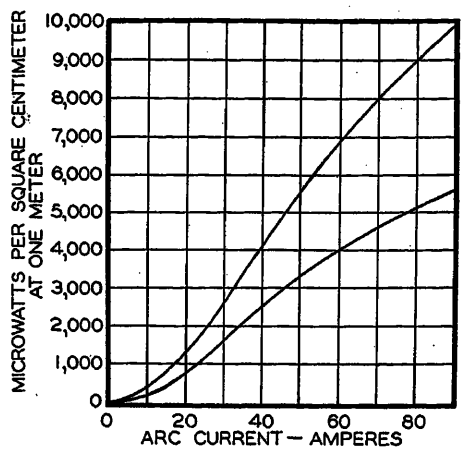



**Fig. 8. Variation of radiation, from 1,700 to 6,500 Angstrom units, with current flame arc at 50 volts, a-c**

Upper curve—Cerium core

Lower curve—Iron-nickel - aluminum core

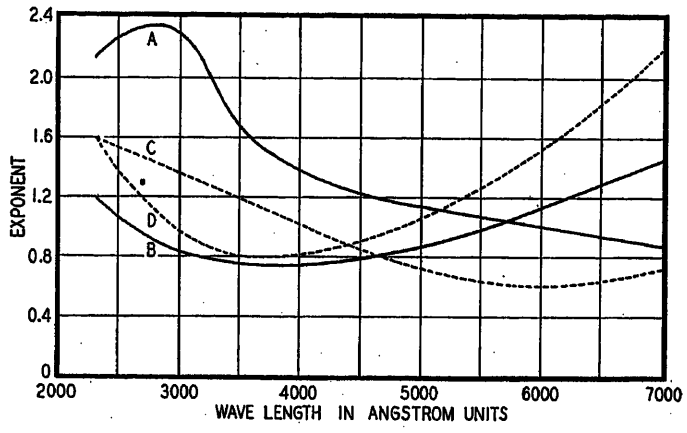



**Fig. 9. Mean exponential relation between arc current and energy emission at different wave lengths, 50 volts, a-c**

*A*—Cerium-cored carbon; 30–60-ampere range
*B*—Cerium-cored carbon; 60–90-ampere range
*C*—Iron-nickel-aluminum-cored carbon; 30–60-ampere range
*D*—Iron-nickel-aluminum-cored carbon; 60–90-ampere range

paratively low and does not materially increase with increased current; and, on the other hand, that the voltage drop within the positive crater is comparatively high and does increase materially as current and crater depth increase (reference 5). When some disturbance to the "high intensity effect" takes place, crater form, depth and voltage are affected, as well as light output. Normal crater conditions and light output are re-established by the increase in current resulting from the drop in arc voltage and the time required to restore normal conditions depends on the amount of current increase. When this low-voltage arc is operated with heavy ballast on a 115-volt power circuit, so much of the total energy is consumed in the ballast that relatively large changes of arc voltage produce only slight changes in arc current. It therefore takes considerable time for restoration of normal crater conditions to be effected. On the other hand, when the voltage of the power source is not greatly above that of the arc, and the ballast correspondingly small, much larger fluctuations in arc current occur in response to a disturbing influence so that normal crater conditions and light output are restored more quickly.

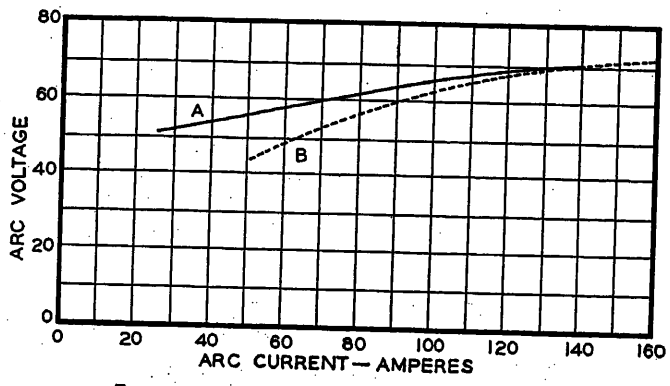



**Fig. 10. Arc voltage versus arc current**

*A*—D-c low-intensity arc
*B*—D-c high-intensity arc

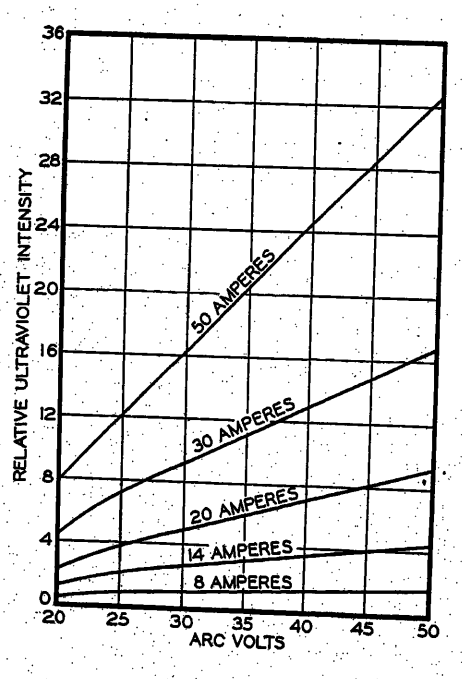



**Fig. 11. Ultraviolet output (2,900 – 3,100 Angstrom units) versus arc voltage, iron - nickel - aluminum core**

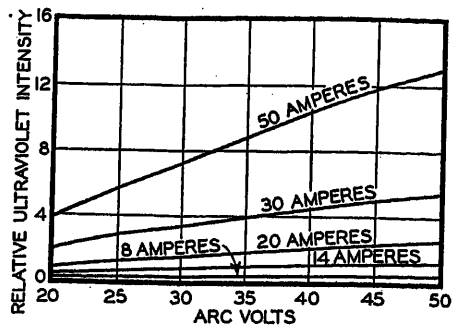



**Fig. 12. Ultraviolet output (2,900–3,100 Angstrom units) versus arc voltage, cerium core**

The operator of a Suprex type of arc, using a low-voltage power source, should therefore expect to see wider fluctuations of current than are customary with other types of arcs. Furthermore, it should be recognized that fluctuation of current is not necessarily associated with corresponding fluctuation of light but is, rather, a stabilizing factor by means of which uniform light output is maintained.

The flame arc can be operated satisfactorily over a considerable range of arc voltage although, under certain conditions or in some particular lamp, best results may be obtained over a relatively narrow voltage range. The effect of changes in arc voltage on ultraviolet output from 2,900 to 3,100 Angstrom units is shown by the curves in figures 11 and 12. The former is for a carbon containing iron, nickel, and aluminum in the core and the latter for a cerium-cored carbon. Relative effect of changes in arc current and in arc voltage can be observed by comparing these curves with those in figure 7.

## Conclusion

The carbon arc is firmly established as a powerful, efficient, and highly flexible source of radiation, possessing certain advantageous characteristics which make it a most useful source of radiant energy for many purposes. It is true of the carbon arc, as it is of all types of light sources, that effective application requires consideration of the inherent characteristics of the source and adaptation of operating conditions to these characteristics. Each type of arc has its own peculiar advantages and fields of application. The foregoing discussion covers some of the features of the various types of arcs to which attention should be given in making the initial application as well as in subsequent operation.

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# Current Loci in the General Linear A-C Network

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FELLOW AIEE

OUR PROBLEM is to find the way in which the currents and voltages vary in a general linear a-c network connected to a single adjustable branch, when the current of that branch is adjusted under some given restriction. In a general linear network, each branch has a fixed impedance; and the impressed voltages and currents (of which there may be any number, but usually is only one) are also fixed.* The impressed voltages and currents are supposed sinusoidal and of the same frequency; and we are concerned only with the steady state. So all voltages and currents are sinusoidal and may be represented analytically by complex numbers and graphically by plane vectors.

If we write for the network a complete set of circuit equations, these will be linear in the unknown voltages and currents, together with the current $I_L$ of the adjustable branch. If we are interested in a certain current $I_M$, we may eliminate all other unknown currents and voltages successively in the usual way, by multiplying the equations by suitable constants and adding them. At each step the resulting equations then remain linear; and we shall finally arrive at a linear equation connecting only $I_M$ and $I_L$:

$$I_M = I_{M0} + K_M I_L \qquad (I_{M0}, K_M \text{ are constants}) \tag{1}$$

Evidently $I_{M0}$ is the value of $I_M$ when $I_L = 0$ and is due to the impressed voltages and currents. While $K_M$ is the value of $I_M$ when $I_L = 1$ and all impressed voltages and currents are removed (making $I_{M0} = 0$): here the unit current $I_L$ must be supplied from a source in its branch; and the impressed voltages must be removed by short-circuiting them, the impressed currents by opening their circuits, so as not to alter the impedances of the network.

If we had been interested in a voltage $E_M$, instead of a current $I_M$, a similar equation would have been found:

$$E_M = E_{M0} + z_M I_L \qquad (E_{M0}, z_M \text{ are constants}) \tag{2}$$

Evidently $E_{M0}$ is the value of $E_M$ when $I_L = 0$; and $z_M$ is the value of $E_M$ when $I_L = 1$ and the impressed voltages and currents are removed. In particular, we have for the voltage $E_L$ across the adjustable branch

$$E_L = E_{L0} - z_S I_L \qquad (E_{L0}, z_S \text{ are constants}) \tag{3}$$

Here $E_{L0}$ is the value of $E_L$ when $I_L = 0$ (i.e., the *open-circuit voltage* of the adjustable branch) and is due to the impressed voltages and currents of the network. While $z_S$ is the value of $E_L$ when $I_L = -1$ and the impressed voltages and currents are removed. If we restrict ourselves (as we shall) to an adjustable branch connected to the network *only through 2 terminals* (in particular, having no mutual inductance to the network), then $z_S$ is the impedance *looking into the network* between these terminals, since $-I_L = 1$ represents the current sent *into* the network by the voltage $E_L$ due to a source in the adjustable branch.†

In place of an *open-circuit* calculation to determine $I_{M0}$ (or $E_{M0}$) and $E_{L0}$, or in place of an *impedance* calculation to determine $K_M$ (or $z_M$) and $z_S$, we may use a *short-circuit* calculation, in which the adjustable branch is short-circuited, making $E_L = 0$. If $I_M$, $E_M$, and $I_L$ under this condition are denoted by $I_{MS}$, $E_{MS}$, and $I_{LS}$, equations 1, 2, and 3 give

$$\left.\begin{aligned} I_{MS} &= I_{M0} + K_M I_{LS} \\ E_{MS} &= E_{M0} + z_M I_{LS} \\ 0 &= E_{L0} - z_S I_{LS} \end{aligned}\right\}, \text{ whence } \left\{\begin{aligned} I_{M0} &= I_{MS} - K_M I_{LS} \\ E_{M0} &= E_{MS} - z_M I_{LS} \\ E_{L0} &= z_S I_{LS} \end{aligned}\right\} \text{ or}$$

$$\left.\begin{aligned} K_M &= \frac{I_{MS} - I_{M0}}{I_{LS}} \\ z_M &= \frac{E_{MS} - E_{M0}}{I_{LS}} \\ z_S &= \frac{E_{L0}}{I_{LS}} \end{aligned}\right\} \tag{4}$$

If not restricted, the current $I_L$ would be represented by a vector whose extremity could lie anywhere in its plane. When, however, $I_L$ is restricted by a single real equation, the extremity of its vector will in general lie on a curve, called the *locus* of $I_L$ for this restriction. For example, if the restriction is that the apparent power of the variable branch be constant, $E_L I_L = A_L$, the locus of $I_L$ will be one of those shown in figure 1*a*, according to the value of $A_L$.** Now multiplying $I_L$ by the complex constant $K_M$ will change its magnitude in a fixed ratio and its phase by a fixed angle; so the loci of $K_M I_L$ will be similar to those for $I_L$ and similarly related to one another, but will in general be changed in scale and rotated, as represented in figure 1*b*, with $O'$ as the origin. Then adding the complex constant $I_{M0}$, to give $I_M$ according to equation 1, merely shifts the origin to a new point $O$, figure 1*b*. That is, *every variable current $I_M$ (and every variable voltage $E_M$) of the network will have loci similar to those of $I_L$.*

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* We do not exclude amplifiers, which involve one-way action; so our treatment is more general than the usual network theories, in which amplifiers are supposed absent, resulting in certain symmetries in the circuit relations. Voltages and currents in amplifiers which are proportional to other voltages or currents are, of course, not considered as *impressed*, even though they are derived from separate sources of energy; for they are taken into account by transfer *impedances*. A similar consideration applies to voltages and currents of negative-resistance devices.

† Equation 3 together with this statement constitutes Thévinin's theorem.

** These curves are the *ovals of Cassini*, each of which is characterized by the property that the product of the distances from any point on it to 2 fixed points is a constant. As may be seen from the discussion immediately following (figure 2*b*), the distance from any point to the "short-circuit point" $A$ represents $E_L/z_S$; and $(E_L/z_S)I_L = A_L/z_S$, which is constant. A special case is the *lemniscate*, drawn heavily in figure 1*a*.

Our problem is thus reduced to that of finding the loci of $I_L$ under various restrictions. The restrictions that we shall consider are that each of the 10 following real quantities in the adjustable branch shall in turn remain *fixed* at various values: current, $I_L$; voltage, $E_L$; their phase difference, $\phi_L$; active power, $P_L = E_L I_L \cos \phi_L$; reactive power, $Q_L = E_L I_L \sin \phi_L$; impedance, $z_L = E_L/I_L$; resistance, $r_L = z_L \cos \phi_L$; reactance, $x_L = z_L \sin \phi_L$; conductance, $g_L = (1/z_L) \cos \phi_L$; susceptance, $b_L = (1/z_L) \sin \phi_L$. We shall find that the loci in each case form a set of circles and that all of these sets of circles are related to a *single framework* (figure 2) made up of 4 fixed points ($O$, $A$, $B$, $C$) and the 6 straight lines joining them, as follows: for fixed $I_L$, $E_L$, $P_L$ or $Q_L$, the centers of the circles lie on one of the 4 points; while for fixed $\phi_L$, $z_L$, $r_L$, $x_L$, $g_L$, or $b_L$, the centers of the circles lie on one of the 6 straight lines. (Figure 2 is drawn for the case where $r_S$ and $x_S$, the rectangular components of $z_S$, are both positive, as is most usual.)

The locus for any fixed magnitude $I_L$ of *current* $\boldsymbol{I}_L$ is obviously a circle having its center at the origin $O$ and the radius $I_L$, figure 2*b*.

The locus for fixed magnitude $E_L$ of *voltage* is found almost as directly: If we write equation 3 in the form,

$$\boldsymbol{I}_L = \frac{\boldsymbol{E}_{L0}}{\boldsymbol{z}_S} - \frac{\boldsymbol{E}_L}{\boldsymbol{z}_S}, \quad \text{or} \quad \boldsymbol{I}_L = \boldsymbol{I}_{LS} - \frac{\boldsymbol{E}_L}{\boldsymbol{z}_S}, \tag{5}$$

we see that the vectors corresponding to the 3 terms form a triangle, as in figure 2*b*, of which the vertex $A$ also is fixed, since the short-circuit current, $\boldsymbol{I}_{LS} = \boldsymbol{E}_{L0}/\boldsymbol{z}_S$, is fixed. Then if the magnitude $E_L$ is fixed, the magnitude of $\boldsymbol{E}_L/\boldsymbol{z}_S$ will also be fixed; so the locus will be a circle having its center at the short-circuit point $A$ and the radius $E_L/z_S$.

The *active power* $P_L = E_L I_L \cos \phi_L$ is found by multiplying $I_L$ by the projection of $\boldsymbol{E}_L$ upon $\boldsymbol{I}_L$. If $\phi_{L0}$ is the phase difference between $\boldsymbol{E}_{L0}$ and $\boldsymbol{I}_L$ and if $r_S$ is the real part of $\boldsymbol{z}_S$, this projection is $E_{LS} \cos \phi_{LS} - I_L r_S$, as illustrated by the usual vector diagram, figure 2*a*. So

$$P_L = I_L(E_{L0} \cos \varphi_{L0} - I_L r_S), \text{ whence } \cos \varphi_{L0} = \frac{I_L^2 + P_L/r_S}{I_L E_{L0}/r_S} \tag{6}$$

To show that with fixed $P_L$ this gives a circular current locus, we may derive the general polar equation of a circle, as illustrated in figure 3. There the well-known "cosine law" of trigonometry gives

$$\cos(\theta - \alpha) = \frac{R^2 + a^2 - b^2}{2Ra} \tag{7}$$

This is of the same form as equation 6, the correspondence being as follows:

$$\text{Variables, } I_L = R, \varphi_{L0} = \theta; \text{ constants, } \frac{P_L}{r_S} = a^2 - b^2, \frac{E_{L0}}{r_S} = 2a, \quad 0 = \alpha.$$

Hence the locus for fixed $P_L$ is a circle whose center is on the $\boldsymbol{E}_{L0}$ vector ($\alpha = 0$) at the fixed distance

$$a = \frac{E_{L0}}{2r_S} \tag{8}$$

and whose radius is

$$b = \left(a^2 - \frac{P_L}{r_S}\right)^{1/2} = \left(\frac{E_{L0}^2}{4r_S^2} - \frac{P_L}{r_S}\right)^{1/2} \tag{9}$$

Such a set of circles is illustrated in figure 2*c*, with centers at $B$. If $P_L$ is positive (power input into the adjustable branch), then $a > b$ and the circle does not enclose the origin. If $P_L$ is negative (power output), then $a < b$ and the circle encloses the origin. If $P_L = 0$, then $a = b$ and the circle passes through the origin, as shown by the heavily drawn circle $C_P$ in figure 2*c*. There will be a maximum possible value of $P_L$, corresponding to $b = 0$, which is

$$P_{Lm} = \frac{E_{L0}^2}{4r_S} \tag{10}$$

This corresponds to the common center $B$, which may thus be called the *maximum-active-power point.*

The loci for fixed *reactive power* $Q_L$ are found in exactly similar fashion, $Q_L$ being given (figure 2*a*) by the equation,

$$Q_L = I_L(E_{L0} \sin \varphi_{L0} - I_L x_S), \text{ whence } \sin \varphi_{L0} = \cos\left(\varphi_{L0} - \frac{\pi}{2}\right) = \frac{I_L^2 + Q_L/x_S}{I_L E_{L0}/x_S}, \tag{11}$$

where $x_S$ is the imaginary part of $\boldsymbol{z}_S$. The loci are again concentric circles, their centers being at the distance

$$a = \frac{E_{L0}}{2x_S} \tag{12}$$

on the line lagging 90 degrees behind $\boldsymbol{E}_{L0}$, and their radii being

$$b = \left(a^2 - \frac{Q_L}{x_S}\right)^{1/2} = \left(\frac{E_{L0}^2}{4x_S^2} - \frac{Q_L}{x_S}\right)^{1/2} \tag{13}$$

as also illustrated in figure 2*c*, with centers at $C$. If $Q_L$ is positive (inductive), the circle does not enclose the origin; if it is negative (capacitive), the circle does enclose the origin; and if $Q_L = 0$, the circle passes through the origin, as shown by the heavily drawn circle $C_Q$, figure 2*c*. There will be a maximum possible value of $Q_L$, corresponding to $b = 0$, which is

$$Q_{Lm} = \frac{E_{L0}^2}{4x_S} \tag{14}$$

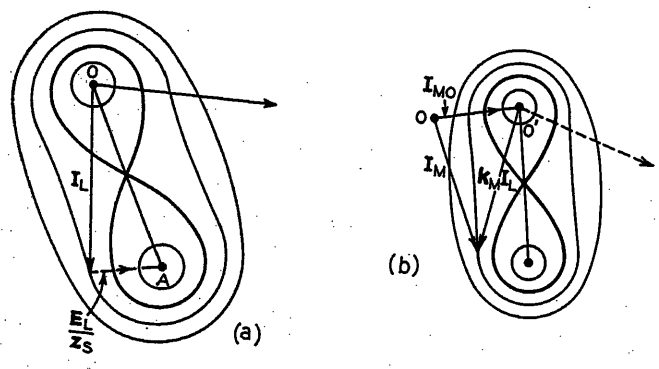



Fig. 1

This corresponds to the common center $C$, which may thus be called the *maximum-reactive-power point.*

The 4 fixed points $O$, $A$, $B$, $C$, which we have now located, and the 6 straight lines joining them make up the framework to which we referred earlier. In the subsequent loci (figure 2*d*, *e*, *f*), each of these straight lines will appear as a special locus itself and also as bearing the centers of a set of circular loci. The circles $C_P$ and $C_Q$ also reappear as loci in each of figures 2*d*, *e*, *f*, and are heavily drawn throughout.

The remaining sets of loci all depend on the property of a circle that its *inverse* with respect to a point is also a circle (including the limiting case of a straight line as a circle of infinite radius). Let a complex variable, $\boldsymbol{R} = Re^{j\theta}$, have a circular locus $C$, so that $R$ and $\theta$ are related by equation 7. The reciprocal, $\boldsymbol{R}' = R'e^{j\theta'} = 1/\boldsymbol{R} = (1/R)\epsilon^{-j\theta}$, then has the magnitude $R' = I/R$ and the phase angle $\theta' = -\theta$. If $a > b$, so that the circle $C$ does not enclose the origin $O$, figure 4*a*, equation 7 may be written in the form,

$$\cos(\theta - \alpha) = mR + \frac{n}{R} \tag{15}$$

where $m = 1/(2a)$ and $n = (a^2 - b^2)/(2a)$ are positive constants.

Putting $\theta = -\theta'$ and $R = 1/R'$, we have

$$\cos(-\theta' - \alpha) = \frac{m}{R'} + nR' \quad \text{or} \quad \cos(\theta' + \alpha) = nR' + \frac{m}{R'} \tag{16}$$

which is of the same form as (15) but with $\alpha$ replaced by $-\alpha$ and with $m$ and $n$ interchanged. The locus of $\boldsymbol{R}'$ is therefore also a circle, as represented by $C'$, figure 4*a*. (The dotted circle $C_t$ is conveniently found first; it is the inverse of $C$ with respect to $O$, only the magnitude having been changed from $R$ to $R'$, not the angle $\theta$.)

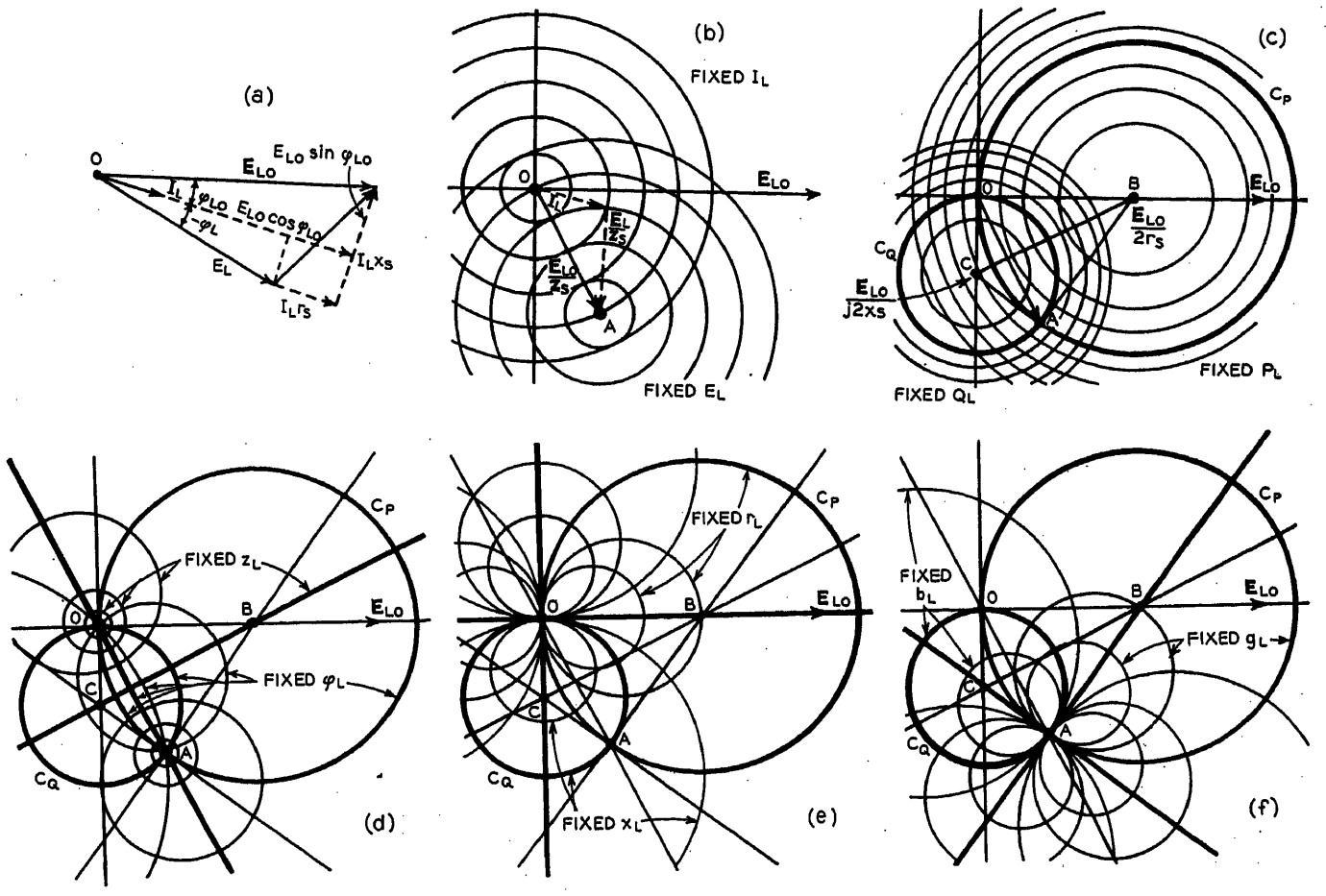



Fig. 2

If $a < b$, so that the circle $C$ encloses the origin $O$, figure 4*b*, equation 7 may be written in the form,

$$\cos(\theta - \alpha) = mR - \frac{n}{R} \tag{17}$$

where $m = 1/(2a)$ and $n = (b^2 - a^2)/(2a)$ are again positive constants. Then, putting $\theta = -\theta'$ and $R = 1/R'$, as before, we have

$$\cos(-\theta' - \alpha) = \frac{m}{R'} - nR' \text{ or } \cos(\theta' + \alpha - \pi) = nR' - \frac{m}{R'} \tag{18}$$

which is of the same form as (17) but with $\alpha$ replaced by $\pi - \alpha$ and with $m$ and $n$ interchanged. The locus of $\boldsymbol{R}'$ is therefore again a circle, as represented by $C'$, figure 4*b*.

If $a = b$, so that the circle $C$ passes through the origin $O$, figure 4*c*, equation (7) becomes

$$\cos(\theta - \alpha) = \frac{R}{2a} \tag{19}$$

So

$$\left.\begin{aligned} &\cos(-\theta' - \alpha) = \frac{1}{2aR'} \\ &\text{or} \\ &R'\cos(\theta' + \alpha) = \frac{1}{2a} \end{aligned}\right\} \quad (20)$$

which is evidently the equation of the straight line $C'$, figure 4*c*.

(The theorem that the inverse of a circle is a circle can also be proved by elementary geometry, using the fact

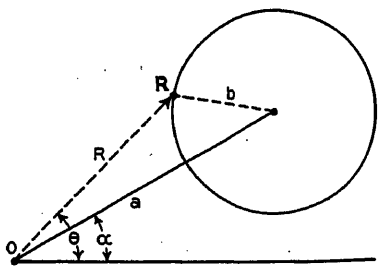



Fig. 3

that an inscribed angle is measured by its subtended arc to prove the similarity of certain triangles.)

The above theorem can be generalized to show that *if* $\boldsymbol{R}$ *has a circular locus, then so has the general linear fraction,*

$$w = \frac{dR + e}{fR + g} \left(d, e, f, g \text{ are complex constants such that } \frac{d}{f} \neq \frac{e}{g}\right) \quad (21)$$

For this equation may be reduced by division to

$$w = \frac{d}{f} + \frac{e - dg/f}{fR + g} \quad (22)$$

Thus $w$ is derived from $R$ by the following steps, each of which turns one circle into another: multiplying by the constant $f$ and adding the constant $g$, thus changing the scale, rotating and translating the circle; inverting, giving a new circle as proved above; and multiplying by the constant $e - dg/f$ and adding the constant $d/f$, thus changing the scale, rotating and translating the new circle.

Now returning to our problem of finding the loci of $I_L$, we may put $E_L = I_L z_L$ in equation 3, giving

$$I_L = \frac{E_{L0}}{z_S + z_L} \quad (23)$$

where

$$z_L = z_L \epsilon^{j\varphi_L} = r_L + jx_L = \frac{1}{g_L - jb_L} \text{ is variable} \quad (24)$$

Evidently $I_L$ is a linear fraction with respect to any of the components $z_L$, $\epsilon^{j\varphi_L}$, $x_L$, $r_L$, $b_L$, or $g_L$ when the associated component is held fixed. Hence in each case the locus of $I_L$ will be a circle, as we have just proved. We proceed to consider each case in turn.

If the *phase difference* $\varphi_L$ is fixed, and $z_L$ varies, the vector $z_L \epsilon^{j\varphi_L}$ will have a straight-line locus (circle of infinite radius). The current is expressed in terms of $\varphi_L$ and $z_L$ by the equation,

$$I_L = \frac{E_{L0}}{z_S + z_L \epsilon^{j\varphi_L}} \quad (25)$$

As $z_L$ varies from 0 to $\infty$, $I_L$ will vary from $E_{L0}/z_S$ to 0, for any $\varphi_L$; so all circular loci will pass through the origin $O$ and the short-circuit point $A$, as drawn in figure 2*d*. Their centers will therefore lie on the line $BC$, which is the perpendicular bisector of $OA$. For very large $z_L$, the term $z_S$ becomes vanishingly small in comparison with $z_L \epsilon^{j\varphi_L}$; so $I_L$ starts off from $O$ at the phase angle $-\varphi_L$, which is thus the inclination of the tangent to the circle at the origin. When $\varphi_L = 0$, we have the zero-active-power circle $C_P$; when $\varphi_L = 90$ degrees, we have the zero-reactive-power circle $C_Q$; and when $\varphi_L = \varphi_S$ (the phase angle of $z_S$), we have the straight line $OA$.

If the *impedance* $z_L$ is fixed and $\varphi_L$ varies, the vector $z_L \epsilon^{j\varphi_L}$ will have a circular locus (since $\epsilon^{j\varphi_L}$ is a vector of unit length and variable angle). The current, given by 25, will then have a circular locus which is most easily located by finding its center and radius. Evidently $I_L$ will have its minimum and maximum magnitudes when $z_L$ is respectively in phase with, and in opposition to, $z_S$; it then becomes

$$\left.\begin{aligned} I_{L\,\min} &= \frac{E_{L0}}{z_S} \cdot \frac{1}{1 + \frac{z_L}{z_S}} \\ &\text{and} \\ I_{L\,\max} &= \frac{E_{L0}}{z_S} \cdot \frac{1}{1 - \frac{z_L}{z_S}} \end{aligned}\right\} \quad (26)$$

The center of the circle is then the extremity of the vector.

$$\frac{I_{L\,\min} + I_{L\,\max}}{2} = \frac{E_{L0}}{z_S} \cdot \frac{1}{2}\left(\frac{1}{1 + \frac{z_L}{z_S}} + \frac{1}{1 - \frac{z_L}{z_S}}\right) = \frac{E_{L0}}{z_S} \cdot \frac{1}{1 - \frac{z_L^2}{z_S^2}} \quad (27)$$

so all centers lie on the line $OA$, which is the vector $E_{L0}/z_S$ produced. And the radius of the circle is the length of the vector,

$$\begin{aligned} \frac{I_{L\,\max} - I_{L\,\min}}{2} &= \frac{E_{L0}}{z_S} \cdot \frac{1}{2}\left(\frac{1}{1 - \frac{z_L}{z_S}} - \frac{1}{1 + \frac{z_L}{z_S}}\right) \\ &= \frac{E_{L0}}{z_S} \cdot \frac{z_L/z_S}{1 - \frac{z_L^2}{z_S^2}} \end{aligned} \quad (28)$$

For $z_L = 0$ and $z_L = \infty$, respectively, the circles shrink to the points $A$ and $O$. For $z_L = z_S$, the circle has an infinite radius and becomes the straight line $BC$.

Inspection of figure 2*d* suggests that the 2 sets of circles are *orthogonal* (cross at right angles). To prove this, we may differentiate (23):

$$dI_L = \frac{-E_{L0}}{(z_S + z_L)^2} dz_L \quad (29)$$

Now if $dz_L$ is given in turn 2 values at right angles, $dI_L$ will also have 2 values at right angles, since the factor $-E_{L0}/(z_S + z_L)^2$ is the same for both. But when $z_L$ varies first with $\varphi_L$ fixed and then with $z_L$ fixed, $dz_L$ will first be radial and then tangential. Hence the corresponding values of $dI_L$ will be at right angles. This relation affords a ready means for locating the constant-$z_L$ circle passing through any point $P$ in the plane: the constant-$\varphi_L$ circle is first drawn (through $P$, $O$, and $A$) and then its tangent is drawn at $P$; the intersection of this tangent with $OA$ is the center of the required circle.*

If the *resistance* $r_L$ is fixed and $x_L$ varies, the vector $z_L = r_L + jx_L$ will have a straight-line locus (vertical). The current is expressed in terms of $r_L$ and $x_L$ by the equation,

$$I_L = \frac{E_{L0}}{z_S + r_L + jx_L} = \frac{E_{L0}}{(r_S + r_L) + j(x_L + x_L)} \tag{30}$$

where $z_S = r_S + jx_S$.

If $x_L = \pm\infty$, $I_L = 0$ for all $r_L$; so all circular loci will pass through the origin $O$. Evidently $I_L$ will have its maximum magnitude when $x_L = -x_S$ and is then

$$I_{L\max} = \frac{E_{L0}}{r_S + r_L} \tag{31}$$

The center of the circle is then the extremity of the vector,

$$\frac{1}{2} I_{L\max} = \frac{E_{L0}}{2(r_S + r_L)} \tag{32}$$

so all centers lie on the line $OB$, which is the vector $E_{L0}$ produced, as drawn in figure 2*e*. For $r_L = \pm\infty$, the circles shrink to the point $O$. For $r_L = 0$, the circle is the zero-active-power circle $C_P$, whose radius was found to be $E_{L0}/(2r_S)$. Positive values of $r_L$ correspond to circles inside $C_P$, negative values to circles outside. For $r_L = -r_S$, the circle has an infinite radius and becomes the straight line $OC$.

If the *reactance* $x_L$ is fixed and $r_L$ varies, the vector $z_L = r_L + jx_L$ will again have a straight-line locus (now horizontal). The current, expressed by (30), will have a similar set of circular loci, all passing through $O$ (for $r_L = \pm\infty$). It will have its maximum magnitude when $r_L = -r_S$ and is then

$$I_{L\max} = \frac{E_{L0}}{j(x_S + x_L)} \tag{33}$$

The center of the circle is then the extremity of the vector,

$$\frac{1}{2} I_{L\max} = \frac{E_{L0}}{j2(x_S + x_L)} \tag{34}$$

so all centers lie on the line $OC$, which is in quadrature with $E_{L0}$, as drawn in figure 2*e*. For $x_L = \pm\infty$, the circles shrink to the point $O$. For $x_L = 0$, the circle is the zero-reactive-power circle $C_Q$, whose radius was found to be $E_{L0}/(2x_S)$. Positive (inductive) values of $x_L$ correspond to circles inside $C_Q$, negative (capacitive) values to circles outside. For $x_L = -x_S$, the circle has an infinite radius and becomes the straight line $OB$.

The 2 sets of circles in figure 2*e* are orthogonal, for the same reason as in figure 2*d*. Equation 29 still applies; and $dz_L$ will first be vertical and then horizontal when $z_L$ is varied first with $r_L$ fixed and then with $x_L$ fixed.

If the *conductance* $g_L$ is fixed and $b_L$ varies, the vector $1/z_L = g_L - jb_L$ will have a straight-line locus (vertical). It will now be conveniently to temporarily shift our origin to $A$ and to consider the locus of the vector (extending *from* $A$, figure 2*b*),

$$-\frac{E_L}{z_S} = -\frac{E_{L0}}{z_S}\cdot\frac{z_L}{z_S + z_L} = -\frac{E_{L0}}{z_S^2}\cdot\frac{1}{\frac{1}{z_S} + \frac{1}{z_L}}$$

$$= -\frac{E_{L0}}{z_L^2}\cdot\frac{1}{(g_S + g_L) - j(b_S + b_L)} \tag{35}$$

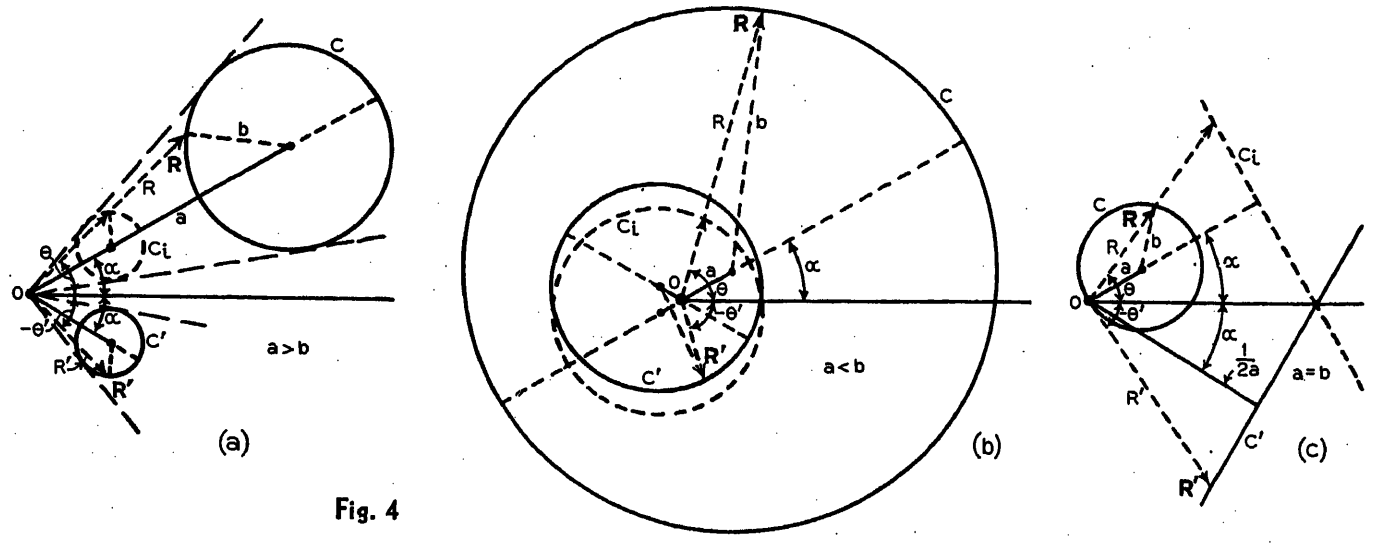



Fig. 4

* If we imagine $z_L$ *mapped* in its plane by drawing radial lines (fixed $\varphi_L$) and concentric circles (fixed $z_L$), these lines will constitute a figure *conformal* with the loci of figure 2*d*. Conformal mapping of one figure on another requires that all corresponding angles be equal. It always results when corresponding loci are drawn for 2 complex variables one of which is an analytic (differentiable) function of the other; for then differential figures will be similar. (Finite figures, however, will be similar only in the special case where the function is *linear*, as in equation 1 and figure 1.)

where $1/z_S = g_S - jb_S$. If $b_L = \pm\infty$, $-E_L/z_S = 0$ for all $g_L$; so all circular loci will pass through $A$. Evidently $-E_L/z_S$ will have its maximum magnitude when $b_L = -b_S$ and is then

$$-\frac{E_{Lmax}}{z_S} = -\frac{E_{L0}}{z_S^2}\cdot\frac{1}{g_S + g_L} \tag{36}$$

The center of the circle is then the extremity of the vector (from $A$),

$$-\frac{1}{2}\frac{E_{Lmax}}{z_S} = -\frac{E_{L0}}{z_S^2}\cdot\frac{1}{2(g_S + g_L)} \tag{37}$$

This vector evidently lags behind $-E_{L0}/z_S$ by the angle $\varphi_S$; so it lies along the line $AB$, on which therefore all centers lie, as drawn in figure 2*f*. For $g_L = \pm\infty$, the circles shrink to the point $A$. For $g_L = 0$, the circle is the zero-active-power circle $C_P$ since then

$$\frac{1}{2}\frac{E_{Lmax}}{z_S} = \frac{E_{L0}}{z_S^2\cdot 2g_S} = \frac{E_{L0}}{2r_S} \tag{38}$$

as found for the radius of $C_P$. Positive values of $g_L$ correspond to circles inside $C_P$, negative values to circles outside. For $g_L = -g_S$, the circle has an infinite radius and becomes the straight line $AC$.

If the *susceptance* $b_L$ is fixed and $g_L$ varies, the vector $1/z_L = g_L - jb_L$ will again have a straight-line locus (now horizontal). And $-E_L/z_S$, expressed by (35), will have a similar set of circular loci, all passing through $A$ (for $g_L = \pm\infty$). It will have its maximum magnitude when $g_L = -g_S$ and is then

$$-\frac{E_{Lmax}}{z_S} = \frac{E_{L0}}{z_S^2}\cdot\frac{1}{j(b_S + b_L)} \tag{39}$$

The center of the circle is then the extremity of the vector (from $A$),

$$-\frac{1}{2}\frac{E_{Lmax}}{z_S} = \frac{E_{L0}}{z_S^2}\cdot\frac{1}{j2(b_S + b_L)} \tag{40}$$

This vector is evidently in quadrature with the vector of equation 37; so it lies along the line $AC$ (perpendicular to $AB$), on which therefore all centers lie, as drawn in figure 2*f*. For $b_L = \pm\infty$, the circles shrink to the point $A$. For $b_L = 0$, the circle is the zero-reactive-power circle $C_Q$, since then

$$\frac{1}{2}\frac{E_{Lmax}}{z_S} = \frac{E_{L0}}{z_S^2\cdot 2b_S} = \frac{E_{L0}}{2x_S} \tag{41}$$

as found for the radius of $C_Q$. Positive (inductive) values of $b_L$ correspond to circles inside $C_Q$, negative (capacitive) values to circles outside. For $b_L = -b_S$, the circle has an infinite radius and becomes the straight line $AB$.

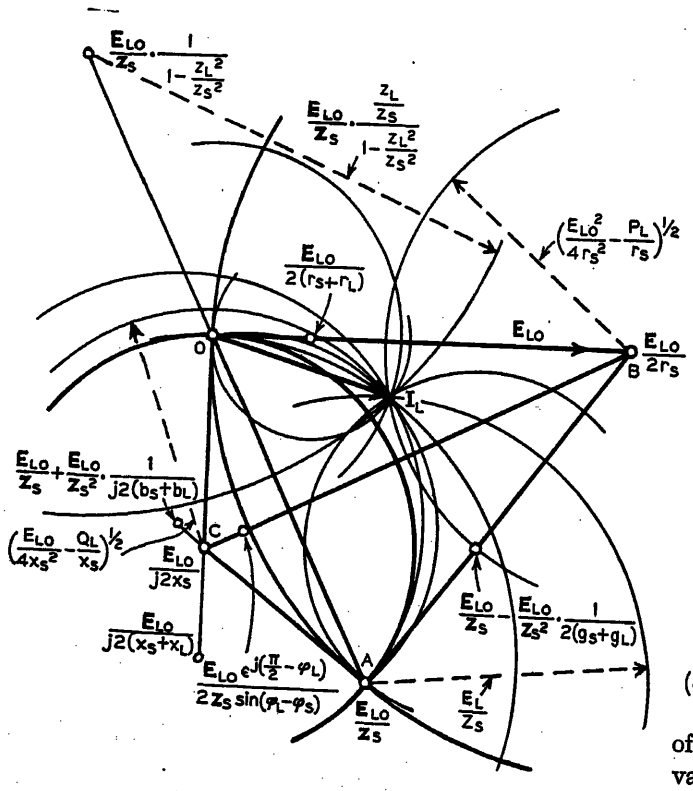
The 2 sets of circles in figure 2*f* are orthogonal, for the same reason as in figure 2*d* and *e*. The equation which applies in this case is found by differentiating equation 35:

$$d\left(-\frac{E_L}{z_S}\right) = \frac{E_{L0}}{z_S^2}\cdot\frac{1}{\left(\frac{1}{z_S} + \frac{1}{z_L}\right)^2}\,d\left(\frac{1}{z_L}\right) \tag{42}$$

for $d(1/z_L)$ will first be vertical and then horizontal when $1/z_L$ is varied first with $g_L$ fixed and then with $b_L$ fixed.

In figure 5*a* we have drawn (to double the scale of figure 2) for a particular current vector $I_L$ the 10 loci which pass through its extremity, values of the radii and locations of the centers being indicated, for convenience of reference. Figure 5*b* is derived from figure 5*a* by multiplying all vectors by the constant $K_M$ and adding the constant $I_{M0}$, to give $I_M$, in accordance with equation 1. This concludes our general problem.

Fig. 5



# A Suggested Rotor Flux Locus Concept of Single-Phase Induction-Motor Operation

By C. T. BUTTON
ASSOCIATE AIEE

THE cross field theory and the revolving field theory are the 2 commonly accepted bases for analytical treatment of the single phase squirrel cage induction motor. For the purpose of quantitative analysis as well as to explain why and how the motor runs, the first mentioned theory resolves fluxes, voltages, and currents into components in 2 axes fixed with reference to the stator; whereas the second theory resolves the flux into 2 rotating components—one rotating in a positive direction at synchronous speed, and the other rotating in a negative direction at synchronous speed.

An alternative concept is outlined below which is perhaps less involved than either of the above theories, although it does not lend itself to quantitative mathematical treatment. In a word, it considers the total flux traversing the air gap, and gives a complete picture of the variation in magnitude and direction of the total or resultant flux. The novelty of the treatment consists in referring the flux to axes fixed with reference to the rotor. Once the mind of the reader becomes accustomed to thinking of the rotor as a fixed basis of reference, the development becomes quite clear and rational. (The rotor may be regarded as stationary with the stator rotating about it, or if it assists in visualizing one can imagine he is hanging to the rotor and turning around with it.)

## Assumptions

Inasmuch as quantitative results are not attempted, stator resistance and leakage reactance will either not be involved, or will be considered zero. For purposes of simplifying the diagrams, a 2 pole motor will be considered (figure 1). Motor torque will be considered as clockwise. The flux crossing the air gap in the axis of the stator winding poles will be called primary flux. At synchronous speed the axis of the primary flux will accordingly be rotating with an angular velocity of $2\pi f$ in a counterclockwise sense, with respect to axes of reference fixed in relation to the rotor.

## Condition at Synchronous Speed

We may first plot the locus of the primary magnetomotive-force vector with reference to the rotor for the synchronous speed condition, as indicated in figure 2. This may also be considered as representing the locus of flux through the rotor if there were no rotor conductors; or as representing the primary flux as defined above. (If the rotor were at standstill, the flux locus would of course be a straight line, the instantaneous magnitude of the flux pulsating sinusoidally positive and negative with respect to time.) At synchronous speed, this primary magnetomotive-force or primary flux vector locus would be a circle as shown, never going below the horizontal (rotor) axis. The maximum primary flux is shown as $F_M$ in figure 2; and one-eighth of a cycle later the vector would be in the position shown dotted. The locus would be traversed (in a C.C.W. sense) by the vector twice per cycle, although its angular velocity is only $2\pi f$, as stated above.

The effect produced by the rotor conductors may be described as follows. The rotor is an inductive body circularly symmetrical, so to speak. It is evident that the effect of rotor inductance (not the leakage reactance) will be to resist any change in magnitude or direction of the total flux through it. In other words, due to change in magnitude and direction of the primary flux (figure 3) currents will flow in the rotor conductors producing a secondary flux at right angles to the primary flux; and this secondary flux will have a magnitude and direction tending to maintain the total resultant rotor flux constant at $OF$. At the instant when the primary flux is zero, the secondary flux will be a maximum, and perpendicular upward. This of course simply means that (to use ordinary terminology) the cross field is maximum when the main field is zero.

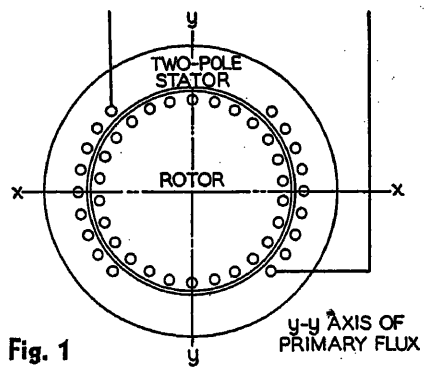


Fig. 1

The inductive effect of the rotor will not be 100 per cent in maintaining constant flux through the rotor at synchronous speed of course, due to the effect of rotor resistance and leakage reactance. The actual total rotor flux at synchronous speed in the practical motor will then be something like the locus indicated in figure 4.

The concept which this treatment attempts to visualize does not emphasize the components $OM$ and $MF$ of figure 3; but rather states simply that (to reiterate) the inductive effect of the rotor resists the amount of total flux change which would exist in an open-circuited rotor condition for the same rotor speed, constraining the total flux to the circular locus of small diameter shown in figure 4.

(It might be mentioned however, that in addition to the main and cross field components, we could also indi-

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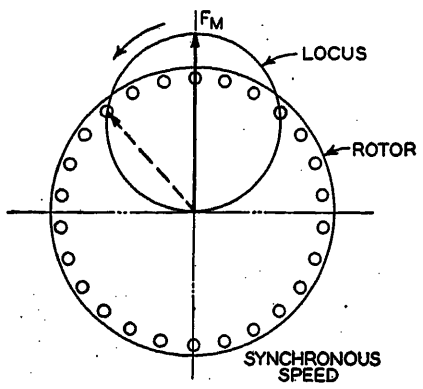



Fig. 2

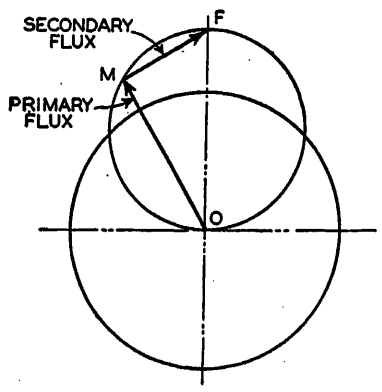



Fig. 3

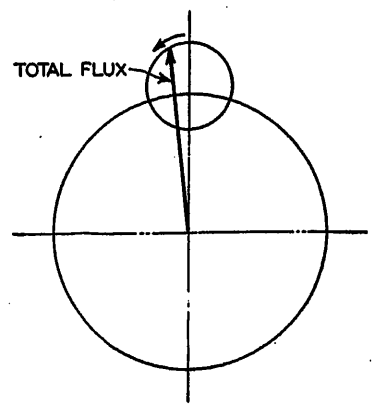



Fig. 4

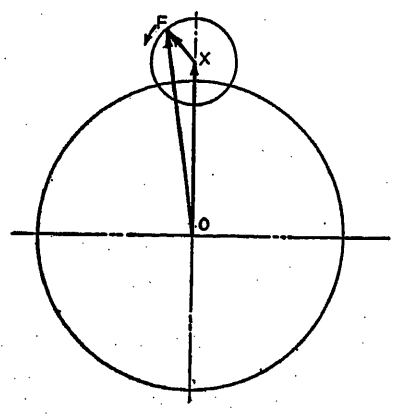



Fig. 5

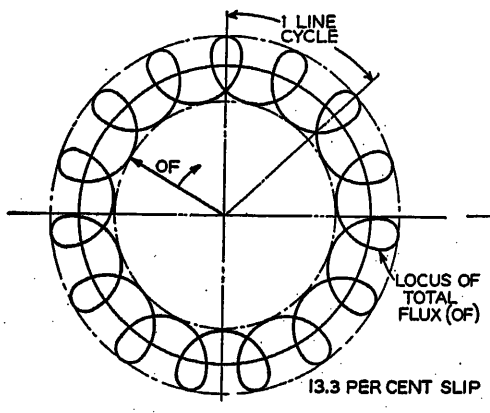



Fig. 6

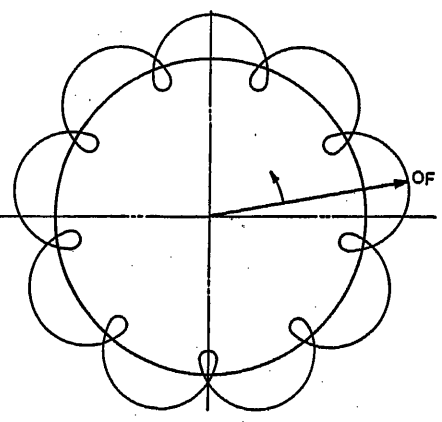



Fig. 7

cate on our diagram the forward and backward rotating flux components $OX$ and $XF$ as in figure 5. $OX$ is constant, and $XF$ is constant in magnitude and rotating with a velocity of $4\pi f$. Again, there is no motive for separation into components except possibly to tie in our diagrams with both of the theories mentioned at the outset.)

## Normal Motoring Condition

It is now but a step to the conception of the locus of total flux at any particular amount of slip. This is shown by figure 6, where the flux vector progresses around the rotor in a clockwise sense (taking 2 steps forward and one step backward, so to speak).

Torque is produced by change in direction of flux through the rotor. The instantaneous torque will be a function of flux magnitude and angular velocity (torque would not be directly proportional to angular velocity of course). Inspection of figure 4 will show that at synchronous speed there is a pulsating torque with a net or average counter clockwise value. In other words, it requires power input to drive the motor at synchronous speed even with losses neglected. Or in still other words, the no load point is at some speed slightly below synchronism.

With normal slip, inspection of the corresponding flux locus (figure 6) will reveal the existence and reason for the pulsating double frequency torque component, and also the average motor torque.

The magnitude of the main flux will be the radius of the outer envelope of the total flux locus; and the quadrature flux will be represented by the radius of the inner envelope.

## Conditions Above Synchronous Speed

In the same way, the total flux locus at a speed above synchronism may be drawn as shown by figure 7.

## Conclusion

It is not claimed that the concepts outlined may be of direct use in calculating performance of single phase motors. However, it is important to have clear mental pictures of just what is going on in any machine under consideration. Such concepts may serve to assist in interpreting results obtained from mathematical treatment, and they may also serve a purpose in connection with general educational work.

The rotor is conceived of briefly as an inductive "circularly symmetrical" rotating body which tends to maintain total flux constant in magnitude and direction with respect to itself. This inductive effect prevents total flux from disappearing at the instant the primary field is zero; and its resistance to change in direction of total flux through it produces torque. The reason for the pulsating and average motor torque components is thus clearly visualized, by reference to the diagrams showing the behavior of the "mutual reactance flux" through stator and rotor.

# Characteristic Constants of Single-Phase Induction Motors Part I: Air-Gap Reactances

By WAYNE J. MORRILL
MEMBER AIEE

## Synopsis

This paper is the first of 2 papers dealing with the development of equations for determining the characteristic constants of single-phase induction motors. It is intended to present in the complete paper a unified tabulation of formulas consistent in symbols with those used in the paper which I presented at the midwinter convention of the AIEE, New York, January 28–February 1, 1929.

This particular section of the paper deals with a rigorous development of the reactances of single-phase motors which result from fluxes crossing the air gap between the stator and rotor.

## Introduction

SINCE 1929 great strides have been made in the design and development of the capacitor motor. As evidence of this fact, the capacitor motor is now the accepted motor for use on domestic refrigeration machines and many other domestic appliances. During the last year over 1,000,000 such motors were built in the United States.

It is felt that at this time a further contribution to the art can be made by presenting in one paper a systematic development consistent within itself, covering the method of calculating the electrical characteristic constants of single-phase induction motors.

It is hoped that such a complete and consistent presentation of the matter will be useful in view of the fact that most of the previous information on the subject has been based upon polyphase formulas adapted to single-phase construction.

While the constants as developed in this paper are intended primarily for use in conjunction with the theory of the capacitor motor and the resistance split-phase motor, the point of view of the development is such as to furnish calculational methods which apply equally well to other types of single phase motors as, for example, the repulsion-start induction-run single-phase motor.

## Plan of Development

The plan of the development follows closely that employed by Chapman for polyphase induction motors and Alger for synchronous motors except, that the single-phase point of view is maintained throughout and the results apply especially to single-phase motors.

The development has as its basis the assumption that only flux of fundamental space distribution links mutually the rotor and stator. Harmonic fluxes are assumed to be self-inductive to the members producing them and their effect is treated as that of self-inductive leakage reactance.

It is shown that spiraling either member reduces the effectiveness of the fundamental flux of one member as regards the other member while having no effect upon the producing member. It follows that where relative spiraling exists between the stator and the rotor the mutual reactance is reduced and since the self-inductive reactance is unchanged there must be effective in each member a component of leakage reactance due to self produced flux of fundamental space distribution. Expressions for exact determination of these effects are derived.

## Results of Development

There results from the development an exact definition of 6 primary reactances and 5 secondary reactances. Only 3 of each are useful in actual calculation, the others being used in the development and for the sake of clarity. The constants and their derived formulas are listed in the tabulation below and their significance indicated by the accompanying equivalent circuits.

For the primary, the reactances defined are:

### Primary Air-Gap Reactances

$X_{T_1}$ = total primary self-inductive reactance due to air-gap flux
$X_{m_1 f}$ = total primary self-inductive reactance due to fundamental flux (both forward and backward)
$X_{m_1}$ = total primary self-inductive reactance due to either fundamental field
$X_{1 \delta f}$ = total primary self-inductive reactance due to harmonic flux
$X_{\alpha 1 f}$ = total primary self-inductive reactance due to spiral
$X_m$ = primary mutual reactance of either forward or backward field

### Secondary Air-Gap Reactances

$X_{T_2}$ = total secondary self-inductive reactance to a revolving field
$X_{m_2}$ = secondary self-inductive reactance due to fundamental flux
$X_{2\delta}$ = secondary self-inductive leakage reactance due to air-gap flux
$X_\alpha$ = secondary self-inductive leakage reactance due to spiral
$X_m$ = secondary mutual reactance (with primary) to either field

## Nomenclature

All of the nomenclature is defined in the course of the development. For convenience those symbols needed in interpreting the results are listed below.

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$f$ = line frequency, cycles per second
$f_T$ = function of primary turns. See remarks preceding (18)
$K$ = $2\pi f 10^{-8}$
$l$ = axial length of air gap section in inches
$m_2$ = total number of rotor slots
$\mathcal{P}$ = $A/\delta$
$A$ = effective air-gap area per square inch
$\delta$ = radial length of air gap in inches
$P$ = number of fundamental poles
$T_pW_k$ = primary effective turns per pole. See (11) and (12)
$\lambda$ = fundamental peripheral pole pitch in inches
$\lambda_\alpha$ = peripheral distance in inches by which one end of spiraled member is displaced from its other end. See (40)

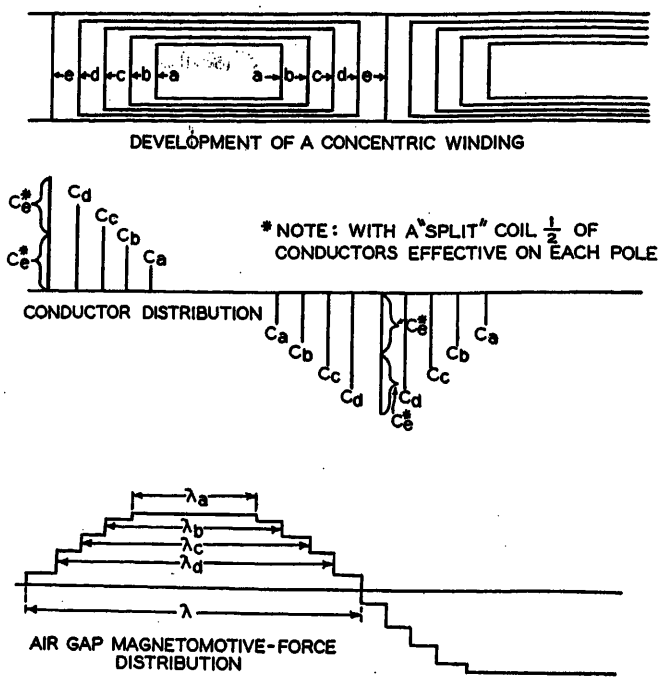



**Fig. 2. Development of a concentric winding**

## Appendix—Development of Expressions for Reactance

### General Assumptions in the Development of Equations for Air-Gap Reactances

The usual assumptions which are made in the exact analysis of induction motors and which are listed in the appendix of my 1929 paper are made in this paper and will not be repeated.

In determining the air-gap reactances of induction motors, however, there are certain assumptions in addition to those already mentioned which must be made for the sake of establishing a simple and exact method of attack. These assumptions are listed below.

(*a*) *Only air gap flux of fundamental sinusoidal space distribution links mutually the rotor and stator winding.* This is true because unless the number of slots in the rotor and stator are made multiples of each other, or the stator winding is carelessly proportioned, experience and theory both show that harmonic fluxes of one winding generate negligible fundamental voltages in the other winding. It is true that the harmonic fluxes of one winding may generate voltages of other than fundamental frequency in the other winding under certain conditions, but the phenomena involved may be treated independently of the fundamental theory of the motor, and therefore, are not touched upon in the present report.

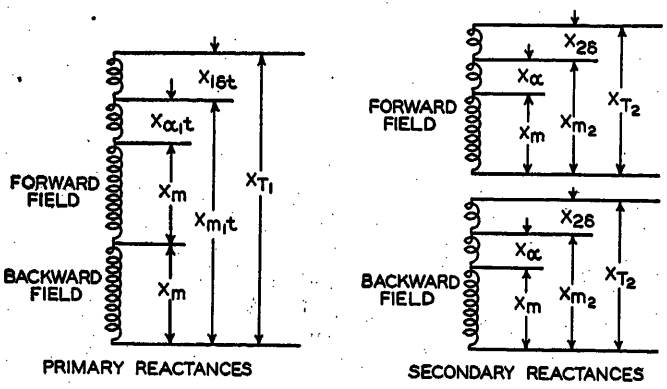



**Fig. 1. Summary of air-gap reactances**

$$X_{T_1} = K\mathcal{P}l\lambda f_T \quad (18)$$

$$X_{m_1 t} = \frac{8}{\pi^2} K\mathcal{P}l\lambda(T_pW_k)^2 \quad (13)$$

$$X_{m_1} = \frac{4}{\pi^2} K\mathcal{P}l\lambda(T_pW_k)^2 \quad (15)$$

$$X_{1\delta t} = X_{m_1}\left[\frac{\frac{\pi^2}{8} f_T}{(T_pW_k)^2} - 1\right] \quad (20)$$

$$X_{\alpha_1 t} = X_{m_1} 2\left[1 - \frac{2}{\pi}\frac{\lambda}{\lambda_\alpha}\sin\frac{\lambda_\alpha}{\lambda}\frac{\pi}{2}\right] \quad (48)$$

$$X_m = X_{m_1}\frac{2}{\pi}\frac{\lambda}{\lambda_\alpha}\sin\frac{\lambda_\alpha}{\lambda}\frac{\pi}{2} \quad (51)$$

$$X_{T_2} = X_{m_2} + X_{2\delta}$$

$$X_{m_2} = X_{m_1} \quad (39)$$

$$X_{2\delta} = X_m\left[\left(\frac{\frac{P}{m_2}\pi}{2\sin\frac{P\pi}{2m_2}}\right)^2 - 1\right] \quad (38)$$

$$X_\alpha = X_{m_1}\left[1 - \frac{2}{\pi}\frac{\lambda}{\lambda_\alpha}\sin\frac{\lambda_\alpha}{\lambda}\frac{\pi}{2}\right] \quad (47)$$

(*b*) *Only that portion of the stator fundamental flux which produces voltage in the rotor winding, and only that portion of the rotor fundamental flux which produces voltage in the stator winding, are considered as mutual fluxes.* The test for mutual flux is that it must generate the same voltage per turn in one member as in the other member, and if this condition is not fulfilled the effect of reduction in voltage in the second member is that of leakage flux and must be so treated.

(*c*) *Those fluxes which are produced by one member and which do not produce fundamental voltage in the other member are treated as leakage fluxes.* From this point of view the difference, between the total flux of any winding and that portion of the flux which generates fundamental voltage in the opposite winding is defined as leakage flux.

### I—Air-Gap Leakage Reactance of a Concentric Stator Winding

The primary windings of single-phase induction motors are invariably of the concentric type (coaxial coils of varying pitch) as shown in figure 2.

The total air-gap reactance of one pole of a concentric type winding can be obtained by taking the summation of the reactances corresponding to each stator tooth and the turns surrounding it. The general equation for the tooth reactance is

$$X_{tn} = K\mathcal{P}l\lambda_{tn}(\Sigma_n T)^2 \quad (1)$$

where

$l$ = axial length of air gap
$X_{tn}$ = reactance due to "$n$th" tooth flux
$K$ = constant to convert to ohms
$\lambda_{tn}$ = peripheral pitch of "$n$th" tooth section
$\Sigma_n T$ = sum of turns surrounding "$n$th" tooth section
$\mathcal{P}$ = permeance per square inch of air gap (see nomenclature)

By reference to figure 2 it is possible to write the expression for

the reactance corresponding to the innermost teeth whose total peripheral pitch is $\lambda_a$.

$$X_{ta} = K\mathcal{P}l\lambda_a(T_a + T_b + T_c + T_d + T_e)^2 \tag{2}$$

On each side of the $\lambda_a$ section there are 2 sections of total peripheral pitch $\lambda_b - \lambda_a$. The reactance due to these sections is:

$$X_{tb} = K\mathcal{P}l(\lambda_b - \lambda_a)(T_b + T_c + T_d + T_e)^2 \tag{3}$$

By the same method of reasoning the remaining reactances may be determined and the total reactance becomes:

$$X_{T_1} = K\mathcal{P}l\lambda \begin{bmatrix} \frac{\lambda_a}{\lambda}(T_a + T_b + T_c + T_d + T_e)^2 \\ \frac{\lambda_b - \lambda_a}{\lambda}(T_b + T_c + T_d + T_e)^2 \\ \frac{\lambda_c - \lambda_b}{\lambda}(T_c + T_d + T_e)^2 \\ \frac{\lambda_d - \lambda_e}{\lambda}(T_d + T_e)^2 \\ \frac{\lambda - \lambda_d}{\lambda}(T_e)^2 \end{bmatrix} \tag{4}$$

If only the air-gap magnetomotive-force distribution of the $n$th primary coil is considered, a diagram as shown in figure 3 is obtained.

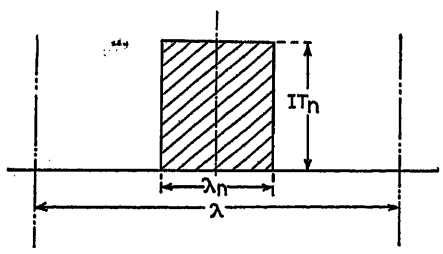



**Fig. 3. Air-gap magnetomotive force of nth primary coil**

By Fourier analysis it is possible to express the amplitude of the corresponding fundamental component of magnetomotive-force, $a_n$:

$$a_n = \frac{4}{\pi} IT_n \sin \frac{\pi}{2}\frac{\lambda_n}{\lambda} \tag{5}$$

By the use of (5) the amplitude of the fundamental component of magnetomotive-force due to all the coils on a pole may be written:

$$a = \Sigma a_n \tag{6}$$

$$a = \frac{4}{\pi} I \begin{bmatrix} T_a \sin \frac{\pi}{2}\frac{\lambda_a}{\lambda} \\ T_b \sin \frac{\pi}{2}\frac{\lambda_b}{\lambda} \\ T_c \sin \frac{\pi}{2}\frac{\lambda_c}{\lambda} \\ T_d \sin \frac{\pi}{2}\frac{\lambda_d}{\lambda} \\ T_e \sin \frac{\pi}{2}\frac{\lambda_e}{\lambda} \end{bmatrix}$$

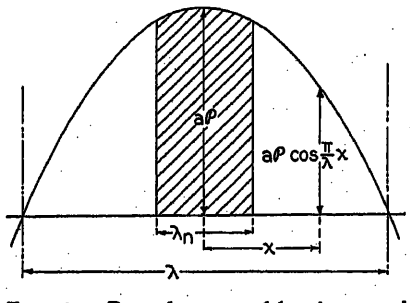



**Fig. 4. Distribution of fundamental flux**

The flux density at any point on the air gap periphery corresponding to a magnetomotive-force wave having a maximum amplitude of $a$ may be expressed:

$$B = a\mathcal{P}\cos\frac{\pi}{\lambda}x \tag{7}$$

where

$B$ = flux density at point $x$
$\mathcal{P}$ = permeance per square inch of air gap

The portion of fundamental flux which links the $n$th stator coil can be obtained by multiplying equation (7) by the axial length in inches $l$ and integrating between the limits of $-\frac{\lambda_n}{2}$ and $+\frac{\lambda_n}{2}$ as indicated in (8). This is the equivalent of finding the flux cross hatched in figure 4.

$$\Phi_{1n} = \int_{-\lambda_n/2}^{+\lambda_n/2} a\mathcal{P}l\cos\frac{\pi}{\lambda}x\,dx \tag{8}$$

$$\Phi_{1n} = a\mathcal{P}l\frac{\lambda}{\pi}\left[\sin\frac{\pi}{\lambda}x\right]_{-\lambda_n/2}^{+\lambda_n/2}$$

$$\Phi_{1n} = 2a\mathcal{P}l\frac{\lambda}{\pi}\sin\frac{\pi}{2}\frac{\lambda_n}{\lambda} \tag{9}$$

The reactance of the $n$th stator coil due to the fundamental flux which links it may be expressed by multiplying (9) by the number of turns in the coil, $T_n$, and by $K/I$ to convert to ohms.

$$X_{1n} = 2a\mathcal{P}l\frac{\lambda}{\pi}\frac{K}{I}T_n\sin\frac{\pi}{2}\frac{\lambda_n}{\lambda} \tag{10}$$

The total reactance of the stator winding due to the self-produced fundamental flux is obtained as the sum of $X_{1n}$ for all coils:

$$X_{m_1l} = 2a\mathcal{P}l\frac{\lambda}{\pi}\frac{K}{I}\begin{bmatrix} T_a \sin \frac{\pi}{2}\frac{\lambda_a}{\lambda} \\ T_b \sin \frac{\pi}{2}\frac{\lambda_b}{\lambda} \\ T_c \sin \frac{\pi}{2}\frac{\lambda_c}{\lambda} \\ T_d \sin \frac{\pi}{2}\frac{\lambda_d}{\lambda} \\ T_e \sin \frac{\pi}{2}\frac{\lambda_e}{\lambda} \end{bmatrix} \tag{11}$$

The bracketed member of (6) and (11) is termed the "effective turns" per pole of the primary winding and is symbolized by:

$$\text{Effective turns per pole} = T_P W_K \tag{12}$$

where

$T_P$ = total turns per pole
$W_K$ = winding constant to convert to "effective turns"

If (6) and (12) are substituted in (11) the following is obtained:

$$X_{m_1l} = \frac{8}{\pi^2}\mathcal{P}l\lambda K(T_P W_k)^2 \tag{13}$$

Equation (13) expresses the total reactance of the primary winding due to pulsating self produced flux of fundamental sinusoidal distribution.

It has long been known that a pulsating wave of sinusoidally distributed flux may be represented by 2 equal oppositely gliding waves of flux each having a constant amplitude equal to half the amplitude of the pulsating wave. In my 1929 paper I defined the magnetizing reactance of a single-phase motor as that value of reactance corresponding to either of the gliding fields of flux. In equation (19) of that paper its value was given as:

$$X_{m_1} = 2\pi f C_m^2 \frac{1}{16}\mathcal{P}l\lambda 10^{-8} \tag{14}$$

In the present case, since the reactance due to each gliding (or revolving) wave of flux has the same value, the primary reactance

due to either must be equal to half the total primary magnetizing reactance:

$$X_{m_1} = \frac{1}{2} X_{m_1 t} \tag{15}$$

$$X_{m_1} = \frac{4}{\pi^2} \mathcal{P} l \lambda K (T_p W_k)^2$$

If the following substitutions are made in (14) and (15) the 2 equations will be found to be identical.

$$C_m = \frac{8}{\pi} T_p W_k \tag{16}$$

$$K = 2\pi f 10^{-8} \tag{17}$$

It will be found convenient in the present paper to express as many air-gap reactances as possible in terms of per unit of $X_{m_1}$.

If the bracketed member of (4) be called $f_T$ (function of turns), the equation for $x_{T_1}$ is:

$$X_{T_1} = K \mathcal{P} l \lambda f_T \tag{18}$$

Equation (18) expresses the total reactance of the primary winding due both to the flux of fundamental sinusoidal distribution and the leakage flux which is of other than fundamental distribution. The reactance due to air-gap leakage flux may, therefore, be expressed as the difference between the total reactance and the total reactance due to the fundamental flux:

$$X_{1\delta t} = X_{T_1} - X_{m_1 t} \tag{19}$$

Expressed in terms of $X_{m_1}$ the total per-unit leakage reactance due to air gap flux is:

$$\text{Per unit } X_{1\delta t} = \frac{X_{T_1} - X_{m_1 t}}{X_{m_1}} \tag{20}$$

$$\text{Per unit } X_{1\delta t} = 2 \left[ \frac{\frac{\pi^2}{8} f_T}{(T_p W_k)^2} - 1 \right] \tag{21}$$

Equation (21) is a dimensionless formula and because of its dimensionless character gives a clear picture of the relationships involved. In order to obtain the actual total primary air-gap leakage reactance it is necessary to multiply (21) by $X_{m_1}$

## The Air-Gap Leakage Reactance of a Rotor With Uniformly Spaced Slots Wound One Phase per Slot

In the case of a motor of the repulsion-start induction-run type, the rotor winding employed during running operation is a winding having as many phases as there are slots in the rotor. If the rotor has an even number of slots or a number of slots corresponding to a multiple of the number of poles, certain of these phases may be repetitions of each other, but the analysis to be presented will be found to include such special cases.

If a rotor of the type described be acted upon by a revolving field of stator flux, the voltages generated in succeeding coils (phases) and the currents which result will have a peripheral distribution in the rotor slots as shown in figure 5. The upper diagram indicates the slot distribution of the ampere conductors of the left hand sides of the coils and the lower diagram indicates the ampere-conductor distribution of the right-hand coil sides. The sum of these 2 diagrams furnishes the total ampere-conductors distributed in each slot.

Proceeding from the distribution shown in figure 5, it is possible to develop 2 magnetomotive-force distribution diagrams as shown in figure 6. The sum of these 2 diagrams furnishes the resultant magnetomotive-force distribution produced by the rotor winding.

It is possible to express analytically the ampere-conductor distribution in the rotor slots due to the left coil sides shown in the upper diagram, figure 5.

$$I_{nL} C_c = I_{2n \max} C_c \cos \frac{P\lambda}{m_2} n \frac{\pi}{\lambda} \tag{22}$$

where

$C_c$ = conductors per coil side
$I_{nL}$ = amperes per conductor in left side of $n$th coil
$I_{2n \max}$ = maximum amperes per conductor in rotor coils
$n$ = integer indicating the number of the rotor phase under consideration, starting with a rotor phase carrying maximum current as the zero phase and counting in a forward direction
$P$ = number of fundamental poles
$\lambda$ = pole pitch in inches
$m_2$ = number of rotor phases (total)

The equation for the ampere-conductor distribution in the $n$th slot due to the right-hand coil side is very similar to that of the left-hand coil side except displaced by a difference corresponding to the coil pitch and reversed in sign. This distribution is given by equation 23.

$$I_{nR} C_c = - I_{2n \max} C_c \cos \frac{P\lambda}{m_2} (n - t_c) \frac{\pi}{\lambda}$$

$t_c$ = number of rotor teeth included by one rotor coil (23)

The sum of equation (22) and (23) gives the total ampere-conductor distribution in the $n$th rotor slot.

$$I_n C_c = (I_{nL} + I_{nR}) C_c =$$

$$I_{2n \max} C_c \left[ \cos \frac{P\lambda}{m_2} n \frac{\pi}{\lambda} - \cos \frac{P\lambda}{m_2} (n - t_c) \frac{\pi}{\lambda} \right] \tag{24}$$

The sum of the ampere-conductors in each of the slots from the "zero" slot to the $n$th slot is the number of ampere-conductors tending to produce flux across the air gap from the face of the $n$th tooth.

$$MMF_n = \sum_0^n I_{2n \max} C_c \left[ \cos \frac{P\pi}{m_2} n - \cos \frac{P\pi}{m_2} (n - t_c) \right] \tag{25}$$

$$MMF_n = I_{2n \max} C_c \left[ \frac{\cos \frac{P\pi}{2m_2} (2n + 1 - t_c) \sin \frac{P\pi}{2m_2} t_c}{\sin \frac{P\pi}{2m_2}} \right] \tag{26}$$

The flux in the $n$th tooth which will be produced by $MMF_n$ may

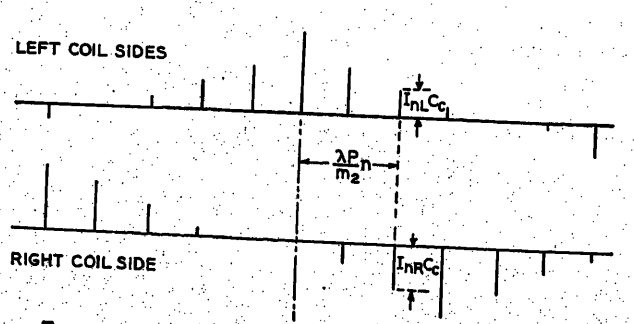



Fig. 5. Rotor slot ampere-conductor distribution

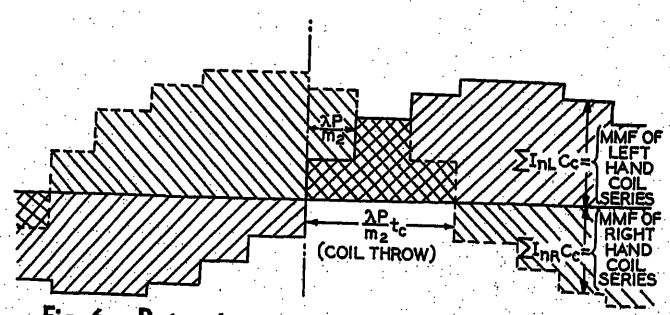



Fig. 6. Rotor-air-gap magnetomotive force distribution

be obtained by multiplying $MMF_n$ by the permeance per tooth. It can be expressed as in (27).

$$\Phi_n = MMF_n \frac{\lambda Pl}{m_2} \mathcal{P} =$$

$$I_{2n\,\max} C_c \frac{\lambda Pl}{n} \mathcal{P} \left[ \frac{\cos \frac{P\pi}{2m_2} (2n + 1 - t_c) \sin \frac{P\pi}{2m_2} t_c}{\sin \frac{P\pi}{2m_2}} \right] \quad (27)$$

The total flux per pole is the sum of the fluxes in each tooth across one pole face:

$$\Phi_{T_2} = \sum_{0}^{\frac{m_2}{P}-1} \Phi_n = I_{2n\,\max} C_c \frac{\lambda Pl}{m_2} \mathcal{P} \left[ \frac{\sin \frac{P\pi}{2m_2} t_c}{\sin \frac{P\pi}{2m_2}} \right] \quad (28)$$

$l$ = axial length of air gap
$\mathcal{P}$ = permeance per square inch of air gap

The amplitude of the fundamental component of the rotor flux can be obtained by Fourier analysis. In figure 7 is shown the flux of one rotor tooth. The amplitude of the fundamental sine component of this flux will be derived. (Due to the choice of axis the cosine component drops out in taking a summation of the sine and cosine components across one pole and the cosine component is, therefore, being omitted.)

The amplitude of the fundamental sine component of the flux shown in figure 7 is given by the expression of equation (29) which can be converted to (30) and (31).

$$a_{\Phi n} \int_0^{\lambda} \sin^2 \frac{\pi}{\lambda} x dx = \int_{\frac{\lambda\rho}{m_2} n}^{\frac{\lambda\rho}{m_2}(n+1)} MMF_n \mathcal{P} \sin \frac{\pi}{\lambda} x dx \quad (29)$$

$$a_{\Phi n} = -\frac{2}{\pi} MMF_n \mathcal{P} \left[ \cos \frac{\pi P}{m_2} (n + 1) - \cos \frac{\pi P}{m_2} n \right] \quad (30)$$

$$a_{\Phi n} = \frac{4\mathcal{P}}{\pi} I_{2n\,\max} C_c \left[ \frac{1}{2} \sin \frac{\pi P}{2m_2} (4n + 2 - t_c) + \frac{1}{2} \sin \frac{\pi P}{2m_2} t_c \right] \sin \frac{\pi P}{2m_2} t_c \quad (31)$$

The value of $a_{\Phi n}$ is the maximum density of the sine component of the flux of the $n$th rotor tooth. To obtain the amplitude of the total sine component the summation of $a_{\Phi n}$ across one pole pitch is taken:

$$a_\Phi = \sum_{0}^{\frac{m_2}{P}-1} a_{\Phi n} \quad (32)$$

$$a_\Phi = \frac{4\mathcal{P}}{\pi} I_{2n\,\max} C_c \frac{m_2}{P} \left[ \frac{1}{2} \sin^2 \frac{\pi P}{2m_2} t_c \right] \quad (33)$$

The quantity $a_\Phi$ is the maximum amplitude of the fundamental flux component produced by the rotor winding. In order to express the value of the flux it is necessary to integrate the wave corresponding to $a_\Phi$ over one pole pitch and for an axial length, $l$.

$$\Phi_{m_2} = \int_0^{\lambda} la \sin \frac{\pi}{\lambda} x dx = \frac{2}{\pi} \lambda a \quad (34)$$

$$\Phi_{m_2} = \frac{4}{\pi^2} l\lambda \mathcal{P} I_{2n\,\max} C_c \frac{m_2}{P} \sin^2 \frac{\pi P}{2m_2} t_c \quad (35)$$

Since all the currents which produce both $\Phi_{m_2}$ and $\Phi_{T_2}$ vary sinusoidally with respect to time, $\Phi_{m_2}$ and $\Phi_{T_2}$ vary sinusoidally with respect to time and their difference, $\Phi_{T_2} - \Phi_{m_2}$, varies in the same fashion. All of these fluxes completely link each rotor bar, and since all of them are of the same frequency with respect to the rotor they generate voltages of the same frequency which referred to the stator winding is the fundamental frequency of the motor.

Since, with a given value of current, the magnitude of reactance is proportional to generated voltage, the total rotor-air-gap reactance (referred to primary) $X_{T_2}$ and the fundamental rotor air gap reactance $X_{m_2}$ must be proportional respectively to the total rotor air gap flux $\Phi_{T_2}$ and the fundamental air gap flux $\Phi_{m_2}$.

$$\frac{X_{T_2}}{X_{m_2}} = \frac{\Phi_{T_2}}{\Phi_{m_2}} \quad (36)$$

In the same way that the per-unit air-gap leakage reactance of the primary was defined we may write

$$\text{Per unit } X_{2\delta} = \frac{X_{T_2} - X_{m_2}}{X_{m_2}} = \frac{\Phi_{T_2} - \Phi_{m_2}}{\Phi_{m_2}} \quad (37)$$

If the values for $\Phi_{T_2}$ and $\Phi_{m_2}$ be substituted from (28) and (35) respectively equation (38) is obtained.

$$\text{Per unit } X_{2\delta} = \frac{I_{2n\,\max} C_c \frac{\lambda Pl}{m_2} \mathcal{P} \left[ \frac{\sin \frac{P\pi}{2m_2} t_c}{\sin \frac{P\pi}{2m_2}} \right]^2}{I_{2n\,\max} C_c \lambda l \mathcal{P} \frac{m_2}{P} \sin^2 \frac{\pi P}{2m_2} t_c} \quad (38)$$

Equation (38) simplifies to:

$$\text{Per unit } X_{2\delta} = \left( \frac{P}{m_2} \right)^2 \frac{\pi}{4 \sin^2 \frac{P\pi}{2m_2}} - 1 \quad (39)$$

Equation (39) expresses the rotor-air-gap leakage reactance in per unit of $X_{m_2}$ but a valuable simplification can be made if it be recognized that:

$$X_{m_2} = X_{m_1} \quad (40)$$

This is true because the dimensions of the magnetic circuits of $X_{m_2}$ and $X_{m_1}$ are the same and $X_{m_2}$ is "referred to the primary," which means that the effective turns are the same.

## The Air-Gap Reactance Due to Spiral

Thus far in the discussion of the air-gap reactances of single-phase induction motors only fluxes of other than fundamental distribution have acted in the rôle of leakage fluxes. We come now to a reactance caused by flux of fundamental distribution.

If one of the members (stator or rotor) of an induction motor is spiraled, no change is produced in either the fundamental air-gap flux reactance or the total air-gap reactance as far as the spiraled member is concerned. There is, however, a change in the effectiveness of the spiraled flux in inducing voltage in the other member and since the proof of mutual flux is that it induce equal volts per turn at the same frequency in both members, it must be concluded that the reduced effectiveness of the primary flux is a leakage-reactance phenomenon.

The equation for the 3-dimension wave of flux when the producing member is spiraled is given by (41).

$$B = MMF_{\max} \mathcal{P} \cos \left[ \frac{\pi}{\lambda} \left( x - \frac{\lambda_\alpha}{l} z \right) - \omega t \right] \quad (41)$$

$\lambda_\alpha$ = peripheral amount by which one end of the spiraled member is displaced from the other end
$z$ = axial distance measured from one end of spiraled member toward the other end
$l$ = axial length of air gap

The voltage per conductor generated in the unspiraled member is equal to the integral of the rate of change of the flux as $z$ varies from zero to $l$.

$$E_{c\alpha} = \int_0^l K_c MMF_{\max} \mathcal{P} \frac{d}{dt} \cos \left[ \frac{\pi}{\lambda} \left( x - \frac{\lambda_\alpha}{l} z \right) - \omega t \right] dz \quad (42)$$

$$E_{c\alpha} = K_e MMF_{max}\, \rho\, \omega\, \frac{\lambda}{\pi}\, \frac{l}{\lambda_\alpha} \left\{ \begin{matrix} \cos\left[\frac{\pi}{\lambda}(x - \lambda_\alpha) - \omega t\right] \\ - \cos\left[\frac{\pi}{\lambda} x - \omega t\right] \end{matrix} \right\} \quad (43)$$

$$E_{c\alpha} = 2K_e MMF_{max}\, \rho\, \omega\, \frac{\lambda}{\pi}\, \frac{l}{\lambda_\alpha} \times \sin\left[\frac{\pi}{\lambda}\left(x - \frac{\lambda_\alpha}{2}\right) - \omega t\right] \sin \frac{\lambda_\alpha}{\lambda}\, \frac{\pi}{2} \quad (44)$$

Equation (44) indicates the voltage per conductor generated in the unspiraled member by the spiraled flux. The voltage which would be generated in the same conductor by the same fundamental flux if there were no spiral can be obtained from (44) by allowing $\lambda_\alpha$ to approach zero as a limit. This voltage is given by equation (45).

$$E_c = K_e MMF_{max}\, \rho \omega l \sin\left(\frac{\pi}{\lambda} x - \omega t\right) \quad (45)$$

The ratio of the mutual fundamental flux to the self-inductive fundamental flux must be equal to (44) divided by (45)

$$\frac{\Phi_m}{\Phi_{m_1}} = \frac{2}{\pi}\, \frac{\lambda}{\lambda_\alpha} \sin \frac{\lambda_\alpha}{\lambda}\, \frac{\pi}{2} \quad (46)$$

The ratio of the leakage flux of fundamental distribution to the fundamental flux must, therefore, be:

$$\frac{\Phi_{m_1} - \Phi_m}{\Phi_{m_1}} = \left[1 - \frac{\Phi_m}{\Phi_{m_1}}\right] = 1 - \frac{2}{\pi}\, \frac{\lambda}{\lambda_\alpha} \sin \frac{\lambda_\alpha}{\lambda}\, \frac{\pi}{2} \quad (47)$$

The ratio expressed in (47) is also the ratio of the leakage reactance to the primary fundamental air-gap reactance.

$$\text{Per unit } X_\alpha = \left[1 - \frac{2}{\pi}\, \frac{\lambda}{\lambda_\alpha} \sin \frac{\pi}{2}\, \frac{\lambda_\alpha}{\lambda}\right] \quad (48)$$

In order to obtain either the primary or secondary forward or backward field leakage reactance due to spiral it is necessary to multiply (48) by $X_{m_1}$. Since each stator phase produces a forward field of flux just equal to its backward field the total primary reactance due to spiral is equal to twice the spiral reactance of either field:

$$X_{\alpha t} = 2X_\alpha = 2X_{m_1}\left[1 - \frac{2}{\pi}\, \frac{\lambda}{\lambda_\alpha} \sin \frac{\pi}{2}\, \frac{\lambda_\alpha}{\lambda}\right] \quad (49)^*$$

The rotor forward-field flux is not equal to its backward-field flux and the value $X_{\alpha_2}$ must be introduced separately into the equivalent circuit for each field.

It is obvious from the development that it makes no difference which member is spiraled in so far as the resultant effect upon the mutual flux and the leakage-reactance fluxes are concerned.

## Mutual Magnetizing Reactance Due to Fundamental Flux

In connection with the reactance due to spiral, it should be further noticed that the reduction in fundamental flux effectiveness mentioned at the start of the spiral reactance discussion amounts to a reduction in $X_m$, the mutual flux reactance. The reduction is precisely the same as the leakage reactance due to spiral for that is the way the spiral reactance was defined. If there is no spiral:

$$X_m = X_{m_1} \text{ when there is no spiral} \quad (50)$$

When relative spiral exists the mutual reactance, $X_m$ is reduced.

$$X_m = X_{m_1}[1 - \text{Per unit } X_\alpha] \quad (51)$$

$$X_m = X_{m_1}\, \frac{2}{\pi}\, \frac{\lambda}{\lambda_\alpha} \sin\left(\frac{\lambda_\alpha}{\lambda}\, \frac{\pi}{2}\right) \quad (52)$$

It will be noticed that when the spiral is equal to twice the pole pitch the fundamental mutual magnetizing reactance becomes zero and all the fundamental air gap flux produced by the primary winding acts as leakage flux.

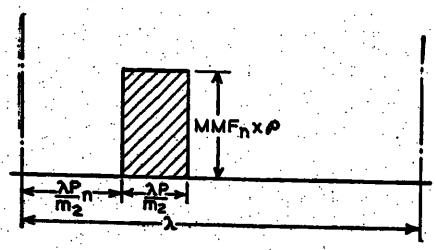



**Fig. 7. Flux distribution from rotor tooth**

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* It is important to notice that only when the primary phases are in quadrature, as is usual with capacitor motors and split-phase motors, can $X_{\alpha_1}$ be treated as a self-inductive reactance. Under other conditions $X_{\alpha_1}$ becomes mutual with other primary phases.

# Rectifier Circuit for Measurement of Small Power-Angle Oscillations

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KNOWLEDGE of transient oscillations of synchronous machines is of considerable importance because of the application of such information to studies on system load changes which may lead to loss of synchronism, to voltage fluctuations, or to hunting. Although in many instances very large angular swings must be taken into account, for many investigations only relatively small angular swings are considered. In this latter class are problems of determining the effects of saturation on load angle, angular variations with attendant current pulsations for variable torque loads, and the prediction of stability under large load changes as determined from studies of loads causing small displacements.

Rotor swinging has been observed under stroboscopic illumination, and displacement angles have been recorded by a motion picture camera taking 30 frames per second used in conjunction with the stroboscope.[1] A mark on a moving field pole may be followed exactly in its oscillations, a plot of displacements shown on the films yielding the time-angle relation of the rotor. Rotor oscillations also have been determined by means of a pilot alternator direct connected to the shaft of the main machine.[2] In this case, 2 phases (single-phase line-to-line voltages), one from each machine, are tied together at one end, and the rotor and voltage of the pilot alternator so adjusted that the voltage difference between the other 2 phase terminals is zero at the reference angle, which may be for zero or any specified load. The voltage difference appearing under load is a direct measure of the corresponding displacement angle, and the voltage carried to an oscillograph results in a wave of line frequency with a varying amplitude if the rotor is swinging.

The first method, although by far the best, because it gives the displacement angle directly under all conditions of operation, involves apparatus not generally available. The second method has the disadvantages of requiring an auxiliary alternator and a replot of the test data. Oscillations about a reference axis introduce a change of phase which may be difficult to determine under some conditions. In addition, the difference voltage is not proportional to angle outside a region of 60 electrical degrees. This last disadvantage, however, is eliminated when studies are confined to small angular displacements, as many investigations are.

## The Circuit

It is probable that the second method is more readily adaptable to studies undertaken in most laboratories because of availability of equipment, in which case it then is of convenience to have the oscillograph plot the actual displacement curve directly rather than the wave of system frequency with varying amplitude. The full wave rectifier tube is well suited to this problem because of the practically linear relationship between the plate current and the applied voltage. The addition of a filter circuit to reduce the unidirectional pulsations at line frequency to an average value greatly simplifies the resulting oscillogram.

With a single rectifier and filter circuit driven by the voltage difference between the pilot alternator and the machine under investigation, there results a single trace on the oscillogram the amplitude of which is directly proportional to the difference voltage. The magnitude of

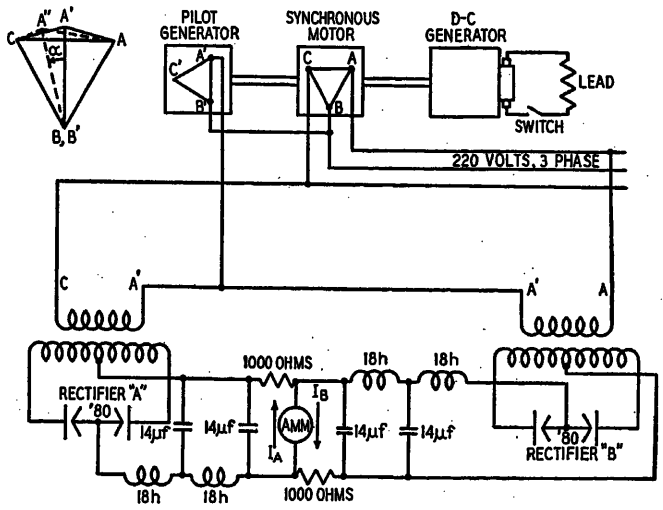



**Fig. 1. Rectifier circuit for determination of angular oscillations of a synchronous machine**

the difference voltage is proportional to sin $(\alpha/2)$ where $\alpha$ is the displacement angle between the machine terminal voltage and the pilot alternator voltage. As the sine of the angle is almost proportional to the angle itself for the range between 0 and 30 degrees, this circuit will give practically linear deflections up to torque-angles of 60 electrical degrees. All of the deflections, however, are above the zero axis, those for negative as well as for positive angles because of the characteristics of the rectifier. This difficulty may be overcome if 2 such circuits are used in opposition and are driven by 2 such difference voltages equal in magnitude at the reference angle. At the zero position the currents will balance out, the current through

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1. For all numbered references see list at end of paper.

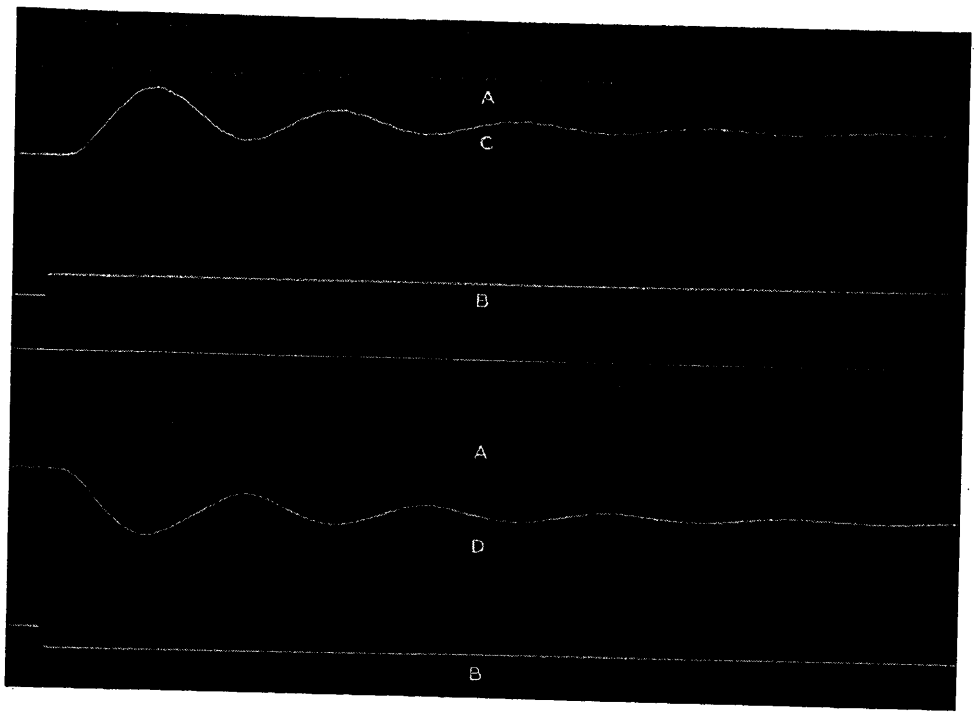



**Fig. 3. Oscillograms showing angular oscillations of a synchronous motor under sudden load changes**

*A*—60-cycle timing wave
*B*—Load current
*C*—Machine angle, load applied (20.5 electrical degrees maximum angle)
*D*—Machine angle, load dropped (8.5 electrical degrees initial angle)

the oscillograph element being zero for this rotor position. The circuit is shown in figure 1.

## Circuit Action

The line voltages of the motor under observation are represented by the sides of the triangle $ABC$. The single-phase voltage, $B'A'$, of the pilot alternator represents the rotor position of the motor. This voltage is made equal in magnitude to the line voltage of the motor, and is adjusted in phase so that it lies midway between the line voltages $BA$ and $BC$. The difference voltages, $CA'$ and $AA'$, are equal and produce equal rectifier currents, $I_A$ and $I_B$, which are in opposition, thus resulting in zero current through the instrument.

If a load is applied to the motor shaft there will be an angular displacement between the stator magnetomotive force and rotor poles which will be indicated by a shift in position of the pilot alternator voltage through the angle $\alpha$, i.e., from $B'A'$ to $B'A''$. The new rectifier voltages will be $CA''$ and $AA''$, resulting in an increased voltage on rectifier $B$ and a decreased voltage on rectifier $A$. $I_B$ will increase, $I_A$ will decrease, and the instrument or oscillograph will indicate a current equal to the new difference. In this discussion it is assumed that the machine under investigation is connected to an infinite bus. Practically, a drop of 5 per cent in line voltage will introduce about a 2 per cent error in the difference voltage.

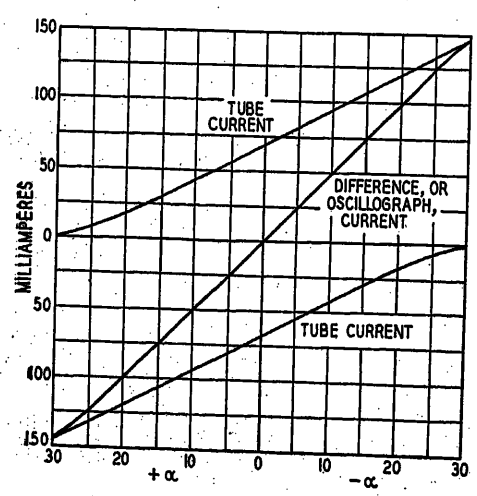



**Fig. 2. Characteristic curves for rectifier circuit showing tube currents and difference current as functions of angle $\alpha$**

The characteristic curves of each rectifier, and the resulting characteristic, are given in figure 2. It will be observed that if the displacement angle is greater than 30 electrical degrees both rectifier voltages will increase with angle, and the oscillograph current will remain constant, being the difference of 2 increasing currents. This circuit eliminates any question on change of phase. The filter circuit, with the constants as given in figure 1, may be relied upon with an error not over one per cent for oscillations of the rotor up to 4.5 cycles per second. This is a frequency of rotor swing much higher than normally would be found for either large or small machines.

The oscillograms of figure 3 illustrate the application of the device just described, and show the angular oscillations of a synchronous motor as load is thrown on and off. The pilot alternator had an adjustable stator, thus allowing ready phase adjustment between the 2 machines, although a phase shifting transformer or a wound rotor induction motor with rotor blocked may be employed. Angle calibration may be obtained with a stroboscope, from a vector diagram for the difference voltages, from a calibrated phase shifting device, or perhaps by calculation from the power-angle relation for the motor.

## References

1. A Stroboscopic Power Angle Recorder, H. E. Edgerton. Electrical Engineering (AIEE Transactions), volume 54, May 1935, pages 485–88.

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# Current and Voltage Loci in 3-Phase Circuits Part III: Δ-Y Connection

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## Introduction

IT HAS been shown that the method of circular loci may be conveniently applied to obtain the variation of currents and voltages when self-impedances are changed in various types of circuits operated at constant frequency. Part I[1] dealt with this problem in a Y-Y connection and part II[2] in a Δ-Δ connection. In both of these papers current equations were given involving all the impedances and voltages of the most general types of Y-Y and Δ-Δ circuits and required only the substitution of numerical values to obtain the locus of any current or voltage existing in the system. The same treatment will now be applied to the Δ-Y connection.

## The Δ-Y Circuit

In figure 1 is shown the general Δ-Y circuit. Internal voltages of like frequency are assumed to exist in both source and load phases and to have any magnitude and phase angle. Self impedances are considered in the interconnecting lines as well as in the source and in the load. For the sake of generality mutual impedances are assumed in the source and load and also between the lines. There are no restrictions on the values of any of the self- and mutual-impedance elements other than they be linear and bilateral.

Equations will be set up for the 6 phase currents which in this case also include the 3 line currents. The voltages in the system will be obtained by adding internal voltages to appropriate impedance drops.

Adding the potential differences about meshes $a102ba$, $b203cb$, and $c301ac$, and summing up the currents about junctions, $o$, $a$, and $b$, the requisite equations are:

$$I_1A_1 + I_2A_2 + I_3A_3 + I_aZ_{aa} + I_bZ_{ab} + I_cZ_{ac} = K_1 \quad (1)$$
$$I_1B_1 + I_2B_2 + I_3B_3 + I_aZ_{ba} + I_bZ_{bb} + I_cZ_{bc} = K_2 \quad (2)$$
$$I_1C_1 + I_2C_2 + I_3C_3 + I_aZ_{ca} + I_bZ_{cb} + I_cZ_{cc} = K_3 \quad (3)$$
$$I_1 + I_2 + I_3 = 0 \quad (4)$$
$$I_1 + I_a - I_c = 0 \quad (5)$$
$$I_2 - I_a + I_b = 0 \quad (6)$$

in which

$$\left.\begin{aligned} A_1 &= Z_{r3} - Z_{rr} + Z_{12} - Z_{11} \\ B_2 &= Z_{s1} - Z_{ss} + Z_{23} - Z_{22} \\ C_3 &= Z_{tr} - Z_{tt} + Z_{31} - Z_{33} \\ A_2 &= Z_{s3} - Z_{sr} + Z_{22} - Z_{21} \\ B_3 &= Z_{t1} - Z_{ts} + Z_{33} - Z_{32} \\ C_1 &= Z_{rr} - Z_{rt} + Z_{11} - Z_{13} \\ A_3 &= Z_{t3} - Z_{tr} + Z_{32} - Z_{31} \\ B_1 &= Z_{r1} - Z_{rs} + Z_{13} - Z_{12} \\ C_2 &= Z_{sr} - Z_{st} + Z_{21} - Z_{23} \\ K_1 &= E_{01} - E_{02} + E_{ab} \\ K_2 &= E_{02} - E_{03} + E_{bc} \\ K_3 &= E_{03} - E_{01} + E_{ac} \end{aligned}\right\} \quad (7)$$

By Cramers' rule the currents may be expressed as

$$\left.\begin{aligned} I_a &= \frac{\Delta I_a}{\Delta} & I_1 &= \frac{\Delta I_1}{\Delta} \\ I_b &= \frac{\Delta I_b}{\Delta} & I_2 &= \frac{\Delta I_2}{\Delta} \\ I_c &= \frac{\Delta I_c}{\Delta} & I_3 &= \frac{\Delta I_3}{\Delta} \end{aligned}\right\} \quad (8)$$

Here Δ is the general determinant or the common denominator and $\Delta I_a$, $\Delta I_b$, etc., are the specific determinants obtained from the general determinant by replacing the coefficients of the current desired by the column of $K$'s.

The expansions of the common denominator and the numerators follow below. It should be noted that although the mutual elements are bilateral, i.e., $Z_{23} = Z_{32}$, both sequences of subscripts are used in order to display the cyclicity of terms.

$$\begin{aligned} \Delta = {} & (Z_{aa} + Z_{ab} + Z_{ac})\{-(B_3C_3 - B_3C_2) + (B_1C_3 - B_3C_1) - (B_1C_2 - B_2C_1)\} + \\ & (Z_{bb} + Z_{bc} + Z_{ba})\{(A_2C_3 - A_3C_2) - (A_1C_3 - A_3C_1) + (A_1C_2 - A_2C_1)\} + \\ & (Z_{cc} + Z_{ca} + Z_{cb})\{-(A_2B_3 - A_3B_2) + (A_1B_3 - A_3B_1) - (A_1B_2 - A_2B_1)\} + \\ & (Z_{aa}Z_{bb} - Z_{ab}^2)(C_3 - C_1) + \\ & (Z_{bb}Z_{cc} - Z_{bc}^2)(A_1 - A_2 - Z_{aa}) + \\ & (Z_{cc}Z_{aa} - Z_{ca}^2)(B_2 - B_3) + \\ & (Z_{ab}Z_{bc} - Z_{bb}Z_{ca})(A_3 - A_1 + C_1 - C_2 - Z_{ac}) + \\ & (Z_{bc}Z_{ca} - Z_{cc}Z_{ab})(A_2 - A_3 + B_1 - B_2 - Z_{ab}) + \\ & (Z_{ca}Z_{ab} - Z_{aa}Z_{bc})(B_3 - B_1 + C_2 - C_3) \end{aligned} \quad (9)$$

$$\begin{aligned} \Delta I_1 = {} & (Z_{aa} + Z_{ab} + Z_{ac})\{K_3(C_3 - C_2) - K_3(B_3 - B_2)\} + \\ & (Z_{bb} + Z_{bc} + Z_{ba})\{K_3(A_3 - A_2) - K_1(C_3 - C_2)\} + \\ & (Z_{cc} + Z_{ca} + Z_{cb})\{K_1(B_3 - B_2) - K_2(A_3 - A_2)\} + \\ & K_1(Z_{bb}Z_{cc} - Z_{bc}^2) - K_3(Z_{aa}Z_{bb} - Z_{ab}^2) + (K_3 - K_1)(Z_{ab}Z_{bc} - Z_{bb}Z_{ca}) + \\ & K_2\{(Z_{ac}Z_{cb} - Z_{cc}Z_{ab}) - (Z_{ac}Z_{ab} - Z_{aa}Z_{cb})\} \end{aligned} \quad (10)$$

$$\begin{aligned} \Delta I_2 = {} & (Z_{aa} + Z_{ab} + Z_{ac})\{K_3(B_3 - B_1) - K_2(C_3 - C_1)\} + \\ & (Z_{bb} + Z_{bc} + Z_{ba})\{K_1(C_3 - C_1) - K_3(A_3 - A_1)\} + \\ & (Z_{cc} + Z_{ca} + Z_{cb})\{K_2(A_3 - A_1) - K_1(B_3 - B_1)\} + \\ & K_2(Z_{aa}Z_{cc} - Z_{ca}^2) - K_1(Z_{bb}Z_{cc} - Z_{bc}^2) + \\ & (K_1 - K_2)(Z_{ac}Z_{cb} - Z_{cc}Z_{ab}) + \\ & K_3\{(Z_{ab}Z_{ac} - Z_{aa}Z_{bc}) - (Z_{ab}Z_{bc} - Z_{bb}Z_{ac})\} \end{aligned} \quad (11)$$

$$\begin{aligned} \Delta I_3 = {} & (Z_{aa} + Z_{ab} + Z_{ac})\{K_2(C_2 - C_1) - K_3(B_2 - B_1)\} + \\ & (Z_{bb} + Z_{bc} + Z_{ba})\{K_3(A_2 - A_1) - K_1(C_2 - C_1)\} + \\ & (Z_{cc} + Z_{ca} + Z_{cb})\{K_1(B_2 - B_1) - K_2(A_2 - A_1)\} + \\ & K_3(Z_{aa}Z_{bb} - Z_{ab}^2) - K_2(Z_{aa}Z_{cc} - Z_{ac}^2) + (K_2 - K_3) \times \\ & (Z_{ba}Z_{ac} - Z_{aa}Z_{bc}) + \\ & K_1\{(Z_{ba}Z_{cb} - Z_{bb}Z_{ca}) - (Z_{ca}Z_{bc} - Z_{cc}Z_{ba})\} \end{aligned} \quad (12)$$

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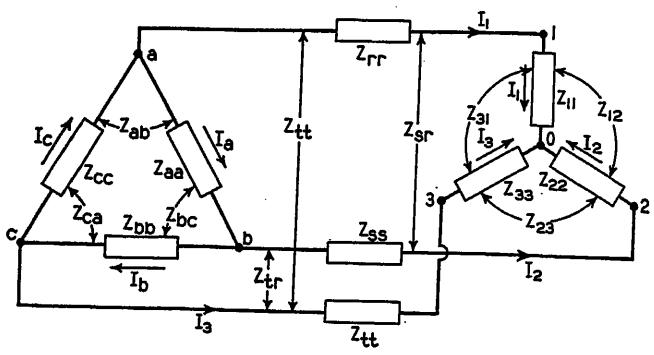



**Fig. 1. General circuit Y-Δ connection**

$$\Delta I_a = K_1\{-(Z_{bb}Z_{cc} - Z_{cb}^2) + Z_{cc}(B_2 - B_3) + Z_{bc}(C_3 - C_2 + B_1 - B_3) + Z_{bb}(C_3 - C_1) - (B_2C_3 - B_3C_2) + (B_1C_3 - B_3C_1) - (B_1C_2 - B_2C_1)\} + K_2\{-(Z_{cb}Z_{ac} - Z_{cc}Z_{ba}) + Z_{cc}(A_3 - A_2) + Z_{cb}(A_3 - A_1) + Z_{ab}(C_1 - C_3) + Z_{ac}(C_2 - C_3) + (A_2C_3 - A_3C_2) - (A_1C_3 - A_3C_1) + (A_1C_2 - A_2C_1)\} + K_3\{-(Z_{ba}Z_{cb} - Z_{bb}Z_{ac}) + Z_{bb}(A_1 - A_3) + Z_{ab}(B_3 - B_1) + Z_{ac}(B_3 - B_2) + Z_{bc}(A_2 - A_3) - (A_2B_3 - A_3B_2) + (A_1B_3 - A_3B_1) - (A_1B_2 - A_2B_1)\} \quad (13)$$

$$\Delta I_b = K_1\{-(Z_{ca}Z_{bc} - Z_{cc}Z_{ab}) + Z_{cc}(B_2 - B_1) + Z_{ba}(C_1 - C_3) + Z_{ca}(B_3 - B_1) + Z_{bc}(C_1 - C_2) - (B_2C_3 - B_3C_2) + (B_1C_3 - B_3C_1) - (B_1C_2 - B_2C_1)\} + K_2\{-(Z_{aa}Z_{cc} - Z_{ac}^2) + Z_{aa}(C_3 - C_1) + Z_{ca}(A_1 - A_3 + C_2 - C_1) + Z_{cc}(A_1 - A_2) + (A_2C_3 - A_3C_2) - (A_1C_3 - A_3C_1) + (A_1C_2 - A_2C_1)\} + K_3\{-(Z_{ba}Z_{ac} - Z_{aa}Z_{bc}) + Z_{aa}(B_1 - B_3) + Z_{ba}(A_3 - A_1) + Z_{ac}(B_1 - B_2) + Z_{bc}(A_2 - A_1) - (A_2B_3 - A_3B_2) + (A_1B_3 - A_3B_1) - (A_1B_2 - A_2B_1)\} \quad (14)$$

$$\Delta I_c = K_1\{-(Z_{ba}Z_{cb} - Z_{bb}Z_{ca}) + Z(_{bb}C_2 - C_1) + Z_{ba}(C_2 - C_3) + Z_{ca}(B_3 - B_2) + Z_{cb}(B_1 - B_2) - (B_2C_3 - B_3C_2) + (B_1C_3 - B_3C_1) - (B_1C_2 - B_2C_1)\} + K_2\{-(Z_{ca}Z_{ab} - Z_{aa}Z_{cb}) + Z_{aa}(C_3 - C_2) + Z_{ca}(A_2 - A_3) + Z_{ab}(C_1 - C_2) + Z_{cb}(A_2 - A_1) + (A_2C_3 - A_3C_2) - (A_1C_3 - A_3C_1) + (A_1C_2 - A_2C_1)\} + K_3\{-(Z_{aa}Z_{bb} - Z_{ab}^2) + Z_{aa}(B_2 - B_3) + Z_{ba}(A_3 - A_2 + B_2 - B_1) + Z_{bb}(A_1 - A_2) - (A_2B_3 - A_3B_2) + (A_1B_3 - A_3B_1) - (A_1B_2 - A_2B_1)\} \quad (15)$$

The Δ-Y connection contains passive impedance elements and sinusoidal electromotive forces of the same frequency only. This means that if any one self-impedance be varied all voltages and currents will follow circular loci according to the following theorem:[3]

In a network consisting of any number of linear and bilateral self- and mutual-impedance elements connected in any manner with constant sinusoidal electromotive forces of like frequency connected in any arms, all currents and voltages existing in the system follow circular loci when any one self-impedance is varied along a straight line in the complex plane.

If any numerator and the denominator of the phase currents be expanded term by term it will be seen that self-impedances occur only to the first power. Then if any self-impedance be chosen as the variable, the terms of the denominator Δ, may be collected into 2 parts $\gamma$ the summation of the terms free of the variable, and $\delta$, the summation of the terms containing the variable as a factor. The denominator may then be written as

$$\Delta = \gamma + \delta\rho$$

in which $\rho$ is the scalar variable ranging from zero to infinity as the variable self-impedance varies from short circuit to open circuit.

In the same way, the numerator of any current, such as $\Delta I_a$ may be divided into 2 sets of terms, the first $\alpha$ being the summation of terms free of the variable and the second, $\beta$, being the summation of terms multiplied by the variable. The numerator may then be expressed as

$$\Delta I_a = \alpha + \beta\rho$$

The current $I_a$ then becomes

$$I_a = \frac{\alpha + \beta\rho}{\gamma + \delta\rho}$$

which is the canonical form of a circular locus expressed as a linear fractional transformation. That is, the vector $I_a$ describes a circle as $\rho$ varies from minus to plus infinity.

The theorem also states that all voltages follow circular loci when any one self-impedance is varied. That this is true may be readily shown by mere inspection of any current equation. The numerator of any current equation is free of all impedance elements through which the current flows. Therefore the product of any current and impedance to obtain a potential difference between 2 points will remain linear with respect to all self-impedances.

To illustrate this condition, the voltage $V_{01}$ across phase 1 of the load will be considered. This voltage is

$$V_{01} = E_{01} + I_1Z_{11} + I_2Z_{12} + I_3Z_{13}$$

$$= \frac{\Delta \times E_{01} + \Delta I_1Z_{11} + \Delta I_2Z_{12} + \Delta I_3Z_{13}}{\Delta}$$

The numerator may be separated into a constant portion $\alpha'$, which is free of the variable and a group of remaining terms $\beta'$, having $\rho$ as a factor.
Then

$$V_{01} = \frac{\alpha' + \beta'\rho}{\gamma + \delta\rho}$$

Thus the voltage $V_{01}$ follows a circular locus.

The equations are not linear with respect to mutual impedances and on this account the variation of self-impedances must not change any of the mutual elements in the circuit. The 3-point method is used to determine the loci, that is, evaluation of the desired quantity at the 2 invariant points, $\rho = 0$ and $\rho = \infty$, and some third convenient value of $\rho$. Only the current equations are used in analyti-

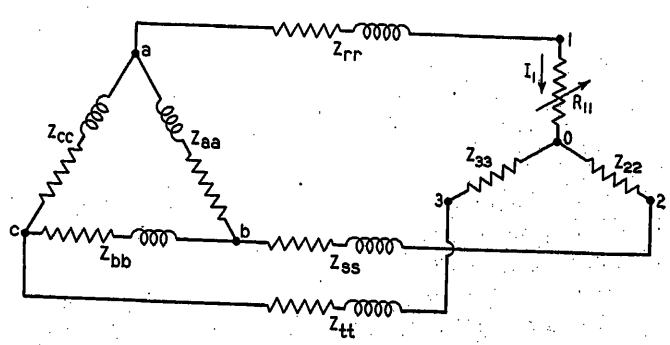



**Fig. 2. Circuit for example**

cal form and once these are reduced to numerical form as linear fractional transformations, all voltage loci may be computed directly therefrom by operating on the currents with impedances. Inasmuch as the denominator of all current and voltage expressions is common, it follows that all summations of currents and voltages remain in the form of linear fractional transformations. Hence the loci of all symmetrical components are also circular.

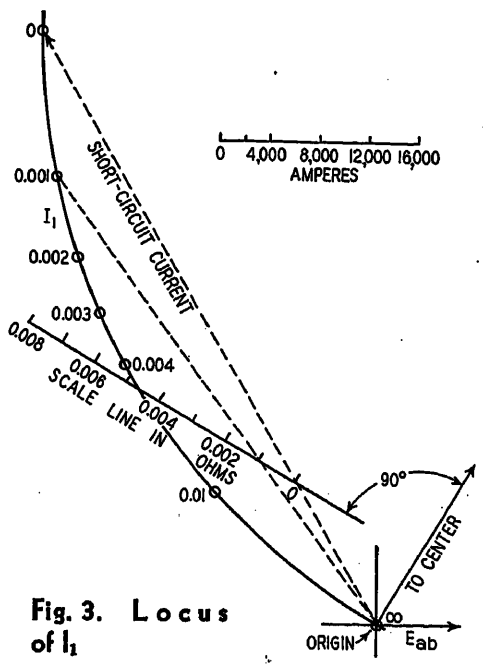



**Fig. 3. Locus of $I_1$**

It is not anticipated that a practical problem will involve as many unbalanced elements as have been treated in this circuit. However problems arise in which any one section of the circuit may be heavily unbalanced, as for example, single-phase loads. Substitution of such conditions into the equations simplifies them considerably, especially when mutual elements are absent.

## Numerical Example

The circuit drawn in figure 2 will show the application of this method to an actual problem. The source phases are assumed to be balanced with respect to both internal voltages and impedances. No mutual impedances are present in the source phases. The connecting lines have equal resistances but unequal reactances. The load is entirely resistive, 2 arms being equal and the third will be considered as the variable self-impedance. The loci of the current in the variable load phase $Z_{11}$ and the voltage across it will be determined as the variable $R_{11}$ varies from short circuit to open circuit. The constants of the circuit are as follows:

$Z_{aa} = Z_{bb} = Z_{cc} = (0.404 + j2.02)10^{-3}$ ohms
$Z_{rr} = (0.08 + j1.131)10^{-3}$ ohms
$Z_{ss} = (0.08 + j0.98)10^{-3}$ ohms $\quad Z_{ss} = (5.88)10^{-3}$ ohms
$Z_{tt} = (0.08 + j0.754)10^{-3}$ ohms $\quad Z_{ab} = Z_{bc} = Z_{ca} = 0$
$Z_{rs} = (j0.452)10^{-3}$ ohms $\quad Z_{12} = Z_{22} = Z_{21} = 0$ ohms
$Z_{st} = (j0.415)10^{-3}$ ohms $\quad E_{21} = E_{32} = E_{13} = 0$ volts
$Z_{tr} = (j0.528)10^{-3}$ ohms $\quad E_{ab} = 230\angle 0°$ volts
$Z_{11} = R_{11} + j0$ ohms $\quad E_{bc} = 230\angle -120°$ volts
$Z_{22} = (5.88)10^{-3}$ ohms $\quad E_{ca} = 230\angle 120°$ volts

Substituting in equations (7) the group constants are:

$A_1 = (-0.08 - j0.679)10^{-3} - R_{11} \quad A_2 = (0 - j0.113)10^{-3}$

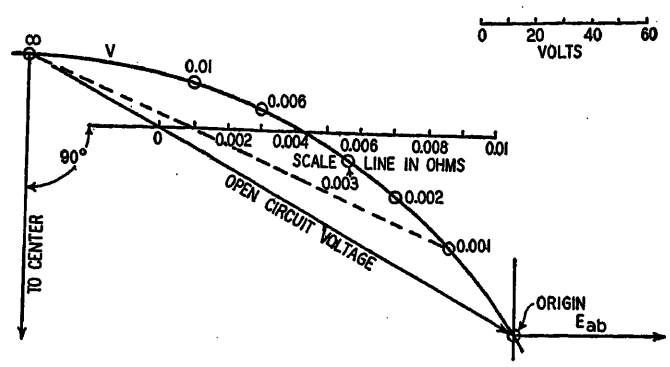



**Fig. 4. Locus of $V_{01}$**

$B_2 = (-5.96 - j0.565)10^{-3} \quad B_1 = (0 + j0.076)10^{-3}$
$C_2 = (-5.96 - j0.226)10^{-3} \quad C_2 = (0 + j0.037)10^{-3}$
$A_2 = (5.96 + j0.528)10^{-3} \quad K_1 = 230 + j0$
$B_2 = (5.96 + j0.339)10^{-3} \quad K_2 = -115 - j199.2$
$C_1 = (0.08 + j0.603)10^{-3} \quad K_3 = -115 + j199.2$

From equation (9) the denominator becomes

$$\Delta = (0.134 - j0.252)10^{-6} + R_{11}(-1.14 - j76.6)10^{-6}$$

From equation (10) the numerator of $I_1$ is

$$\Delta I_1 = (8000 + j13300)10^{-6}$$

The current $I_1$ written as a linear fractional transformation is then

$$I_1 = \frac{8000 + j13300}{(0.134 - j0.252) + R_{11}(-1.14 - j76.6)}$$

Determining the invariant points and using $R_{11} = 0.001$ ohm for the third point the corresponding currents are:

| $R_{11}$ ohms | $I_1$ amperes |
|---|---|
| 0 | 54400 ∠121.0° |
| 0.001 | 44800 ∠126.9° |
| ∞ | 0 |

These 3 points determine the locus of $I_1$ which is drawn in figure 3.

The voltage $V_{01}$ across phase 1 of the load is

$$V_{01} = I_1 Z_{11} = \frac{R_{11}(8000 + j13300)}{(0.134 - j0.252) + R_{11}(-1.14 - j76.6)}$$

Evaluating $V_{01}$ at the same 3 points gives:

| $R_{11}$ ohms | $V_{01}$ volts |
|---|---|
| 0 | 0 |
| 0.001 | 44.8 ∠126.9° |
| ∞ | 205 ∠149.8° |

These points determine the locus of $V_{01}$ which is plotted in figure 4.

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# Intersheet Eddy-Current Loss in Laminated Cores

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CORE LOSS in laminated structures subjected to an alternating magnetomotive force is made up of a hysteresis loss and an eddy-current loss. In modern power transformers the eddy-current loss is approximately $^1/_4$ to $^1/_3$ of the total loss.

In the calculation of the eddy-current loss it is usually tacitly assumed that the parasitic currents are confined to the individual laminations, and that there is no appreciable cross flow from sheet to sheet. Further, it is assumed for the purposes of calculation that the current flow in the individual laminations is everywhere parallel to the width of the laminations, and the end effects are ignored; and usually, also, the demagnetizing effect is not taken into account.

While those assumptions have always appeared to be fully justified for engineering purposes; nevertheless, the validity of the assumption that the intersheet eddy-current losses are negligible is often questioned. For it is evident that as the width of the laminations is increased, the resistance across the packet decreases, whereas the flux increases; and it may very well be, therefore, that the intersheet loss is appreciable for large cores; particularly in those cases where the clamping pressure is very high, because the resistance rapidly decreases with the pressure.

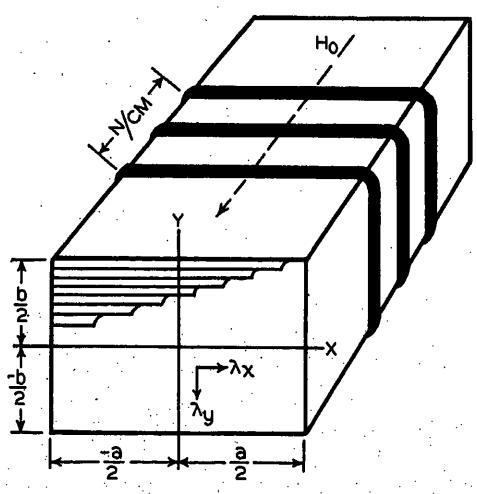



Fig. 1. Cross section of rectangular core

The investigation described herein was undertaken to determine the magnitude of the intersheet eddy-current loss, and incidentally to obtain a more rigorous formula for the eddy currents in rectangular sections that gives the actual distribution. While such refinements are found to be quite unnecessary as far as transformers are concerned, yet they may prove useful in other applications, particularly in cases where the punchings are not enamel insulated and immersed in insulating oil. Moreover, the results for the case where the ratio of conductivities is equal to unity apply exactly to a solid rectangular block, and also indicate the true end-effect correction in laminations even in the case of perfectly insulated punchings of finite thickness.

The cross section of a rectangular core is shown in figure 1. Uniform conductivities $\lambda_x$ and $\lambda_y$ along and across the sheets are assumed. For definiteness, the core is considered as placed inside a long solenoid with $N\,I$ ampere-turns per centimeter length, so that the field perpendicular to the core section is given by

$$H_0 = 0.4\pi\, N\, I \tag{1}$$

For the purposes of analysis, co-ordinates $(x, y)$ are chosen with origin at the center of the core. The mathematical derivations are given in the appendix, and are briefly as follows:

*a.* From Maxwell's equations there are obtained the differential equations for the field intensity $H$, and the relationship between $H$ and the electric intensity $E$.

*b.* The solution of the differential equation, subject to the boundary condition $H = H_0$ around the periphery of the core is obtained. The process of solution is the conventional method of product solutions and sums of these that satisfy the boundary conditions (see, for example, chapter IV of Byerly's "Fourier Series and Spherical Harmonics").

*c.* The flux $\phi$ is readily found by integrating $H$. Using the usual representation of sinusoidal quantities by complex numbers, the flux $\phi$ is given by either of the formulas:

$$\frac{\phi}{\phi_0} = \frac{\tanh\left[(\alpha a)/(2\sqrt{r})\right]}{(\alpha a)/(2\sqrt{r})} + \frac{8}{\pi^2}\sum_{1,3,\ldots}^{\infty} \frac{1}{n^2}\left(\frac{\alpha}{\beta_n}\right)^2 \frac{\tanh(\beta_n b/2)}{(\beta_n b/2)} \tag{2}$$

$$\frac{\phi}{\phi_0} = \frac{8}{\pi^2}\sum_{1,3,\ldots}^{\infty} \frac{1}{n^2}\left\{\frac{\tanh(\alpha_n a/2)}{(\alpha_n a/2)} + \frac{\tanh(\beta_n b/2)}{(\beta_n b/2)}\right\} \tag{3}$$

where

$\phi_0$ = flux corresponding to the maximum (crest value) of $H_0$ or the applied current $I$

$$\alpha_n^2 = \left(\alpha^2 + \frac{n^2\pi^2}{b^2}\right)\frac{1}{r} \qquad \beta_n^2 = \left(\alpha^2 + r\,\frac{n^2\pi^2}{a^2}\right)$$

$\alpha^2 = j\omega 4\pi\lambda_x\mu 10^{-9}$
$\omega = 2\pi f$
$\lambda_x$ = conductivity along laminations
$\lambda_y$ = conductivity across laminations
$r = \lambda_x/\lambda_y$ = ratio of conductivities
$\mu$ = permeability of the iron (assumed constant)
$a, b$ = core dimensions

*d.* The induced electromotive force in the winding is given by

$$E = -j\omega N\phi 10^{-8} \tag{4}$$

where $N$ is the number of terms.

The loss $W$ may be found from the real part of $E$, which

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is in phase with the exciting current, and turns out to be given by

$$W = \frac{\omega \phi_0 H_0}{8 \times 10^7} [- \mathfrak{I} (\phi/\phi_0)] \text{ watts per centimeter} \tag{5}$$

in which

$I$ = the maximum (crest value) of the current and $\mathfrak{I}(x + jy) = y$ = imaginary part of the complex number $(x + jy)$

For large values of $r$ ($> 1{,}000$) the formula (2) may be replaced by its first term:

$$\frac{\phi}{\phi_0} \cong \frac{\tanh [(\alpha a)/(2\sqrt{r})]}{(\alpha a)/(2\sqrt{r})} \tag{6}$$

This identical result is obtained if the currents are assumed to flow straight across the laminations and the end effects are neglected.

For small values of $[(\alpha a)/(2\sqrt{r})]$, (5) may be replaced by

$$W = \frac{\lambda y}{24} \left(\frac{\omega \phi_0}{10^8}\right)^2 \frac{a}{b} \text{ watts per centimeter} \tag{7}$$

This latter expression is also obtained if the currents are assumed to flow across the laminations and their demagnetizing effect be neglected.

The calculation of the losses by (5) or (6) is seen to hinge on the evaluation of complex functions of the form

$$\frac{\tanh (p + jq)}{(p + jq)} = U + jV$$

On account of the great differences between the conductivities $\lambda_x$ and $\lambda_y$ (their ratio may be as great as $10^7$:1), great care must be taken in evaluating these functions in order to secure sufficient accuracy. Methods are given in the appendix.

Direct calculations of the losses by integration throughout the core section is possible, but proves to be quite involved. The application of Poynting's vector, however, leads to the same result for the losses with only slightly more labor than the total flux method.

## Appendix

Maxwell's equations in centimeter-gram-second practical units are

$$\nabla \times H = 0.4\pi i \tag{8}$$

$$\nabla \times E = -10^{-8} \frac{\partial B}{\partial t} \tag{9}$$

where $H$ is the magnetic field, $E$ the dielectric field (volts per centimeter), $i$ the current density vector, and $B$ the flux density. Replace $B$ by $\mu H$, and assume the time $t$ to enter as a factor $e^{j\omega t}$ (but omit this factor in subsequent equations). Then supposing the only nonvanishing component of the magnetic field to be $H_z$ the component along the solenoid axis, while the induced field and current components are perpendicular to the $z$ axis; and finally that the field aspect is independent of $z$, there follows from (8) and (9)

$$\frac{\partial H}{\partial y} = 0.4\pi i_x, \quad \frac{\partial H}{\partial x} = -0.4\pi i_y \tag{10}$$

$$\frac{\partial E_y}{\partial x} - \frac{\partial E_x}{\partial y} = -j\omega\mu 10^{-8} H \tag{11}$$

the subscript in $H_z$ having been omitted since this is the only component present and there can be no confusion. Since the conductivities $\lambda_x$ and $\lambda_y$ are different in the 2 orthogonal directions, there is (neglecting the displacement currents)

$$i_x = \lambda_x E_x, \qquad i_y = \lambda_y E_y \tag{12}$$

Eliminating $i_x$, $i_y$, $E_x$, $E_y$ there is by (10), (11), and (12)

$$\frac{\lambda_x}{\lambda_y} \frac{\partial^2 H}{\partial x^2} + \frac{\partial^2 H}{\partial y^2} = j\omega 4\pi \lambda_x \mu 10^{-9} H \tag{13}$$

or putting $r = \lambda_x/\lambda_y$ and $\alpha^2 = j\omega 4\pi\lambda_x\mu 10^{-9}$

$$r \frac{\partial^2 H}{\partial x^2} + \frac{\partial^2 H}{\partial y^2} = \alpha^2 H \tag{13a}$$

It is of interest to point out that the relations of the form (12) exist in crystalline media which are homogeneous but not isotropic, though in the general case the 3 current components are expressible linearly in each of the field components by means of 9 conductivity constants, and similarly for the relation between the magnetic field and flux components.

Returning to the differential equation 13$a$, which is the differential equation of the problem, a solution $H$ is sought which takes on the boundary conditions

$$H = H_0 \text{ along } x = \pm a/2 \text{ and } y = \pm b/2 \tag{14}$$

where $H_0$ is given by (1).

To satisfy the boundary conditions (14) we may try to satisfy them first along 2 opposite sides of the rectangular boundary. A solution of (13$a$) independent of $y$ and which satisfies the boundary condition (14) along $x = \pm a/2$ is

$$H_1 = H_0 \frac{\cosh \alpha' x}{\cosh \alpha' a/2}, \quad \alpha' = \frac{\alpha}{\sqrt{r}} \tag{15}$$

Writing the complete solution

$$H = H_1 + H_2 \tag{16}$$

it remains to find $H_2$ such that

$$H_2 = 0 \text{ along } x = \pm a/2 \tag{17}$$

$$H_2 + H_1 = H_0 \text{ along } y = \pm b/2 \tag{18}$$

Product solutions of (13$a$) of the form

$$\cos \frac{n\pi x}{a} \cosh \beta_n y, \qquad \beta_n^2 = \alpha^2 + \frac{rn^2\pi^2}{a^2}$$

for $n = 1, 3, \ldots$ satisfy (17). To satisfy (18), or more explicitly

$$H_2 = H_0 \left(1 - \frac{\cosh \alpha' x}{\cosh \alpha' a/2}\right) \text{ along } y = \pm \frac{b}{2} \tag{18a}$$

an infinite series of the product solutions will be used:

$$H_2 = H_0 \sum_{1,3,\ldots}^{n} C_n \cos \frac{n\pi x}{a} \cosh \beta_n y \tag{19}$$

To satisfy (18$a$) the constants $C_n$ must be chosen so that

$$\sum C_n \cosh \frac{\beta_n b}{2} \cos \frac{n\pi x}{a} = 1 - \frac{\cosh \alpha' x}{\cosh \alpha' a/2} = f(x) \tag{20}$$

By Fourier's theorem, an arbitrary even function $f(x)$ in the interval $(-a/2, a/2)$ can be expanded in a series

$$\sum_{1,3,\ldots}^{n} A_n \cos \frac{n\pi x}{a}$$

and the series converges to $f(x)$ at $x = \pm a/2$ only if $f(x)$ vanishes there—this is the case at present. Applying the familiar rule for the Fourier coefficients to (20), there follows:

$$C_n \cosh \frac{\beta_n b}{2} = \frac{2}{a} \int_{-a/2}^{a/2} \left(1 - \frac{\cosh \alpha' x}{\cosh \alpha' a/2}\right) \cos \frac{n\pi x}{a} dx \tag{21}$$

To evaluate this integral, write it in the from

$$\int fg''dx$$

where primes denote differentiations, and integrate by parts twice, obtaining

$$\int fg''dx = \int f''gdx + [fg' - f'g] = \int f''gdx$$

since at the end points both

$$f = \left(1 - \frac{\cosh \alpha' x}{\cosh \alpha' a/2}\right) \text{ and } g = \frac{-a^2}{n^2\pi^2} \cos \frac{n\pi x}{a}$$

vanish in the present case. Also $f'' = (\alpha')^2(f - 1)$ while $g = -(a^2/n^2\pi^2)\, g''$, hence

$$\int fg''dx = -\frac{\alpha'^2 a^2}{n^2\pi^2} \int fg''dx - \alpha'^2 \int gdx$$

or

$$\int fg''dx = \frac{-\alpha'^2}{1 + \alpha'^2 a^2/n^2\pi^2} \int gdx$$

Carrying out the latter integration, solving for $C_n$ and substituting in (19), (16) there follows:

$$\frac{H}{H_0} = \frac{\cosh \alpha' x}{\cosh \alpha' a/2} + \frac{4}{\pi} \sum_{1,3,\ldots}^{n} \frac{\sin n\pi/2}{n} \left(\frac{\alpha}{\beta_n}\right)^2 \frac{\cosh \beta_n y}{\cosh \beta_n b/2} \cos \frac{n\pi x}{a} \quad (22)$$

From this, (2) is derived by integration.

Another form for $H$ is offered by

$$\frac{H}{H_0} \frac{4}{\pi} \sum_{1,3,\ldots}^{n} \frac{\sin n\pi/2}{n} \left\{ \frac{\cosh \alpha_n x}{\cosh \alpha_n a/2} \cos \frac{n\pi y}{b} + \frac{\cosh \beta_n y}{\cosh \beta_n b/2} \cos \frac{n\pi x}{a} \right\} \quad (23)$$

where

$$\alpha_n^2 = \left(\alpha^2 + \frac{n^2\pi^2}{b^2}\right) \frac{1}{r}$$

This is obtained by breaking up $H$ into 2 parts, of which one satisfies the boundary conditions (14) along $x = \pm a/2$ and vanishes along $y = \pm b/2$, while the other one satisfies (14) along $y = \pm b/2$ and vanishes along $x = \pm a/2$, and then solving for each one by means of an infinite series of product solutions and Fourier's theorem. From (23) the flux (3) follows by integration.

As compared with (22), the form (23), while more symmetric, involves 2 infinite series and has poorer convergence. This is due to the fact that the former Fourier expansion was for a function that vanished at the end points, while such is not the case for the expansions in (23).

From (2), (3), (5) it is seen that the calculation of the losses hinges on the functions of the form

$$U + jV = \frac{\tanh (p + jq)}{(p + jq)} \quad (24)$$

But it is only the imaginary component, $V$, of this function which contributes to the loss. In the laminated core problem, it so happens, on account of the great differences in conductivity along and perpendicular to the laminations, that either $p$ is very large, or else $p$ and $q$ are small and very nearly alike. For these 2 cases we have:

CASE I

Suppose $p$ is very large (say of the order of 100). Then

$$U + jV = \frac{\tanh (p + jq)}{(p + jq)} = \frac{\tanh p + j \tan q}{1 + j \tanh p \tan q} \frac{1}{p + jq}$$

$$\cong \frac{1}{p + jq} = \frac{p}{p^2 + q^2} - j \frac{q}{p^2 + q^2} \cong \frac{1}{p} - j \frac{q}{p^2} \quad (25)$$

CASE II

Suppose both $p$ and $q$ small compared to unity. Then

$$U + jV = \frac{\tanh (p + jq)}{p + jq} = 1 - \frac{1}{3}(p + jq)^2 + \frac{2}{15}(p + jq)^4 + \ldots \cong \left(1 - \frac{p^2 - q^2}{3}\right) - j\frac{2}{3} pq \quad (26)$$

APPROXIMATIONS

In the differential equation (13$a$) the ratio $\lambda_x/\lambda_y$ may be of the order of $10^7$ and the term $\partial^2 H/\partial y^2$ may then be dropped, so that (13$a$) becomes

$$\frac{\partial^2 H}{\partial x^2} = \frac{\alpha^2}{r} H = \alpha'^2 H \quad (27)$$

subject to the boundary condition $H = H_0$ at $x = \pm a/2$. The solution therefore is

$$H = H_0 \frac{\cosh \alpha' x}{\cosh \alpha' a/2} \quad (28)$$

which is the first term of (22). The flux becomes

$$\frac{\phi}{\phi_0} = \frac{\tanh \alpha' a/2}{\alpha' a/2} \quad (29)$$

which will be recognized as (6). As pointed out above, this is also obtained from (2) due to the smallness of the series. The losses are given by

$$W = \frac{1}{2}\left[\frac{\omega \phi H_0}{8\pi 10^8} \frac{\tanh \alpha' a/2}{\alpha' a/2}\right] \quad (30)$$

If the demagnetizing effect of the eddy currents is negligible, on the right-hand side of (27) put

$$\frac{\partial^2 H}{\partial x^2} = \alpha'^2 H_0 \quad (31)$$

the solution to which is

$$\frac{H}{H_0} = \left[1 - j \frac{4\pi\mu\omega\lambda_y}{10^9} \left(\frac{a^2}{8} - \frac{x^2}{2}\right)\right] \quad (32)$$

The flux is

$$\frac{\phi}{\phi_0} = \left(1 - j \frac{\pi\mu\omega\lambda_y a^2}{3 \times 10^9}\right) \quad (33)$$

and the losses become

$$W = \frac{\lambda_y}{24} \left(\frac{\omega\phi_0}{10^8}\right)^2 \frac{a}{b} \quad (34)$$

This approximation is the exact equivalent of assuming the eddy current to flow straight across the laminations parallel to the $Y$ axis, and neglecting the demagnetizing effect. Thus on these assumptions, the flux included between $-x$ and $+x$ is

$$\phi = 2b\mu H_0 x \quad (35)$$

which induces the voltage

$$e = -j \frac{2\omega}{10^8} \mu H_0 bx \quad (36)$$

The resistance of the elementary path is

$$\frac{2b}{\lambda_y dx} \quad (37)$$

and the losses therefore are ($e_{\text{rms}} = e/\sqrt{2}$)

$$W = \frac{\lambda_y}{2b} \int_0^{a/2} e^2 dx = \frac{\lambda_y}{24} \left(\frac{\omega ab\mu H_0}{10^8}\right)^2 \frac{a}{b} = \frac{\lambda_y}{24} \left(\frac{\omega \phi_0}{10^8}\right)^2 \frac{a}{b} \quad (38)$$

# Some Series Formulas for Mutual Inductance of Solenoids

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ABSOLUTE formulas for the mutual inductance of coaxial solenoids have been derived by Nagaoka, Terezawa, and Olshausen. These all give the mutual inductance as a combination of 4 integrals—2 positive and 2 negative—each of which is a function of one of the 4 distances measured between an end of one solenoid and an end of the other. The expressions for these terms involve elliptic integrals of all 3 kinds, and numerical computations of their values are exacting.

Fortunately, it is possible to use in place of the absolute formulas series expansions of them involving ratios of the dimensions of the coils. However, on account of the number of parameters involved, no single series expansion will suffice for all possible pairs of coils.

The present paper has for its object the derivation of new series formulas suitable for cases not previously covered. A survey is also made of the whole field.

The new formulas here developed are derived from certain basic formulas included in the Bureau of Standards collection of inductance formulas.[2] For the convenience of the reader, there have been here reproduced from that collection, in an appendix, those expressions to which reference will be made. The formula numbers in the original are retained in the appendix with the letter $A$ added, in order to avoid confusion with the formula numbers of the present paper.

Formulas for the mutual inductance of solenoids are usually obtained by integrating expressions for the mutual inductance of circles. For circles comparatively near together, a very useful formula (16)$A$ has been given by T. H. Havelock,[1] which has been extended by E. B. Rosa and F. W. Grover.[2] As the latter authors say in comparing it with their equation (14)$A$, which is an extension of a formula given by Clerk Maxwell, equation (16)$A$ requires only half as many terms to be calculated for a given degree of convergence. Another fundamental formula (56)$A$ for mutual inductance of a solenoid and a coaxial circle was given by Rosa, Scientific Paper 169, page 101.

In this paper, the formulas (16)$A$ and (56)$A$, mentioned above, will be used to derive some formulas for solenoids, and their ranges of application will be investigated by means of numerical examples.

The mutual inductance of 2 coaxial but unequal solenoids which are not far apart, can be obtained by twice integrating the equation (16)$A$, first over the length of one solenoid and second over the length of the other. See figure 1. The result is as follows:

$$\frac{M}{n_1 n_2} = F_{(x1)} - F_{(x2)} - F_{(x3)} + F_{(x4)} \text{ abhenries} \tag{1}$$

where $n_1$ and $n_2$ are the turns per centimeter of the coils, respectively, and where

$$x_1 = s + m_1 + m_2 \tag{2}$$

$$x_2 = s + m_1 - m_2 \tag{3}$$

$$x_3 = s - m_1 + m_2 \tag{4}$$

$$x_4 = s - m_1 - m_2 \tag{5}$$

$$\begin{aligned} F_{(x)} = \frac{\pi d^2\sqrt{Dd}}{2}\Bigg[ & \left\{ \operatorname{logn} \frac{x^2+c^2}{c^2} \right\} \times \\ & \left\{ \frac{c^2}{d^2}\left(1 + \frac{3}{8}\frac{c^2}{Dd} - \frac{5}{64}\frac{c^4}{D^2d^2} + \frac{35}{1024}\frac{c^6}{D^3d^3}\right)\right\} + \\ & \left\{ \operatorname{logn} \frac{16Dd}{x^2+c^2}\right\}\left\{ \frac{x^2}{d^2}\left(1 + \frac{3}{4}\frac{c^2}{Dd} - \frac{15}{64}\frac{c^4}{D^2d^2} + \frac{35}{256}\frac{c^6}{D^3d^3}\right) + \right. \\ & \frac{x^4}{8Dd^3}\left(1 - \frac{5}{8}\frac{c^2}{Dd} + \frac{35}{64}\frac{c^4}{D^2d^2}\right) - \\ & \left. \frac{x^6}{64D^2d^4}\left(1 - \frac{7}{4}\frac{c^2}{Dd}\right) + \frac{5}{1024}\frac{x^8}{D^3d^5} \cdots \right\} - \\ & \frac{4cx}{d^2}\left\{ \tan^{-1}\frac{x}{c}\right\}\left\{ 1 + \frac{c^2}{2Dd} - \frac{c^4}{8D^2d^2} + \frac{c^6}{16D^3d^3}\right\} - \\ & \frac{x^2}{d^2}\left(1 - \frac{9}{8}\frac{c^2}{Dd} - \frac{1}{16}\frac{c^4}{D^2d^2} + \frac{325}{3072}\frac{c^6}{D^3d^3}\right) + \\ & \frac{x^4}{16Dd^3}\left(1 + \frac{3}{2}\frac{c^2}{Dd} - \frac{695}{384}\frac{c^4}{D^2d^2}\right) + \\ & \left. \frac{x^6}{48D^2d^4}\left(1 - \frac{149}{64}\frac{c^2}{Dd}\right) - \frac{109}{12288}\frac{x^8}{D^3d^5}\cdots\right] \end{aligned} \tag{6}$$

where logn denotes natural logarithm.

If $x$ is large, say greater than the radius $a$, or if $c$ is comparatively large, say greater than $a/2$, the following expression for $F_{(x)}$, obtained by integrating equations (56)$A$, may be used:

$$\begin{aligned} F_{(x)} = 2\pi^2a^2A\Bigg[ & \frac{r}{A} - \frac{a^2A}{8r^3} + \frac{a^4A}{16r^5} - \frac{5}{64}\frac{a^4A^3}{r^7} - \\ & \frac{5}{128}\frac{a^6A}{r^7} + \frac{35}{256}\frac{a^6A^3}{r^9} + \frac{7}{256}\frac{a^8A}{r^9} - \frac{105}{1024}\frac{a^8A^5}{r^{11}} - \\ & \frac{189}{1024}\frac{a^8A^3}{r^{11}} - \frac{21}{1024}\frac{a^{10}A}{r^{11}} + \frac{693}{2048}\frac{a^8A^5}{r^{13}} + \frac{231}{1024}\frac{a^{10}A^3}{r^{13}} + \\ & \frac{33}{2048}\frac{a^{12}A}{r^{13}} - \cdots + \left(-1 + \frac{a^2}{8A^2} + \frac{a^4}{64A^4} + \frac{5}{1024}\frac{a^6}{A^6} + \right. \\ & \left. \frac{35}{16384}\frac{a^8}{A^8} + \frac{147}{128\times 1024}\frac{a^{10}}{A^{10}} + \cdots\right)\Bigg] \end{aligned} \tag{7}$$

where

$$r^2 = x^2 + A^2 \tag{8}$$

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1. *Phil. Mag.*, volume 15, 1908, page 332.

2. FORMULAS AND TABLES FOR THE CALCULATION OF MUTUAL AND SELF-INDUCTANCE, E. B. Rosa and F. W. Grover. Scientific Paper 169 of the Bureau of Standards, Washington, D. C. Scientific Paper 169 was published also as part number 1 of volume 8 of the *Bulletin* of the Bureau of Standards.

By grouping together terms of (7) of the same power of $a$, the following alternative form is obtained:

$$F_{(x)} = 2\pi^2 aA^2\left[ C_0 + \frac{a^3}{8r^3} C_2 + \frac{a^5}{64r^5} C_4 + \frac{5}{1024}\frac{a^7}{r^7} C_6 + \frac{35}{16384}\frac{a^9}{r^9} C_8 + \frac{147}{128 \times 1024}\frac{a^{11}}{r^{11}} C_{10} + \ldots + \frac{a}{A}\left(-1 + \frac{a^2}{8A^2} + \frac{a^4}{64A^4} + \frac{5}{1024}\frac{a^6}{A^6} + \frac{35}{16384}\frac{a^8}{A^8} + \frac{147}{128 \times 1024}\frac{a^{10}}{A^{10}} + \ldots\right)\right] \quad (9)$$

where

$$C_0 = \frac{ar}{A^2} = \frac{a\sqrt{(x^2 + A^2)}}{A^2}$$

$$C_2 = -1$$

$$C_4 = 2\left(2 - \frac{5}{2}\frac{A^2}{r^2}\right)$$

$$C_6 = 7\left(-\frac{8}{7} + 4\frac{A^2}{r^2} - 3\frac{A^4}{r^4}\right)$$

$$C_8 = \frac{9}{5}\left(\frac{64}{9} - 48\frac{A^2}{r^2} + 88\frac{A^4}{r^4} - \frac{143}{3}\frac{A^6}{r^6}\right)$$

$$C_{10} = \frac{11}{7}\left(-\frac{128}{11} + 128\frac{A^2}{r^2} - 416\frac{A^4}{r^4} + 520\frac{A^6}{r^6} - 221\frac{A^8}{r^8}\right)$$

Equations (7) and (9) are equivalent to (6) in all respects and they give the same numerical result as (6) for any case to which both the formulas can be properly applied. The criterion as to whether a series is applicable is that the last terms used shall be negligibly small. In other words, the series shall be practically convergent in the number of terms which are used.

Equation (6) is given in terms of diameters and (7) and (9) in terms of radii so that the numerical coefficients in each series will be as small as possible.

It is to be noted that the 4 values of $F_{(x)}$ in (1) need not necessarily be computed all by (6) or all by (7) or by (9), but some can be computed by one expression and some by another. This may be necessary in some cases, for $x_1$ may be so large that (6) cannot be used, and for the same pair of coils $x_4$ may be so small that only (6) can be employed.

There is an advantage in using (7) or (9) for all 4 cases of (1), namely, that then the round bracket of (7) or (9) need not be computed, for it is like a constant of integration and would cancel out when the 2 positive and 2 negative values were added.

The round bracket of (7) and (9) was put in for the purpose of making (7) and (9) equivalent to (6). All these expressions have the same physical interpretation—they are $^1/_2$ the mutual inductance of 2 equal and concentric coils of length $x$ and with one turn per centimeter. See equation (11). Thus, (9) is the same, term for term, as the well known mutual-inductance formula (36)$A$, (Scientific Paper 169, page 53), multiplied by $^1/_2$. A considerable number of additional terms of (7) and (9) can be written down by inspection, from this corresponding formula (36)$A$. The terms of (7), (9), and (21) are the same as those in the paper "Mechanical Forces in Transformers," by J. E. Clem, AIEE TRANSACTIONS, volume 46, 1927, page 577. The general term of the round bracket of (7) and (9) is given in the paper by T. H. Havelock, reference 1, and on page 56 of Scientific Paper 169. (See appendix also.)

Where $a$ is considerably smaller than $A$, the grouping in (9) according to powers of $a$ is convenient, but if $x$ and therefore $r$ are relatively large, the grouping according powers of $r$, as in (7) and (22), is convenient. That is, in general, (7) is for long coils and (9) for short coils, though not as short as those for which (6) is used. However, there is very little difference between (7) and (9) for they contain the same terms and the terms which are not negligible must be computed while those that are negligible will be omitted.

When the 2 coils are concentric as well as coaxial, $s = 0$. It is to be noted that only even powers of $x$ are involved in (6), (7), and (9), and so

$$F_{(x)} = F_{(-x)}$$

Therefore, for concentric coils of unequal length,

$$\frac{M}{n_1 n_2} = 2F_{(m_1+m_2)} - 2F_{(m_1-m_2)} \quad (10)$$

Equation (10), using (6), (7), or (9) as convenient, is thus equivalent to Ròiti's formula, equation (39)$A$, or Searle and Airey's formula extended, equation (43)$A$.

A further simplification results when the 2 concentric coils are of equal length, in which case only one expression is required.

$$\frac{M}{n_1 n_2} = 2F_{(2m_1)} \quad (11)$$

For (6), (7), and (9),

$$F_{(0)} = 0 \quad (12)$$

The round bracket of (7) and (9) was inserted to make this so. As previously mentioned, equation (11), using (7) or (9) is the same as equation (36)$A$. It is equivalent to equation (38) of Scientific Paper 169 or other formulas which are given for this type of problem.

Each dimension of the cross section of a coil should be taken to be the number of wires in a row along that dimension, multiplied by the center-to-center distance between adjacent wires.

If the 2 concentric coils of equal length are shorter than approximately the radius of the inner one, and if $c$ is less than $^1/_2$ the radius, equation (6) used with (11) is appropriate to use. It is a mutual-inductance formula which it is believed has not previously been published. It is very similar to equation (1) of the paper "Mutual Inductance of Short Concentric Solenoids," by H. B. Dwight and P. W. Sayles, *Journal of Mathematics and Physics*, volume 9, 1930, page 162. It is several terms shorter, for the same rapidity of convergence. Equation (6) of this paper contains only even powers of $c$ in the series but equation (1) of the paper referred to contains both odd and even powers of $c$, which increases the number of terms in the formula without any advantage.

A similar shortening of a formula by using (16)$A$ in-

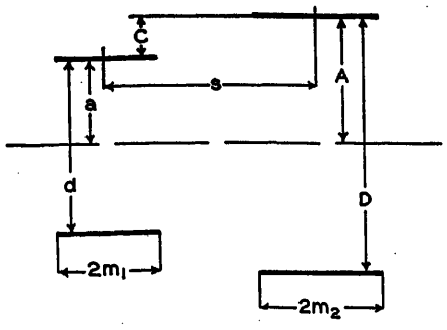



**Fig. 1. Two coaxial solenoids**

stead of (14)$A$, may be made in the case of equation (15)$A$, for the mutual inductance of 2 circles in the same plane. By putting $x = 0$ in (16)$A$, there results

$$M = 4\pi\sqrt{Aa}\left[\left\{\log_n \frac{8\sqrt{Aa}}{c}\right\}\left\{1 + \frac{3}{16}\frac{c^2}{Aa} - \frac{15}{1024}\frac{c^4}{A^2a^2} + \frac{35}{128^2}\frac{c^6}{A^3a^3} - \frac{1575}{2\times 128^3}\frac{c^8}{A^4a^4}\cdots\right\} - 2 - \frac{c^2}{16Aa} + \frac{31}{2048}\frac{c^4}{A^2a^2} - \frac{247}{6\times 128^2}\frac{c^6}{A^3a^3} + \frac{7795}{8\times 128^3}\frac{c^8}{A^4a^4}\cdots\right] \quad (13)$$

This contains only even powers of $c$ in the series, and so can be said to have $^1/_2$ as many terms as equation (15)$A$.

Another simplification of the problem of mutual inductance occurs when the 2 coils are not concentric but have equal radii. This means that $c = 0$ and $A = a$. Formula (6) then becomes $^1/_2$ times a self-inductance formula, namely, (71)$A$ (page 117, Scientific Paper 169). Formulas (7) and (9) similarly become $^1/_2$ times the self-inductance formula (11) published in the AIEE TRANSACTIONS, volume 38, 1919, page 1688. Equation (1) of this paper becomes the same as equation (51)$A$. When 2 coils have equal radii, their mutual inductance can be calculated by the above-mentioned equation (51)$A$, using well-known self-inductance formulas, and corrections can be added for the thickness of the winding and for the shape and spacing of the conductors. See Scientific Paper 169, pages 140–41.

Equation (51)$A$ can be used also for 2 concentric coils of equal length and of appreciable thickness of winding.

It is seen from equations (1) to (5) that if in the dimensions of the lengths, $2m_1$ and $2m_2$ are interchanged, the mutual inductance and also the force (see equation 20), are not changed. This can be called the *principle of interchange of lengths*. It has been pointed out previously for the mutual inductance of concentric solenoids. (See Scientific Paper 169, page 68,) Since it applies to each thin cylindrical element of thick solenoids or coils, it applies to the entire coils.

An inspection of the formulas[3] shows that the principle of interchange of lengths applies also to mutual inductance and force of unequal coils with parallel axes.

This principle applies, of course, to the case of a solenoid and coaxial circle also. That is, the mutual inductance of a solenoid, of length $2m$ and a radius $A$, and a circle of radius $a$ in its end plane, is the same as the mutual inductance of a solenoid of the same length $2m$ but of radius $a$, and a coaxial circle of radius $A$ in its end plane.

Equation (51)$A$ is derived from the knowledge of the properties of mutual and self inductance of coils. A corresponding relationship of mutual inductances for equation (1) of this paper is of interest since it makes clear the physical meaning of the formula. It requires the use of the principle of interchange of lengths, which is dependent on (1), and so it is not to be taken as a proof of (1).

Suppose that in addition to the 2 thin solenoids of figure 1, there are 4 others as in figure 2, the turns per centimeter being the same for all coils of a given radius. Since these touch each other end to end, they form longer solenoids. For instance, the 3 solenoids $P$, $Q$, and $R$ form one long solenoid which can be called $P + Q + R$.

$$M_{(P+Q+R)(p+q+r)} = M_{Pp} + M_{Pq} + M_{Pr} + M_{Qp} + M_{Qq} + M_{Qr} + M_{Rp} + M_{Rq} + M_{Rr}$$

Using the principle of interchange of lengths, by which $M_{Qp} = M_{Pq}$ etc., this becomes

$$M_{Pp} + M_{Qq} + M_{Rr} + 2M_{Pq} + 2M_{Qr} + 2M_{Rp}$$

Similarly,

$$M_{(P+Q)(p+q)} = M_{Pp} + M_{Qq} + 2M_{Pq}$$

and

$$M_{(Q+R)(q+r)} = M_{Qq} + M_{Rr} + 2M_{Qr}$$

Solving these equations simultaneously in such a way as to leave only pairs of coils which are concentric and of equal length on the right-hand side of the equation,

$$2M_{Rp} = M_{(P+Q+R)(p+q+r)} - M_{(P+Q)(p+q)} - M_{(Q+R)(q+r)} + M_{Qq} \quad (14)$$

The lengths of the concentric coils are evidently $x_1$, $x_2$, $x_3$, and $x_4$.

In a similar way, equation (10) can be treated.

In the general formula (10) for concentric solenoids the mutual inductance is given by the difference of 2 series. In the formula of Searle and Airey (formula (43)$A$) a *single* series of terms suffices for its calculation. Searle and Airey's formula may be derived from (10) and (7) by expanding the 2 values of $r$ in powers of the ratios of the solenoid lengths to the diagonal drawn from the center to the end of the longer solenoid and combining terms.

This formula does not converge well when the solenoids are of nearly equal radii and their lengths are small, compared with their radii. In such cases formula (6) must be used in connection with (10).

On the other hand, when the lengths of the coils are large, compared with their radii, the coefficients $X_{2n}$ and $L_{2n}$ may become very large, rendering the use of this

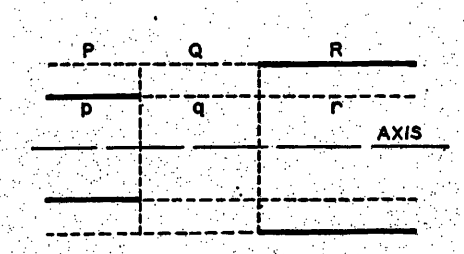



**Fig. 2. Coaxial solenoids**

[3] "The Force Between Unequal Reactance Coils Having Parallel Axes," by H. B. Dwight and R. W. Pursell, *General Electric Review*, volume 33, July 1930, page 401, formulas (1), (2), and (3).

formula uncertain and unsatisfactory (see pages 63 and 222 of Scientific Paper 169).

The following formula (17) is presented as an alternative to (43)$A$. Its coefficients $\lambda_n$ and $\xi_n$ are always less than unity and so it is possible to tell by inspection from the value of $\delta/\rho$ how rapid is the convergence of the series (17), which is a power series in $\delta/\rho$. The change lowers the powers of some of the letters making up the terms. By putting

$$\delta^2 = a^2 + m_1^2 \tag{15}$$

and

$$\rho^2 = A^2 + m_2^2 \tag{16}$$

we can replace

$m_1^2$ by $\delta^2 - a^2$ and $m_2^2$ by $\rho^2 - A^2$ in (43)$A$

giving for the concentric coils,

$$M = \frac{2\pi^2 a^2 N_1 N_2}{\rho}\left[1 - \frac{A^2\delta^2}{2\rho^4}\left\{\lambda_2 + \frac{\delta^2}{\rho^2}\lambda_4\xi_2 + \frac{\delta^4}{\rho^4}\lambda_6\xi_4 + \frac{\delta^6}{\rho^6}\lambda_8\xi_6 + \ldots\right\}\right] \tag{17}$$

where $N_1$ and $N_2$ are the turns per coil of the 2 coils, respectively, and where

$$\lambda_2 = 1 - \frac{7}{4}\frac{a^2}{\delta^2} \qquad \xi_2 = 1 - \frac{7}{4}\frac{A^2}{\rho^2}$$

$$\lambda_4 = 1 - \frac{9}{2}\frac{a^2}{\delta^2} + \frac{33}{8}\frac{a^4}{\delta^4} \qquad \xi_4 = 1 - \frac{9}{2}\frac{A^2}{\rho^2} + \frac{33}{8}\frac{A^4}{\rho^4}$$

$$\lambda_6 = 1 - \frac{33}{4}\frac{a^2}{\delta^2} + \frac{143}{8}\frac{a^4}{\delta^4} - \frac{715}{64}\frac{a^6}{\delta^6}$$

$$\lambda_8 = 1 - 13\frac{a^2}{\delta^2} + \frac{195}{4}\frac{a^4}{\delta^4} - \frac{1105}{16}\frac{a^6}{\delta^6} + \frac{4199}{128}\frac{a^8}{\delta^8}$$

$$\lambda_{10} = 1 - \frac{75}{4}\frac{a^2}{\delta^2} + \frac{425}{4}\frac{a^4}{\delta^4} - \frac{8075}{32}\frac{a^6}{\delta^6} + \frac{33915}{128}\frac{a^8}{\delta^8} - \frac{52003}{512}\frac{a^{10}}{\delta^{10}}$$

The coefficients $\xi_6$, $\xi_8$, etc., are functions of $A^2/\rho^2$ and can be written down by inspection from the similar expressions for $\lambda_6$, $\lambda_8$, etc.

While formulas (17) and (43)$A$ are given for the case of the mutual inductance of a short solenoid and a longer one outside, these formulas can be used for the case when the shorter solenoid is outside, by first applying the principle of interchange of lengths.

Gray's[4] formula (40)$A$ expresses the mutual inductance of 2 coaxial solenoids, not concentric, as the difference of 2 series of terms. It may be derived from the general formula (1) and (7) by expressing the 4 distances $r$ in terms of the distances measured from the center of the coil of smaller radius to the ends of the winding of the other coil. In spite of its smaller number of terms, however, the convergence of Gray's formula is not so good as that of (7), except for coils far apart.

Since Gray's formula contains the same coefficient as (43)$A$, it is subject to the same disadvantage that, for certain proportions of coils, the coefficients become large and it cannot be told by inspection how satisfactory is the convergence of the series. By making the same type of substitution as was used for obtaining (17), the following alternative form of Gray's formula for 2 coils as in figure 1, is obtained:

$$M = \frac{4\pi^2 a^2 n_1 n_2 m_1 q_2}{d_2}\left[1 - \frac{A^2\delta^2}{2d_2^4}\left\{\lambda_2 + \left(\frac{\delta}{d_2}\right)^2\lambda_4\xi_2'' + \left(\frac{\delta}{d_2}\right)^4\lambda_6\xi_4'' + \ldots\right\}\right] - \frac{4\pi^2 a^2 n_1 n_2 m_1 q_1}{d_1}\left[1 - \frac{A^2\delta^2}{2d_1^4}\left\{\lambda_2 + \left(\frac{\delta}{d_1}\right)^2\lambda_4\xi_2' + \left(\frac{\delta}{\delta_1}\right)^4\lambda_6\xi_4' + \ldots\right\}\right] \tag{18}$$

where

$$q_1 = s - m_2$$
$$q_2 = s + m_2$$
$$d_1^2 = A^2 + q_1^2$$
$$d_2^2 = A^2 + q_2^2$$
$$\delta^2 = a^2 + m_1^2$$

where $\lambda_2$, $\lambda_4$, etc., are the same as for (17), where $\xi_n'$ is the same function of $A/d_1$ that $\lambda_n$ is of $a/\delta$ and where $\xi_n''$ is the same function of $A/d_2$ that $\lambda_n$ is of $a/\delta$. The quantities $n_1$ and $n_2$ are the numbers of turns per centimeter of the 2 coils, respectively.

Since the coefficients in (18) are less than unity, the rapidity of convergence of the series is evident at once from the values of $\delta/d_1$ and $\delta/d_2$. The formula also has been simplified to some extent.

If the 2 coils of figure 1 are concentric, $s = 0$, $d_1 = d_2$ and (18) becomes the same as (17).

The convergence of (18) may be improved by employing the principle of interchange of lengths if, by so doing, a smaller value of $\delta$ results.

The convergence of Gray's formula and the alternative form (18), like that of (7) and (9), improves as the distance between the 2 solenoids is increased, but for loosely coupled coils this advantage is offset by the difficulty that the mutual inductance is obtained as the small difference of much larger terms. Thus each series has to be calculated to a much higher accuracy than that required in the value of the mutual inductance.

This difficulty may be avoided by the use of a new formula derived from (18).
Writing

$$d_1 = q_1\sqrt{1 + \frac{A^2}{q_1^2}} \quad \text{and} \quad d_2 = q_2\sqrt{1 + \frac{A^2}{q_2^2}}$$

and expanding powers of $d_1$ and $d_2$ in (18) by the binomial theorem, there results the expression

$$M = \frac{2\pi^2 a^2 A^2 N_1 N_2 s}{q_1^2 q_2^2}\left[1 + \frac{2\delta^2}{q_1^2}\left(\lambda_2 - \frac{3}{4}\frac{A^2}{\delta^2}\right)\left(1 + \frac{m_2^2}{s^2}\right)\frac{s^2}{q_2^2} + \frac{3\delta^4}{q_1^4}\left(\lambda_4 - \frac{5}{2}\frac{A^2}{\delta^2}\lambda_2 + \frac{5}{8}\frac{A^4}{\delta^4}\right)\left(1 + \frac{10}{3}\frac{m_2^2}{s^2} + \frac{m_2^4}{s^4}\right)\frac{s^4}{q_2^4} + \frac{4\delta^6}{q_1^6}\left(\lambda_6 - \frac{21}{4}\lambda_4\frac{A^2}{\delta^2} + \frac{35}{8}\frac{A^4}{\delta^4}\lambda_2 - \frac{35}{64}\frac{A^6}{\delta^6}\right)\times \left(1 + 7\frac{m_2^2}{s^2} + 7\frac{m_2^4}{s^4} + \frac{m_2^6}{s^6}\right)\frac{s^6}{q_2^6} + \ldots\right] \tag{19}$$

[4] "Absolute Measurements in Electricity and Magnetism," by Andrew Gray, edition of 1893, volume 2, part 1, page 274, equation 53, and Scientific Paper 169 of the Bureau of Standards, by E. B. Rosa and F. W. Grover, page 59, equation 40 and 40$a$.

in which $N_1$ and $N_2$ are the total numbers of turns on the coils.

This formula is simpler and more accurate the looser the coupling of the coils, that is, in just those cases where formulas (1) and (7) require the greatest care. The coefficients of $\delta^n/q_1^n$ are less than unity.

Here also the principle of interchange of lengths should be employed so that $\delta$ may have the smaller of the 2 lengths which are possible.

When the 2 coils are not concentric, a mechanical force is exerted by one on the other in the direction of the axis. By a well-known proposition, this force is equal to

$$i_1 i_2 \frac{\partial M}{\partial s} \text{ dynes}$$

where $i_1$ and $i_2$ are in abamperes. This can be written

$$i_1 i_2 n_1 n_2 [Q_{(x_1)} - Q_{(x_2)} - Q_{(x_3)} + Q_{(x_4)}] \text{ dynes} \qquad (20)$$

where $x_1$ to $x_4$ are given by (2) to (5) and where

$$Q_{(x)} = \frac{\partial F_{(x)}}{\partial x}$$

since

$$\partial s = \partial x$$

For small values of $x$, the derivative of (6) may be taken from the first step of the integration by which (6) was obtained. This gives

$$Q_{(x)} = \pi x \sqrt{Dd} \left[ \left\{ \log_n \frac{16Dd}{x^2 + c^2} \right\} \left\{ 1 + \frac{3}{4}\frac{c^2}{Dd} - \frac{15}{64}\frac{c^4}{D^2d^2} + \frac{35}{256}\frac{c^6}{D^3d^3} + \frac{x^2}{4Dd}\left(1 - \frac{5}{8}\frac{c^2}{Dd} + \frac{35}{64}\frac{c^4}{D^2d^2}\right) - \frac{3}{64}\frac{x^4}{D^2d^2} \times \left(1 - \frac{7}{4}\frac{c^2}{Dd}\right) + \frac{5}{256}\frac{x^6}{D^3d^3} \cdots \right\} - \left\{ \frac{2c}{x} \tan^{-1}\frac{x}{c} \right\} \times \left\{ 1 + \frac{c^2}{2Dd} - \frac{c^4}{8D^2d^2} + \frac{c^6}{16D^3d^3} \right\} + \left( -2 + \frac{c^2}{2Dd} + \frac{15}{64}\frac{c^4}{D^2d^2} - \frac{151}{768}\frac{c^6}{D^3d^3} \right) + \frac{x^2}{Dd}\left(\frac{c^2}{4Dd} - \frac{209}{768}\frac{c^4}{D^2d^2}\right) + \frac{x^4}{D^2d^2}\left(\frac{5}{64} - \frac{43}{256}\frac{c^2}{Dd}\right) - \frac{31}{768}\frac{x^6}{D^3d^3} \cdots \right] \qquad (21)$$

For larger values of $x$ the following expression for $Q_{(x)}$ may be obtained by differentiating (7) with respect to $x$:

$$Q_{(x)}'' = \frac{2\pi^2 a^2 x}{r}\left[ 1 + \frac{3}{8}\frac{a^2A^2}{r^4} - \frac{5}{16}\frac{a^4A^2}{r^6} + \frac{35}{64}\frac{a^4A^4}{r^8} + \frac{35}{128}\frac{a^6A^2}{r^8} - \frac{315}{256}\frac{a^6A^4}{r^{10}} - \frac{63}{256}\frac{a^8A^2}{r^{10}} + \frac{1155}{1024}\frac{a^6A^6}{r^{12}} + \frac{2079}{1024}\frac{a^8A^4}{r^{12}} + \frac{231}{1024}\frac{a^{10}A^2}{r^{12}} - \frac{9009}{2048}\frac{a^8A^6}{r^{14}} - \frac{3003}{1024}\frac{a^{10}A^4}{r^{14}} - \frac{429}{2048}\frac{a^{12}A^2}{r^{14}} + \cdots \right] \qquad (22)$$

where

$$r^2 = x^2 + A^2$$

It is easy to show that the mutual inductance $m(x)$ of a solenoid of radius $A$, winding density $n_1$, length $x$, and a coaxial circle of radius $a$ in its end plane is connected with the function $Q(x)$ by the relation $m(x) = n_1 Q(x)$. Thus equation (22), multiplied by $n_1$, gives an expression for the mutual inductance of a solenoid and coaxial circle which is equivalent to (56)$A$ and may in fact be derived from the latter by putting $x^2 = r^2 - A^2$ and collecting like terms. This change is similar to that used in obtaining (17) and (18), and the formula thus derived has the advantage, already noted in these cases also, of avoiding the possibility of large values of the coil length in the numerators of the terms. In (22) $A^2/r^2$ is always less than unity.

Similarly, by multiplying equation (21) by $n_1$, a second formula for the mutual inductance of solenoid and coaxial circle is found, which is suitable for short coils, and those cases where the radii are nearly equal. This formula is believed to be new. The fact that (21) is unchanged, when $d$ and $D$ are interchanged, furnished a proof of the principle of interchange of lengths in the special cases of solenoid and circle also.

The equations for $m(x)$, derived from (21) and (22), are to be used twice, when the plane of the circle does not pass through the end of the solenoid.

It is desired to make acknowledgment of preliminary investigations on this subject done in connection with thesis work by T. S. Chen at Massachusetts Institute of Technology.

*Example I.* A mutual inductance problem where both (6) and (7) can be used to check each other.

$A = 25$, $m_2 = 3$, $a = 20$, $m_1 = 2$, $s = 30$ (centimeter units).
$x_1 = 35$, $x_2 = 29$, $x_3 = 31$, $x_4 = 25$

$F_{(x_1)}$ by (6) $= 10{,}000\pi\sqrt{12.80}$ [0.0614 + 2.6824 − 0.6290 − 0.7549 + 0.0299 + 0.0058 − 0.0016] = 156700

$F_{(x_1)}$ by (7) $= 20{,}000\,\pi^2$ [1.7205 − 0.0157 + 0.0017 − 0.0007 − 0.0002 + 0.0003 − 0.0001 − 0.0001) + (−1.0000 + 0.0800 + 0.0064 + 0.0013 + 0.0004)]
$= 20{,}000\,\pi^2$ (1.7057 − 0.9119)
$= 156700$

In a case such as this, where both (6) and (7) are applicable, not many significant figures can be obtained. However, if (6) is used for a much smaller value of $x$, or (7) for a larger value, the last terms may be smaller than $10^{-7}$ and so 7 or more significant figures can be obtained.

*Example II.* $Q(x_1)$ for the coils of example I, by (21),

$= 35\,\pi\sqrt{2000}$ [3.721 − 0.411 − 1.994 + 0.002 + 0.029 − 0.009]
$= 6580$

By (22), $Q_{(x_1)} = \frac{2\,\pi^2 \times 400 \times 35}{\sqrt{1850}}$ [1 + 0.0274 − 0.0049 + 0.0029 + 0.0009 − 0.0014 − 0.0002 + 0.0004 + 0.0005 − 0.0004 − 0.0002] = 6580

*Example III. Two concentric, coaxial coils.*

Inner solenoid, $a = 2$, $2m_1 = 2$
Outer solenoid, $A = 10$, $2m_2 = 5$
(Example 39, page 84, Scientific Paper 169)

$\frac{M}{n_1 n_2} = 160\,\pi^2$ (1.055268 − 1.006331) = 77.279 by (7).

Equation (43) of Scientific Paper 169 gives 77.27980. It is a better series for this case, in which the coils are too short for more than 5 significant figures to be given by

(7), and in which $c^2/Dd = 0.8$ is too large for (6) to be used. However, equation (7) is applicable to coils which are not concentric, while (43) is not.

*Example IV. Two concentric, coaxial solenoids.*

Inner solenoid, $a = 10$, $2m_1 = 20$
Outer solenoid, $A = 15$, $2m_2 = 200$
(Example 43, page 91, Scientific Paper 169)

$$\text{By (7)}, \quad F(110) = 3000\,\pi^2\,(7.401200 - 0.000137 + 0.000001)$$
$$= 3000\,\pi^2 \times 7.401064$$
$$F(90) = 3000\,\pi^2\,(6.082762 - 0.000247 + 0.000001)$$
$$= 3000\,\pi^2 \times 6.082516$$
$$\frac{M}{n_1 n_2} = 6000\,\pi^2\,(7.401064 - 6.082516)$$
$$\frac{M}{4\pi n_1 n_2} = 6213.51$$

This agrees with the values given on page 91 of Scientific Paper 169. On page 92, a solution which occupies more than a page, is given by means of (45), page 65 of that paper, which is a formula for 2 coaxial solenoids which may or may not be concentric. As stated on page 91, if a series formula can give the accuracy required, it is usually preferable to (45). It is evident that, by using more terms of (7) of this paper, more than 6 significant figures could be obtained in this case.

*Example V.* As an example of the use of formula (19) there may be taken the case where

$a = 2$, $A = 3$, $2m_1 = 10$, $2m_2 = 6$, $s = 18$

Assuming further that $n_1 = n_2 = 10$ it follows that the coils have 100 turns and 60 turns, respectively.

$q_1 = 15$, $q_2 = 21$, $\delta^2 = 29$

Then (19) gives

$$M = \frac{7.776\,\pi^2\,10^6}{(315)^2}\,[1 + 0.102358 - 0.002076 - 0.001099 \ldots]$$
$$= 850.17$$

A more convergent series is obtained if the lengths are interchanged, giving

$2m_1 = 6$, $2m_2 = 10$, $s = 18$, $q_1 = 13$, $q_2 = 23$, and $\delta^2 = 13$.

The mutual inductance is then

$$M = \frac{7.776\,\pi^2\,10^6}{(299)^2}\,[1 - 0.005855 - 0.004150 + 0.000392 + \ldots]$$
$$= 850.19$$

If the solution be carried through by (18), $M = 8{,}000\,\pi^2\,[0.989447 - 0.978679] = 850.21$ with $2m_1 = 10$ and $2m_2 = 6$, and if the lengths be interchanged,

$n = 4800\,\pi^2\,[0.991508 - 0.973561] = 850.22$

## Appendix

### Formulas From the Bureau of Standards Collection for the Calculation of Inductance (Scientific Paper 169)

Formulas quoted in this paper are here collected for easy reference.

MUTUAL INDUCTANCE OF COAXIAL CIRCLES

Placing
$a$ = the smaller radius
$A$ = the larger radius
$c = A - a$ = the difference of the radii
$x$ = the distance between their planes

$$r^2 = c^2 + x^2 \text{ and } \alpha^2 = \frac{r^2}{Aa},$$

then Maxwell's series formula, extended by Rosa and Cohen, is

$$M = 4\pi a\left\{\log\frac{8a}{r}\cdot\left(1 + \frac{c}{2a} + \frac{c^2+3x^2}{16a^2} - \frac{c^2+3cx^2}{32a^3} + \frac{17c^4+42c^2x^2-15x^4}{1024a^4} - \ldots\right) - \left(2 + \frac{c}{2a} - \frac{3c^2-x^2}{16a^2} + \frac{c^3-6cx^2}{48a^3} + \frac{19c^4+534c^2x^2-93x^4}{6144a^4} - \ldots\right)\right\} \quad (14A)$$

If the circles are in the same plane, $x = 0$, and this becomes

$$M = 4\pi a\left\{\log\frac{8a}{c}\cdot\left(1 + \frac{c}{2a} + \frac{c^2}{16a^2} - \frac{c^3}{32a^3} + \frac{17}{1024}\frac{c^4}{a^4} - \ldots\right) - \left(2 + \frac{c}{2a} - \frac{3}{16}\frac{c^2}{a^2} + \frac{c^3}{48a^3} + \frac{19}{6144}\frac{c^4}{a^4} - \ldots\right)\right\} \quad (15A)$$

A formula derived from series expansions of certain integrals by Havelock reads

$$M = 4\pi\sqrt{Aa}\left[\left(1 + \frac{3}{16}\alpha^2 - \frac{15}{1024}\alpha^4 + \frac{35}{(128)^2}\alpha^6 - \frac{1575}{2(128)^3}\alpha^8 + \ldots\right)\log\frac{8\sqrt{Aa}}{r} - \left(2 + \frac{\alpha^2}{16} - \frac{31}{2048}\alpha^4 + \frac{247}{6(128)^2}\alpha^6 - \frac{7795}{8(128)^3}\alpha^8 + \ldots\right)\right] \quad (16A)$$

This gives very accurate results for values of $x$ almost as great as the smaller radius. For a given degree of convergence it requires only half as many terms to be calculated as does formula (14)$A$.

MUTUAL INDUCTANCE OF
A SOLENOID AND A CIRCLE IN ITS END PLANE

The mutual inductance of a solenoid of $N$ turns, radius $A$, and axial length $x$, and a circle of radius $a$ in its end plane may be found from Rosa's formula:

$$M = \frac{2\pi^2 a^2 N}{\rho}\left[1 + \frac{3}{8}\frac{a^2A^2}{\rho^4} + \frac{5}{64}\frac{a^4A^4}{\rho^8}X_2 + \frac{35}{512}\frac{a^6A^6}{\rho^{12}}X_4 + \frac{63}{1024}\frac{a^8A^8}{\rho^{16}}X_6 + \frac{231}{4096}\frac{a^{10}A^{10}}{\rho^{20}}X_8 + \frac{429}{8192}\frac{a^{12}A^{12}}{\rho^{24}}X_{10} + \ldots\right] \quad (56A)$$

in which $\rho^2 = x^2 + A^2$

and

$$X_2 = 3 - 4\frac{x^2}{A^2}$$

$$X_4 = \frac{5}{2} - 10\frac{x^2}{A^2} + 4\frac{x^4}{A^4}$$

$$X_6 = \frac{35}{16} - \frac{35}{2}\frac{x^2}{A^2} + 21\frac{x^4}{A^4} - 4\frac{x^6}{A^6}$$

$$X_8 = \frac{63}{32} - \frac{105}{4}\frac{x^2}{A^2} + 63\frac{x^4}{A^4} - 36\frac{x^6}{A^6} + 4\frac{x^8}{A^8}$$

$$X_{10} = \frac{231}{128} - \frac{1155}{32}\frac{x^2}{A^2} + \frac{1155}{8}\frac{x^4}{A^4} - 165\frac{x^6}{A^6} + 55\frac{x^8}{A^8} - 4\frac{x^{10}}{A^{10}}$$

and the general term for the coefficients $X_{2n}$ is

$$X_{2n} = \sum_{p=0}^{n}\frac{(-1)^{n-p}(2n+1)2n(2n-1)\ldots[2n-(2p-2)]}{\left(\frac{p+1}{4}\right)[2.4.6\ldots(2p)]^2}\left(\frac{x}{A}\right)^{2n-2p}$$

when $p = 0$, the term being $4(-1)^n(x/A)^{2n}$.

### Mutual Inductance of Concentric Coaxial Solenoids

Let the radius, axial length, and number of turns for the outer solenoid be $A$, $2m_2$, and $N_2$, and the corresponding quantities for the inner solenoid $a$, $2m_1$, and $N_1$. (This is a special case of figure 1 with $s = 0$.)

Then, if the length of the outer solenoid be greater than that of the inner, the mutual inductance may be calculated by Searle and Airey's formula:

$$M = \frac{2\pi^2 a^2 N_1 N_2}{\rho}\left[1 + \frac{1}{8}\frac{A^2a^2}{\rho^4}\cdot L_2 + \frac{1}{32}\frac{A^4a^4}{\rho^8}\cdot X_2L_4 + \frac{1}{32}\frac{A^6a^6}{\rho^{12}}\cdot X_4L_6 + \frac{1}{32}\frac{A^8a^8}{\rho^{16}}\cdot X_6L_8 + \ldots + \frac{1}{32}\left(\frac{Aa}{\rho^2}\right)^{2n}\cdot X_{2n-2}L_{2n} + \ldots\right] \quad (43A)$$

in which $\rho^2 = m_2^2 + A^2$, and the quantities $X_{2n}$ are derived from the corresponding coefficients in (56)$A$, with $m_2$ in place of $x$, and the coefficients $L_{2n}$ from the substitution of $m_1$ in place of $x$, and $a$ for $A$, in the same equations. Thus

$$L_2 = 3 - 4\frac{m_1^2}{a^2} \qquad X_2 = 3 - \frac{4m_2^2}{A^2}$$

$$L_4 = \frac{5}{2} - 10\frac{m_1^2}{a^2} + 4\frac{m_1^4}{a^4} \qquad X_4 = \frac{5}{2} - 10\frac{m_2^2}{A^2} + \frac{4m_2^4}{A^4}$$

This formula is very convergent, except for coils of nearly equal radii and of lengths which are short, compared with their radii.

For long coils, the coefficients $X_{2n}$ and $L_{2n}$ oscillate between large positive and negative values, rendering it difficult to be sure of the degree of convergence attained.

*Rôiti's Formula.* With the same nomenclature but with

$$\rho_1^2 = (m_2 - m_1)^2 + A^2 \quad \text{and} \quad \rho_2^2 = (m_2 + m_1)^2 + A^2$$

this formula may be written

$$M = 4\pi^2 a^2 n_1 n_2\left[(\rho_2 - \rho_1) + \frac{a^2A^2}{8}\left(\frac{1}{\rho_1^3} - \frac{1}{\rho_2^3}\right) - \frac{a^4A^2}{16}\left(\frac{1}{\rho_1^5} - \frac{1}{\rho_2^5}\right) + \frac{5}{64}a^4A^4\left(1 + \frac{1}{2}\frac{a^2}{A^2}\right)\left(\frac{1}{\rho_1^7} - \frac{1}{\rho_2^7}\right) - \frac{35}{256}a^6A^4\left(1 + \frac{1}{5}\frac{a^2}{A^2}\right)\left(\frac{1}{\rho_1^9} - \frac{1}{\rho_2^9}\right) + \frac{105}{1024}a^6A^6 \times \left(1 + \frac{9}{5}\frac{a^2}{A^2} + \frac{1}{5}\frac{a^4}{A^4}\right)\left(\frac{1}{\rho_1^{11}} - \frac{1}{\rho_2^{11}}\right) - \frac{693}{2048}a^8A^6 \times \left(1 + \frac{2}{3}\frac{a^2}{A^2} + \frac{1}{21}\frac{a^4}{A^4}\right)\left(\frac{1}{\rho_1^{13}} - \frac{1}{\rho_2^{13}}\right) + \frac{3003}{16384}a^8A^8 \times \left(1 + 4\frac{a^2}{A^2} + \frac{10}{7}\frac{a^4}{A^4} + \frac{1}{14}\frac{a^6}{A^6}\right)\left(\frac{1}{\rho_1^{15}} - \frac{1}{\rho_2^{15}}\right) - \ldots\right] \quad (39A)$$

*Maxwell's Formula for Concentric Solenoids of Equal Lengths.* Let the common length be $2m$, and the winding densities, in turns per centimeter, $n_1$ and $n_2$. Then, with $\rho^2 = (2m)^2 + A^2$

$$M = 4\pi^2 a^2 n_1 n_2[2m - 2A\alpha]$$

in which

$$\alpha = \frac{A - \rho + 2m}{2A} - \frac{a^2}{16A^2}\left(1 - \frac{A^3}{\rho^3}\right) - \frac{a^4}{64A^4}\left(\frac{1}{2} + 2\frac{A^5}{\rho^5} - \frac{5}{2}\frac{A^7}{\rho^7}\right) - \frac{35}{2048}\frac{a^6}{A^6}\left(\frac{1}{7} - \frac{8}{7}\frac{A^7}{\rho^7} + 4\frac{A^9}{\rho^9} - 3\frac{A^{11}}{\rho^{11}}\right) - \frac{63}{2(128)^2}\frac{a^8}{A^8}\left(\frac{5}{9} + \frac{64}{9}\frac{A^9}{\rho^9} - 48\frac{A^{11}}{\rho^{11}} + 88\frac{A^{13}}{\rho^{13}} - \frac{143}{3}\frac{A^{15}}{\rho^{15}}\right) - \frac{231}{(512)^2}\frac{a^{10}}{A^{10}}\left(\frac{7}{11} - \frac{128}{11}\frac{A^{11}}{\rho^{11}} + 128\frac{A^{13}}{\rho^{13}} - 416\frac{A^{15}}{\rho^{15}} + 520\frac{A^{17}}{\rho^{17}} - 221\frac{A^{19}}{\rho^{19}}\right) - \frac{429}{2(1024)^2}\frac{a^{12}}{A^{12}}\left(\frac{21}{13} + \frac{512}{13}\frac{A^{13}}{\rho^{13}} - 640\frac{A^{15}}{\rho^{15}} + 3200\frac{A^{17}}{\rho^{17}} - 6800\frac{A^{19}}{\rho^{19}} + 6460\frac{A^{21}}{\rho^{21}} - 2261\frac{A^{23}}{\rho^{23}}\right) \ldots \quad (36A)$$

In this expression the general term of the series in powers of $a^2/A^2$ is, as was shown by Havelock,

$$-\frac{(2n-1)[1.3.5\ldots(2n-3)]^2}{2^{2n+1}n!\,(n+1)!}\left(\frac{a}{A}\right)^{2n}$$

*Gray's Formula.* Gray gave the following formula for the mutual inductance of coaxial solenoids, not concentric. With the notation of figure 1 and

$$q_1 = s - m_2,\ q_2 = s + m_2,\ d_1^2 = A^2 + q_1^2,\ d_2^2 = A^2 + q_2^2$$

Gray's formula becomes

$$M = \pi^2 a^2 A^2 n_1 n_2[K_1k_1 + K_3k_3 + K_5k_5 + \ldots] \quad (40A)$$

in which

$$K_1 = \frac{2}{A^2}\left(\frac{q_2}{d_2} - \frac{q_1}{d_1}\right)$$

$$K_3 = \frac{1}{2}\left(\frac{q_1}{d_1^3} - \frac{q_2}{d_2^3}\right)$$

$$K_5 = -\frac{A^2}{8}\left\{\frac{q_1}{d_1^9}\left(3 - 4\frac{q_1^2}{A^2}\right) - \frac{q_2}{d_2^9}\left(3 - 4\frac{q_2^2}{A^2}\right)\right\}$$

$$k_1 = 2m_1$$

$$k_3 = -a^2m_1\left(3 - 4\frac{m_1^2}{a^2}\right)$$

$$k_5 = a^4m_1\left(\frac{5}{2} - 10\frac{m_1^2}{a^2} + 4\frac{m_1^4}{a^4}\right)$$

### Mutual Inductance by Means of Self-Inductance Formulas

The mutual inductance of 2 coils having the same radii and the same number of turns per unit length may be calculated from a knowledge of several self-inductances.

If the 2 coils be designated as $A$ and $B$, and a coil $C$, having the same radius and winding density, be imagined to exactly fill up the space between $A$ and $B$, the inductance of coils $A$, $B$, and $C$ in series will be

$$L_{ABC} = L_A + L_B + L_C + 2M_{AC} + 2M_{BC} + 2M_{AB}$$

Similarly, the self inductance of the coils $A$ and $C$ in series, and of $B$ and $C$ in series, are given by

$$L_{AC} = L_A + L_C + 2M_{AC}$$
$$L_{BC} = L_B + L_C + 2M_{BC}$$

Eliminating $M_{AC}$ and $M_{BC}$ in the equation above, we find

$$2M_{AB} = (L_{ABC} + L_C) - (L_{AC} + L_{BC}) \quad (51A)$$

If the radii of the 2 coils are equal but their winding densities $n_1$ and $n_2$ are unequal, the expression (51)$A$ may first be calculated, assuming unit winding density on each coil. The result so found, multiplied by $n_1n_2$, is the desired mutual inductance.

The self-inductances in (51)$A$ may, in general, be calculated by Nagaoka's formula and tables. For a coil of $N$ turns, whose axial length $2m$ does not exceed its radius $a$, Coffin's extension of the Rayleigh and Niven formula is accurate and convenient.

$$L = 4\pi aN^2\left\{\log\frac{8a}{2m} - \frac{1}{2} + \frac{1}{8}\frac{m^2}{a^2}\left(\log\frac{8a}{2m} + \frac{1}{4}\right) - \frac{1}{64}\frac{m^4}{a^4}\left(\log\frac{8a}{2m} - \frac{2}{3}\right) + \frac{5}{1024}\frac{m^6}{a^6}\left(\log\frac{8a}{2m} - \frac{109}{120}\right) - \frac{35}{16384}\frac{m^8}{a^8}\left(\log\frac{8a}{2m} - \frac{431}{420}\right) + \ldots\right\} \quad (71A)$$

# An Analysis of Copper-Oxide Rectifier Circuits

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## Summary

THE analysis of circuits containing copper-oxide rectifiers is based upon the selection of a proper representation of the variable impedance of the rectifier element. In this analysis, the element is replaced by 2 constant resistances effective during the 2 directions of current flow through the rectifier. On the basis of this representation, an equivalent circuit is developed, which is a modification of the usual perfect rectifier circuit. The method is illustrated by analyzing circuits in which the loads consist of resistance and inductance and of resistance and capacitance. The computed results are then compared with observations made by an oscillograph.

## Introduction

Copper-oxide rectifiers are finding greater use in connection with measurement of alternating voltages and currents. This is particularly true in connection with special electrical instruments designed to measure physical quantities such as motion, pressure, etc. It is often desirable to analyze the circuit in order to predict its operation, but the usual assumption, neglecting rectifier imperfections, is frequently not sufficiently accurate.

This paper presents an approximate representation of the copper-oxide rectifier, taking into account its asymmetrical conduction properties. Two constant resistances are introduced, to represent the direct and inverse properties of the real rectifier. Using this approximation, an equivalent circuit is established.

A general discussion of the methods used to analyze circuits, consisting of copper-oxide rectifiers is given, together with a consideration of the circuits for which the rectifier conducts during only part of the cycle. The analysis is made on the assumptions that the applied voltage is sinusoidal with a constant maximum value, and that the successive half-waves are identical.

Circuits of resistance, resistance and inductance, and capacitance in parallel with resistance, are analyzed to show the application of the method presented in this paper. The circuits are also analyzed for the usual idealization of perfect rectifiers. The theoretical wave forms computed by each of these 2 methods is compared with the results obtained by an oscillographic study of an example of each type of load mentioned. The measurements included in this paper were made on commercial rectifiers and are included only as illustrations of the method of circuit analysis.

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1. For all numbered references see list at end of paper.

## The Rectifier Element

Grondahl[1,2] has given an excellent description of the copper-oxide rectifier and its construction, together with an explanation of some of its properties. The rectifier element consists of a disk of copper upon one side of which an oxide has been formed by heat treatment. Rectification takes place in the area of contact between the copper and its oxide, because the impedance to current flow from oxide to copper is low, while the impedance to current flow, in the opposite direction, is high.

The difference in impedance for the 2 directions of flow presents a problem which has no simple solution, but which is, nevertheless, of much importance. Without an analytical approach, it would be necessary to make an oscillographic study of wave form to determine the behavior of each new circuit. It is desirable to obtain a method of computing results to be anticipated for a given circuit, so that the oscillographic study can be eliminated. This is especially true in the design of instruments using rectifiers.

For circuit analysis, the rectifier must be replaced by some combination of standard impedances. Deutschmann and Schottky[3] presented 4 types of equivalent combinations, of which pure resistance is the simplest, yet representative for many applications. This resistance is a variable depending upon the voltage applied to the rectifier element. The type of variation is shown in figure 1, but actual values will differ depending upon the kind of rectifier and size of disk.

Since the resistance varies continually during the cyclic change of current and voltage, an exact analysis is quite difficult. As an approximation, Cremer[4] replaced the changing resistances by 2 constant values, $D$ and $S$, where $D$ represents an equivalent constant value for current flow from oxide to copper, and $S$ an equivalent constant value for current flow in the opposite direction. These approximations are used in this paper to simplify the study of rectifier circuits. The term "constant rectifier" refers to one in which the approximation of 2 constant resistances is used. A "perfect rectifier" is one in which $D$ is zero and $S$ is infinite.

## Full-Wave Rectifier Circuits

There are 2 standard circuits used to obtain full wave rectification, the transformer bridge and the Graetz bridge, shown in figure 2. The choice between them depends upon the relative cost of rectifier elements and transformer, and also on certain conditions peculiar to

the special problem. Unless otherwise stated, this paper deals with the Graetz bridge only.

The rectifiers in the bridge of figure 2*b* may be replaced by the approximate equivalent resistances, $D$ and $S$, for direct and inverse impedances, respectively, and an alternating voltage of constant maximum value applied. When $a$ has a positive potential, current flows from $a$ to $c$. Rectifiers in legs $ab$ and $dc$ are conducting and are represented by the constant direct resistance, $D$. Rectifiers in legs $bc$ and $ad$ are opposing the flow of current and are represented by the constant inverse resistance, $S$. During the next half-cycle, when $c$ is positive, current flows from $c$ to $a$, opposite to the direction in the previous half-cycle. Thus rectifiers in legs $ab$ and $dc$ now oppose the flow of current and are represented by $S$, while those in legs $bc$ and $ad$ are conducting and are represented by $D$.

If the rectifiers may be assumed to have like characteristics, the entire behavior can be described by one half-cycle. This assumption simplifies the discussion and is

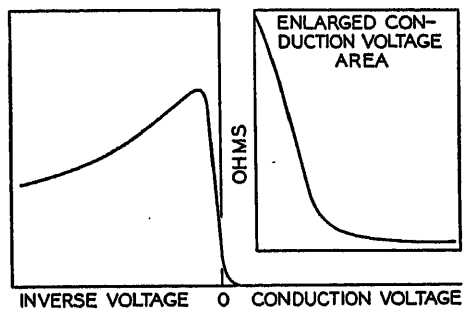



**Fig. 1. Copper-oxide rectifier resistance variation**

used here. Thus the analysis is confined to the half-cycle of voltage, where $a$ is positive, the next half-cycle assumed identical to it.

Analysis of the Graetz bridge circuit of circuits *abc*, *abdc*, and junction $b$ in figure 2*b*, yields the equations

$$Di_D + Si_S = e$$
$$2Di_D + e_L = e$$
$$i_L = i_D - i_S$$

Combining the first and third, gives

$$i_D = \frac{e + Si_L}{D + S} \quad \text{and} \quad i_S = \frac{e - Di_L}{D + S}$$

Substitution of $i_D$ in the second equation above, gives the basic Graetz bridge equation

$$\phi e = e_L + Pi_L \tag{1}$$

where

$$P = \frac{2DS}{D + S} \quad \text{and} \quad \phi = \frac{S - D}{S + D}$$

An equivalent circuit, to represent the constant rectifier with load, can be set up from equation 1. The load current, $i_L$, for a constant rectifier, may be found by adding a resistance, $P$, in series with a perfect rectifier, having the same load, and applying a voltage $\phi e$ to the resulting circuit. This substitution is used here to solve the constant rectifier problem. A circuit of this kind is shown in figure 4*c*.

Applying similar analysis to the transformer bridge in figure 2*a*, the analogous equations become

$$i_D = \frac{2e + Si_L}{D + S}; \quad i_S = \frac{2e - Di_L}{D + S}; \quad \phi e = \frac{P}{2} i_L + e_L$$

where $P$ and $\phi$ are the same as defined above. Thus the constant transformer bridge can be represented by a perfect rectifier bridge with a series resistance, $P/2$, and a voltage $\phi e$ applied to the system.

## Determination of Equivalent Resistances

Even if the curve of d-c values of figure 1 were known, the equivalent dynamic values, $D$ and $S$, could not be easily established and so some method of direct measurement is desirable.

These constants may be determined by 2 sets of measurements on the Graetz bridge. Using the assembled rectifier bridge, measure the alternating current and voltage with effective value meters, for these 2 conditions: (*a*) d-c load terminals open, and (*b*) d-c load terminals shorted. Call the impedance from the first measurement, the open-circuit impedance, $Z_o$, and the impedance from the second measurement, the short-circuit impedance, $Z_s$. Study of the parallel impedances of figure 3 shows that

$$Z_o = \frac{D + S}{2} \approx \frac{S}{2} \quad \text{and} \quad Z_S = \frac{2DS}{D + S} = P$$

Since $S$ is much greater than $D$, the following definitions hold,

$$S \approx 2Z_o; \qquad D \approx P/2; \qquad \phi = \frac{S - D}{S + D} = 1 - \frac{P}{S}$$

$Z_s = P$ is concerned primarily with rectifier conduction, and so in use depends upon the current, while $Z_o$ is concerned primarily with the inverse or leakage characteristic of the rectifier and in use depends upon the voltage.

For any given case, the values of $P$ and $S$ can be found from graphs similar to figure 3, the value of line current determining $P$, and the line voltage determining $S$.

Some precautions must be taken in the measurement of $Z_o$ to obtain consistent and reliable results. A fairly good set of measurements can be obtained by taking the readings with decreasing voltages, controlling the voltage by a tapped transformer rather than with a potentiometer.

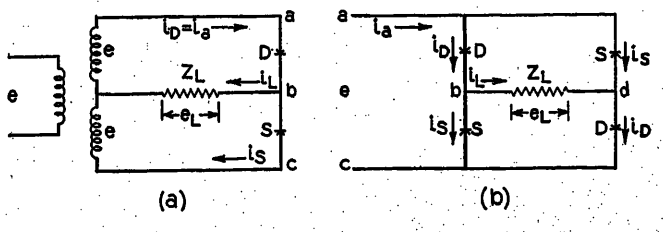



**Fig. 2. Full-wave rectifier circuits**

*a*—Transformer bridge *b*—Graetz bridge

## Analysis of Rectifier Circuits With D-C Loads

Now that the equivalent circuit for the constant rectifier has been established, and an experimental means for finding $P$ and $\phi$ has been presented, a few typical circuits will be analyzed to show the application of equation 1. Comparison of the wave forms obtained by this method will be made with the wave forms obtained by oscillographic study of the circuit. The analysis of these loads will also be made assuming a perfect rectifier, for the purpose of comparing results with those obtained by the constant rectifier method.

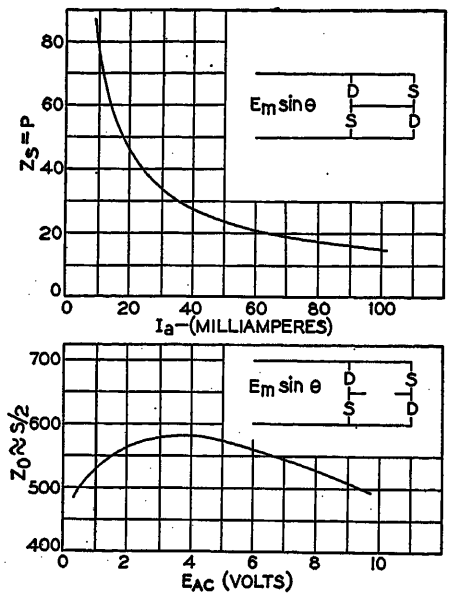



**Fig. 3. Equivalent resistance determination**

Several studies of perfect rectifier circuits have been published. The reader is referred to the series methods presented by Wheatcroft[5] and by Stout.[6] A filter circuit study was made by Lee[7] and the equations for a thyratron rectifier were given by Cockrell.[8]

Distinction must be made, in rectifier work, between 2 kinds of loads;

*a.* Loads for which rectifier conducts during the entire half-cycle. Most of the loads under this group are resistance and inductance in series or pure resistance, but some arrangements of capacitance in parallel with series inductance and resistances fall into this group. A discussion of a load of resistance and inductance in series is presented to illustrate this type.

*b.* A second group of loads are those having parallel capacitance of such magnitude that the load current tends to become negative during the half-wave, with the result that the rectifier stops conducting and a cut-off period must be studied in addition to the usual conduction period. A discussion of this type of load follows and the case of resistance and capacitance in parallel illustrates this kind of load.

The circuit analyses in this paper are made with the following assumptions:

1. The impressed alternating voltage is sinusoidal with a constant maximum value, $e = E_m \sin \omega t = E_m \sin \theta$.

2. It is assumed that the system has been in operation for sufficient time so that a steady state has been reached.

3. The successive half-waves are identical. All wave-forms and developments are based on the half-cycle, $\theta = 0$, to $\theta = \pi$.

4. Since the successive half-waves are identical, the currents must have the same value at $\theta = 0$ as at $\theta = \pi$.

## Load of Resistance and Inductance in Series

As mentioned above, a load of resistance and inductance in series is an example of the group in which the rectifier conducts during the entire half-cycle. See figure 4 for the circuits for this type of load.

### Perfect Rectifier

Refer to figure 4*b* for the equivalent circuit for this case. The rectifier impedance is zero and so the current solution is obtained by applying the voltage directly to the load. The equation for this case is

$$Ri_L + L\frac{di_L}{dt} = E_m \sin\theta$$

which has the solution

$$i_L = K_1 \epsilon^{-a\theta} + K_2 \sin\theta + K_3 \cos\theta$$

where $a = R\omega/L$. $K_1$ is obtained from the condition that $i_L$ is the same for $\theta = 0$ and $\theta = \pi$. $K_2$ and $K_3$ are known from the steady state of the inductive circuit for alternating voltage, so that

$$K_1 = \frac{\omega L E_m}{R^2 + (\omega L)^2} \frac{2}{1 - \epsilon^{-a\pi}}; \quad a = \frac{R}{\omega L}$$

$$K_2 = \frac{RE_m}{R^2 + (\omega L)^2}; \quad K_3 = \frac{-\omega L E_m}{R^2 + (\omega L)^2}$$

### Constant Rectifier

Refer to figure 4*c*. Equation 1 and its discussion show that the constant rectifier can be represented by a perfect rectifier with a series resistance, $P$, and a modified voltage, $\phi e$. Thus the same equations that were developed for the perfect rectifier are valid, except that the

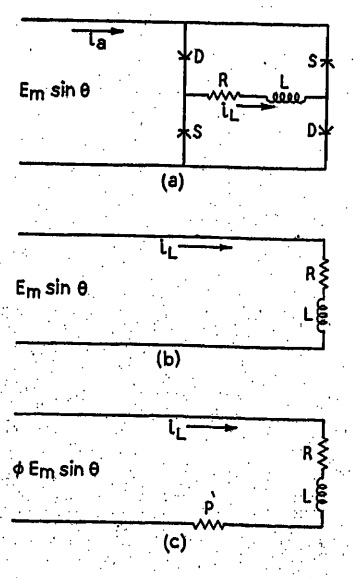



**Fig. 4. Graetz bridge circuits for resistance and inductance in series**

*a*—Conventional circuit, first half-wave

*b*—Equivalent circuit for perfect rectifier

*c*—Equivalent circuit for constant rectifier

resistance term, $R$, is replaced by the term $(R + P)$. Thus we can write the coefficients directly

$$K_1 = \frac{\omega L \phi E_m}{(R+P)^2 + (\omega L)^2} \frac{2}{1 - \epsilon^{-a\pi}}; \quad a = \frac{R+P}{\omega L}$$

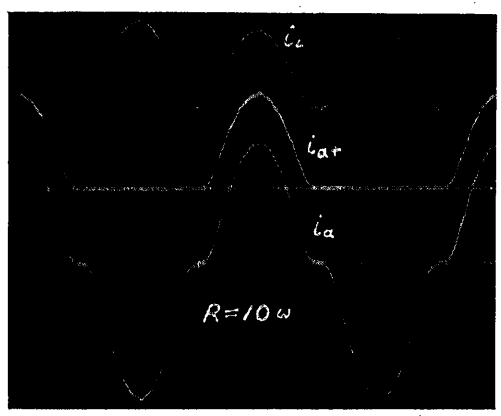
$$K_3 = -\frac{\omega L \phi E_m}{(R+P)^2 + (\omega L)^2}; \quad K_2 = \frac{(R+P)^2 \phi E_m}{(R+P)^2 + (\omega L)^2}$$

For resistance only the equations become

$$i_L = \frac{E_m}{R} \sin\theta, \text{ for perfect rectifier}$$

$$i_L = \frac{\phi E_m}{R+P} \sin\theta, \text{ for constant rectifier}$$

Figures 5 and 6 show the comparison of wave-forms computed from the above formulas, with an observed wave-form obtained from loads of resistance and from resistance and inductance in series. Figure 5*a* shows that the computed forms differ from the observed, but the constant rectifier method gives a much closer approximation than the perfect rectifier, the reason being that the load is of the same order of magnitude as the direct resistance of the rectifier and so the rectifier resistance cannot be neglected. A similar discrepancy will be found if the load is of the same order of magnitude as the inverse resistance of the rectifier, in which case the assumption of infinite resistance is in error.



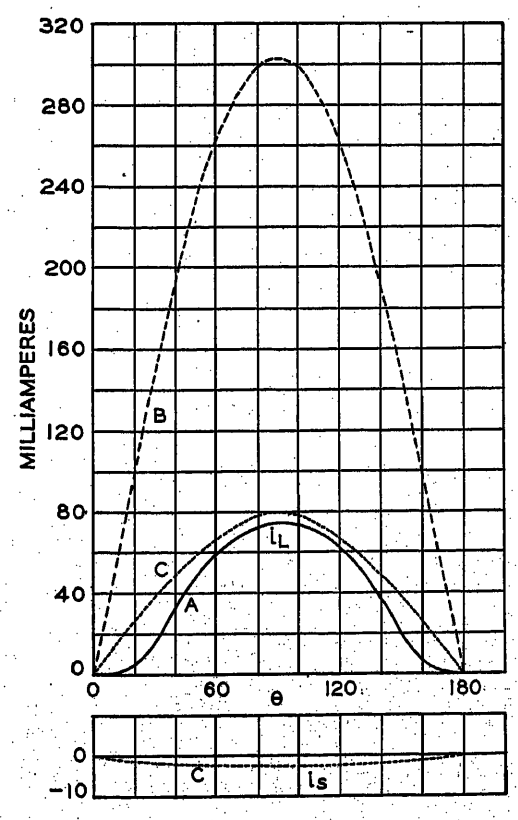




**Fig. 5a. Comparison with typical case of resistance load**

$R$ = 10 ohms,
$E_m$ = 3.1 volts,
$\omega$ = 377
*A*—Oscillogram
*B*—Perfect rectifier
*C*—Constant rectifier

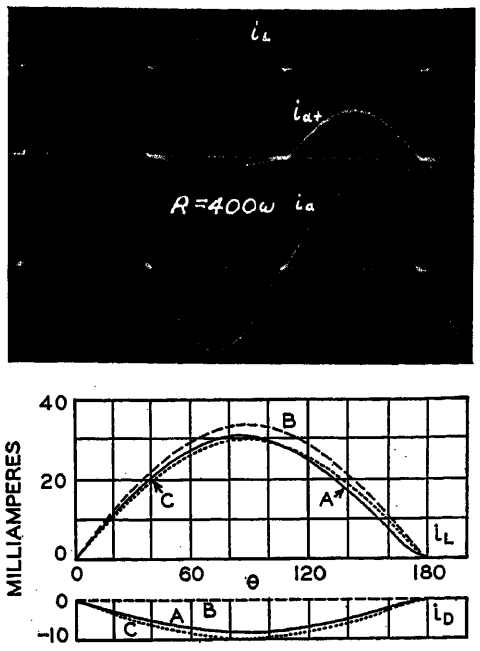



**Fig. 5b. Comparison with typical case of resistance load**

*A*—Oscillogram
*B*—Perfect rectifier
*C*—Constant rectifier
$R$ = 400 ohms,
$E_m$ = 13.7 volts,
$\omega$ = 377

## Circuits That Have Cut-Off

For the group of loads having a cut-off period, the load current tends to become negative at some point in the cycle. The rectifier does not allow this and so a different type of behavior takes place during the rest of the cycle. These loads have 2 or more paths in parallel, one or more of which contain capacitance. A typical circuit of this type is shown in figure 8*a*.

Reference to figure 7 will aid the following discussion. Begin consideration sometime during the conduction period, when the voltage $e$ is the voltage applied to the load, and the circuit follows its normal a-c behavior until $\theta_2$ is reached. At that point the current through leg $D$ reaches zero due to the fact that the condenser discharge becomes sufficient to supply the load.

After $\theta_2$, the current through leg $D$ reverses and legs $ab$ and $dc$ change their characteristic from $D$ to $S$. Legs $bc$ and $ad$ retain their $S$ characteristic since they experience no change in current direction. The circuit is now that for cut-off as shown in figure 8*d*. This cut-off period begins at $\theta_2$, the cut-off angle. Its significance can be most easily seen in the case of a perfect rectifier where $S$ is infinite. At $\theta_2$, the condenser has a charge corresponding to that voltage ($q = CE_m \sin\theta_2$) which must discharge through the resistance path, since the impedance in the outer circuit is infinite, or open circuited. This discharge continues until the voltage across it dies down to the voltage of the next oncoming sine wave, defined

as the cut-in angle at $\theta = \theta_1 + \pi$. At this point the condenser ceases to discharge and again charges according to sine voltage behavior. Thus the conduction period, or normal a-c behavior, continues from $\theta_1$ to $\theta_2$, and the cut-off period, or discharge of condenser, is from $\theta_2$ to $\theta_1 + \pi$.

The discharge path in the constant rectifier case is the resistance branch in parallel with an $S$ combination, shown in figure 8*f*. At $\theta_1$ the legs $ab$ and $dc$ change their characteristic behavior from $S$ to $D$ and at $\theta_2$ change back from $D$ to $S$. Since this change is caused by a reversal of the current through these legs, the current must be equal to zero at the instant of change. But this current is $i_D$. Therefore $\theta_1$ and $\theta_2$ are defined as the values of $\theta$ when $i_D$ equals zero. Since $i_D$ equals zero, it can be seen that $e = e' = e_L$ at $\theta = \theta_1$ and $\theta = \theta_2$. This is a basic fact in solution for the current equations in these circuits.

A uniform procedure in problems of this type is given below and is further illustrated in the circuits following:

1. Set up the differential equation of the circuits for conduction and cut-off periods to obtain the general form of the currents, as well as the exponents of the transient terms.

2. Determine the steady state coefficients using the bridge equation 1 and other usual methods used in circuit analysis, such as parallel relations between the two load branches.

3. Determine the cut-off angle, using the definition that $i_D = 0$. It is necessary to assume that the transient term for the conduction section is zero at cut-off to facilitate solution. This assumption is quite reasonable since $\epsilon^{-a\theta}$ is usually a large damping factor which reduces the transient term to a small quantity by the time $\theta_2$ is reached.

4. Determine the coefficients for the cut-off period using conditions of continuity, voltage equality, or others, at $\theta_2$ and circuit relations during the cut-off period.

5. From conditions existing at $\theta_1 + \pi$ determine the value of the cut-in and the values of the transient term constants. It will be necessary to solve some of these equations by trial since they involve trigonometric and exponential terms.

6. Now knowing the transient term, check back and revise the cut-off angle, if necessary. (The new cut-off solution may be a trial solution.) Then repeat the steps 4 and 5, using the transient term as obtained. Continue until the desired accuracy is reached. Usually the revision produces but minor changes in the values. For simple circuits a graph or table can be set up giving $\theta_2$ and $\theta_1$ for given load conditions.

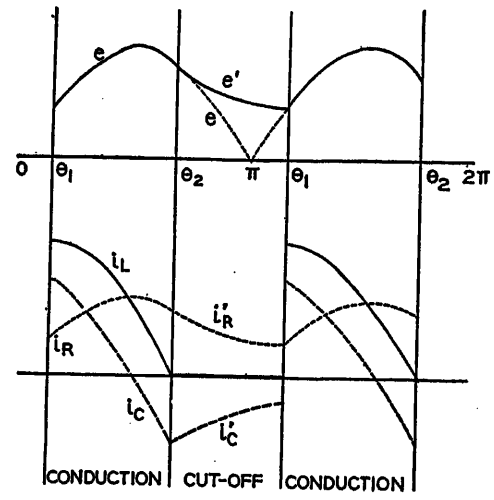
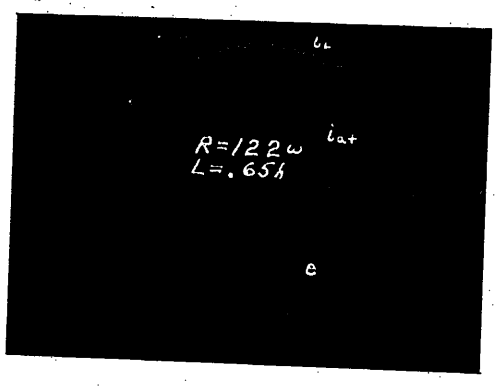



**Fig. 7. Wave forms in a cut-off-circuit**



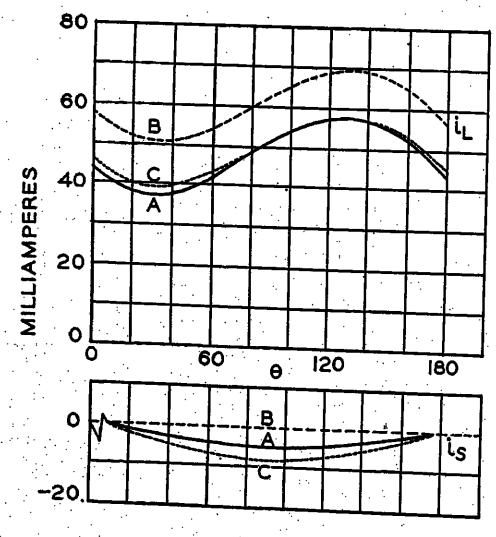




**Fig. 6. Comparison with typical case of resistance and inductance in series**

*A*—Oscillogram
*B*—Perfect rectifier
*C*—Constant rectifier
$R$ = 122 ohms,
$L$ = 0.65 henry,
$E_m$ = 11.6 volts,
$\omega$ = 377

## Load of Resistance and Capacitance in Parallel

The load of resistance and capacitance in parallel is the simplest kind of load that falls into the cut-off group. The method of solving this circuit is outlined and the main equations given.

### Perfect Rectifier

The equivalent circuits for this case are shown in figures 8*b* and 8*e*. The circuit equations for the 2 periods are:

During the conduction period:

$$i_R = \frac{E_m}{R}\sin\theta \quad \text{and} \quad i_C = \omega C E_m \cos\theta$$

During the cut-off period,

$$e' = he^{-b\theta} \quad \text{where} \quad b = \frac{1}{\omega CR}$$

$$i_R' = -i_C' = \omega b h e^{-b\theta}; \qquad i_L' = i_D = i_S = 0$$

When $\theta$ equals the cut-off angle, $\theta_2$, $i_D = 0$ and $e = e'$

$$\tan\theta_2 = \omega RC \quad \text{and} \quad he^{-b\theta_2} = \omega C E_m \sin\theta_2$$

At the cut-in angle for the next half-cycle, $\theta = \theta_1 + \pi$, $e = e'$, also $\sin\theta_1 = (\sin\theta_2)e^{-b(\theta_1+\pi-\theta_2)}$

Knowing the coefficient, $h$, the cut-off and cut-in angles,

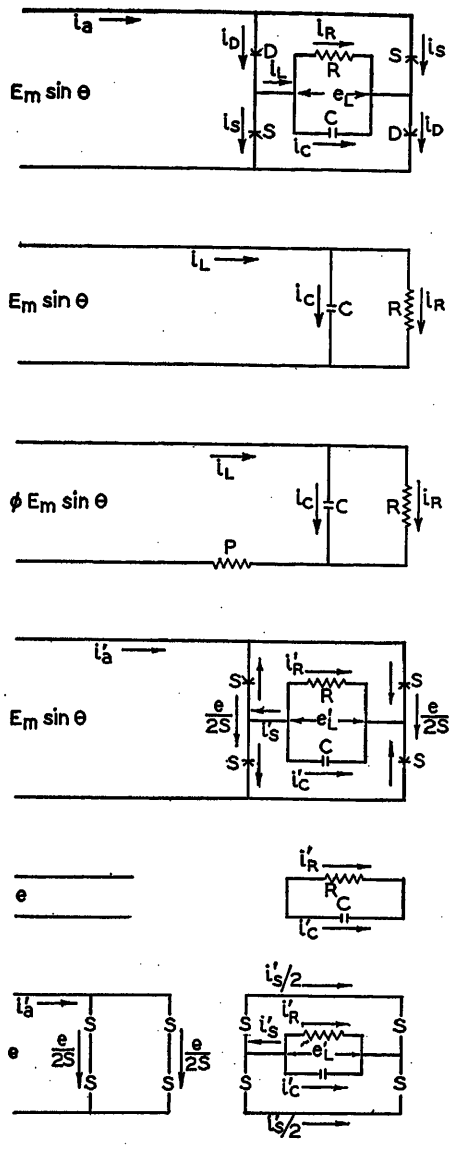



**Fig. 8**

a—Conduction period currents

b—Equivalent circuit for perfect rectifier, during conduction

c—Equivalent circuit for constant rectifier, during conduction

d—Cut-off period currents

e—Equivalent circuits for perfect rectifier, during cut-off

f—Equivalent circuit for constant rectifier, during cut-off

$\theta_2$ and $\theta_1$, the entire circuit behavior is determined for the perfect rectifier.

CONSTANT RECTIFIER

Figure 8*c* again shows the equivalent circuits for this case. The bridge equation 1 for this kind of circuit becomes:

$$e_L = \frac{q}{C} = Ri_R = \phi e - Pi_L$$

during the conduction period. This equation has the solutions

$$q = -\frac{H_1}{\omega a}\epsilon^{-a\theta} - \frac{H_2}{\omega}\cos\theta + \frac{H_3}{\omega}\sin\theta$$

$$i_C = \frac{dq}{dt} = H_1\epsilon^{-a\theta} + H_2\sin\theta + H_3\cos\theta, \text{ where } a = \frac{R+P}{\omega PRC}$$

$$i_R = K_1\epsilon^{-a\theta} + K_2\sin\theta + K_3\cos\theta$$

During cut-off period, see figure 8*f*, the circuit equations are,

$$Ri_R' = Si_S' = \frac{q'}{C}$$

which give

$$q' = h\epsilon^{-b\theta}; \quad i_C' = \omega bh\epsilon^{-b\theta}; \quad i_R' = \frac{h}{RC}\epsilon^{-b\theta}$$

$$i_S' = -i_L' = \frac{h}{SC}\epsilon^{-b\theta}$$

$$b = \frac{R+S}{\omega RCS}$$

$$i_D' = \frac{e}{2S} - i_S'; \quad i_S = \frac{e}{2S} + i_S'$$

Solving for the coefficients results in

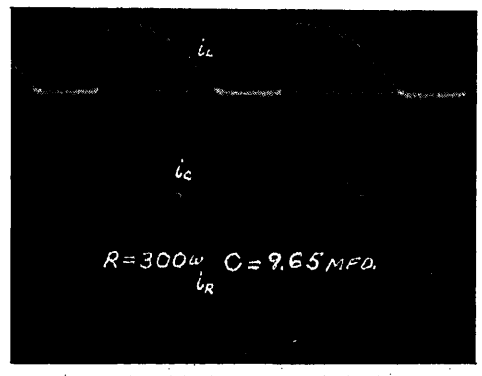
$$H_1 = -\omega aRCK_1; \qquad H_2 = -\omega RCK_3; \qquad H_3 = -\omega RCK_2$$

$$K_2 = \frac{(R+P)\phi E_m}{(R+P)^2 + (R\omega CP)^2}$$

$$K_3 = -\frac{\omega RCPE_m}{(R+P)^2 + (\omega RCP)^2}$$

$$h\epsilon^{-b\theta_2} = CE_m \sin\theta_2$$

Assuming that the transient term, $K_1\epsilon^{-a\theta}$, is zero at $\theta = \theta_2$, due to high rate of decay as mentioned in the



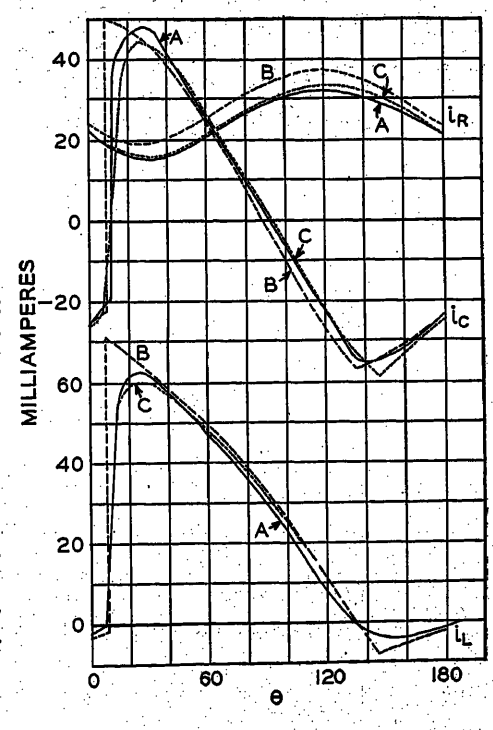




**Fig. 9. Comparison with typical case of resistance and capacitance in parallel**

*A*—Oscillogram

*B*—Perfect rectifier

*C*—Constant rectifier

$R$ = 300 ohms, $C$ = 9.65 microfarads, $E_m$ = 14.1 volts, $\omega$ = 377

method of solution, the condition that $i_D = 0$ at $\theta = \theta_2$, becomes

$$\tan \theta_2 = \frac{\omega RC\,(\phi\, RS)}{(\omega\, RCP)^2 + (R+P)^2 + \phi S(R+P) + \phi SP(\omega RC)^2}$$

which reduces to the perfect rectifier form

$$\tan \theta_2 = -\omega RC$$

for $P = 0$ and $S = \infty$. $H_1$ and $K_1$ can now be determined from the boundary conditions that exist at the cut-in angle, $\theta = \theta_1 + \pi$, namely, $i_D = 0$ and $e' = e_L = e$. Next find $K_1\epsilon^{-a\theta_2}$ to see if further revisions are needed, or if that term is negligible as was assumed in finding $\theta_2$.

Figure 9 shows the relation between the wave-forms observed and those obtained from the equations developed here. The first solution was satisfactory since the transient term became very small at $\theta_2$.

## Load of Capacitance in Parallel With Resistance and Inductance in Series

The solution of more complicated circuits, especially those having cut-off, becomes rather difficult when treated in general form. In a given numerical case the coefficients and exponents can be evaluated as soon as found, thus reducing the length and difficulty of the computations. A common circuit can be obtained by putting inductance in series with the resistance in the previous case. Figure 8 can be likewise modified to fit this case. The method of solving this case for a constant rectifier is outlined here, and the resulting wave-forms compared with an observed wave-form obtained from a typical case, see figure 10.

Set up the differential equations for the circuits and solve them for the general form of the current equations for both conduction and cut-off periods. These will be in the form

$$i_C = H_1\epsilon^{m_1\theta} + H_2\epsilon^{m_2\theta} + H_3 \sin\theta + H_4 \cos\theta$$

$$i_R = K_1\epsilon^{m_1\theta} + K_2\epsilon^{m_2\theta} + K_3 \sin\theta + K_4 \cos\theta$$

$$i_C' = h_1\epsilon^{n_1\theta} + h_2\epsilon^{n_2\theta}$$

$$i_R' = k_1\epsilon^{n_1\theta} + k_2\epsilon^{n_2\theta}$$

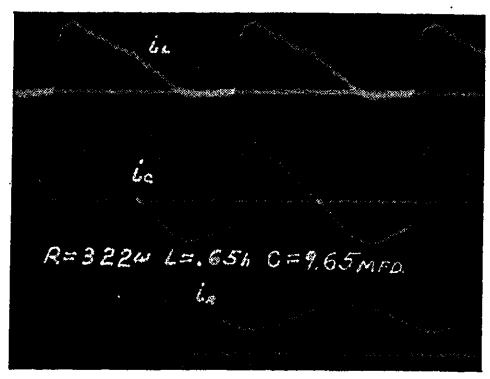
where

$$m = -\frac{R}{2\omega L} + \frac{1}{2\omega PC} \pm \sqrt{\left(\frac{R}{2\omega L} - \frac{1}{2\omega PC^2}\right) - \frac{1}{\omega^2 LC}}$$

$$n = -\frac{R}{2\omega L} + \frac{1}{2\omega SC} \pm \sqrt{\left(\frac{R}{2\omega L} - \frac{1}{2\omega SC}\right)^2 - \frac{1}{\omega^2 LC}}$$

Assuming the transient terms to be zero at $\theta = \theta_2$, and using the condition that $i_D = 0$, the cut-off angle, $\theta_2$, can be determined. The other coefficients can be found by using circuit relations and boundary conditions existing for the problem at hand. Solution of cut-in angle conditions gives the values of $\theta_1$ and the transient term coefficients.

Knowing the transient terms, check back and find a revised $\theta_2$, using the values found above, instead of zero first assumed. If necessary, repeat the computation for the cut-off currents, revising $\theta_1$ and obtaining a second value for the transient terms, and then a third value of $\theta_2$, etc. The number of repetitions necessary depends upon the accuracy desired. For the comparative curves shown in figure 10, 2 revisions were made, but the first produced the greatest change. In many problems it is possible to stop with the first analysis.



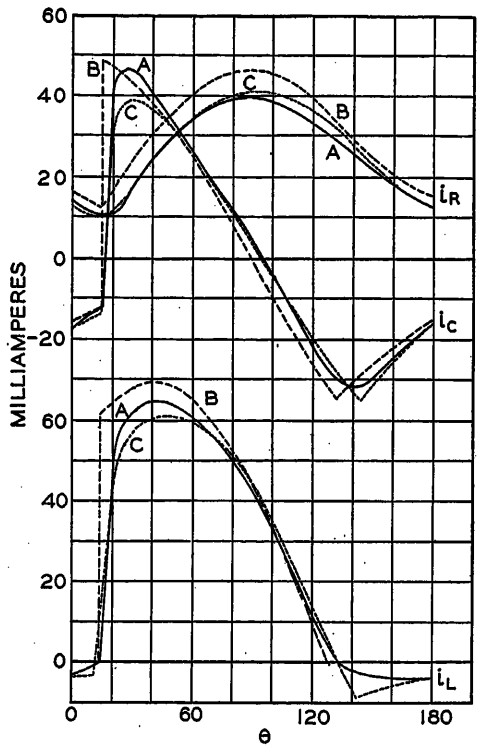




**Fig. 10. Comparison with typical case of resistance and inductance in parallel with capacitance**

*A*—Oscillogram
*B*—Perfect rectifier
*C*—Constant rectifier
$R$ = 322 ohms, $L$ = 0.65 henry, $C$ = 9.65 microfarads, $E_m$ = 14.2 volts, $\omega$ = 377

## Conclusion

This paper has presented a useful method of analyzing the behavior of copper-oxide rectifier circuits. The varying resistance characteristic of the rectifier element is replaced by 2 constant resistances, $D$, effective for direct flow, and $S$, effective for inverse flow. This approximate representation of the rectifier is called the "constant rectifier."

This approach gives solutions of a highly satisfactory degree of accuracy. Under certain load conditions, there

(*Concluded on pages 366–67*)

# Effect of Varying Weather Conditions on Energy Required for Traction and Heating of Multiple-Unit Trains

By H. E. PRESTON
NONMEMBER AIEE

THE HEATING of passenger cars electrically together with the additional energy required for traction purposes when cold weather prevails cause increases in operating expenses which are of great importance on the Illinois Central Railroad where power is purchased.

This article deals primarily with the experience of the Illinois Central in operating its electrified suburban service in Chicago during the past 9 years.

Before discussing the accompanying curves which are based on average conditions a brief summary of weather conditions in Chicago and data on the Illinois Central equipment follows.

The daily range of temperature for Chicago is 14 degrees between normal maximum and normal minimum temperatures. The record minimum is −23 degrees and the record maximum is 105 degrees.

The average temperatures for the past 64 years are as follows:

| Jan. | Feb. | Mar. | Apr. | May | June | July |
|---|---|---|---|---|---|---|
| 24.5 | 26.6 | 35.7 | 47.1 | 57.4 | 67.6 | 72.7 |
| **Aug.** | **Sept.** | **Oct.** | **Nov.** | **Dec.** | **Year** | |
| 71.6 | 65.3 | 53.8 | 40.2 | 29.0 | 49.3 | |

The average hourly velocity of the wind in all directions is 11 miles per hour.

The average number of days during the year when the minimum temperature is 32 degrees or below is 108.

The average number of days during the year when the minimum temperature is 0 degrees or below is 8.

During the past 9 years there have been approximately 210 days each year when heating was used on the cars for at least a portion of the day.

There are 280 cars in multiple unit service. All of the cars are heated with electric heaters of the enclosed element type, operating on 1,500 volts direct current, and equipped with thermostatic control set to maintain a temperature of 56 degrees Fahrenheit. The cars have approximately 4,500 cubic feet of air space and seat 84 passengers. Each car is equipped with 29,500 watts in heaters located under the rattan-covered seats. The motorman's cab is equipped with a 3,000-watt heater. The cars are insulated with hairfelt under the composition floors and 3-ply Salamander applied to the sides and roof sheets. Ventilation is provided by monitor sash ventilators.

During the past 9 years there has been an average of 495 scheduled trains daily except Sundays and holidays, and there has been operated an average of 824,000 car miles per month.

The average distance between stops including all classes of service is approximately 0.96 mile.

During the winter season of 1933 a unit of the equipment, comprising a motor car and a trailer car, was equipped with graphic meters which recorded the operations of the heating relay and the current in the traction motors. Integrating meters were also installed on this unit to measure separately the energy used by the traction motors, the air compressor motor, the motor generator set, and the heater circuits. This specially equipped unit was operated in regular service similar to any of the other equipment and a record kept of the meter readings at the conclusion of each trip together with other pertinent data such as, the class of service rendered by the train, the weather conditions and the position of the cars in the train when consisting of more than 2 cars. Personal observations were made at various times to enable an accurate interpretation of the meter readings to be made.

The energy used for traction will be considered for the purposes of this article as including in addition to the energy used by the motors and their control equipment, the total line loss between substations and trains, the energy used by the air compressors, the energy used by the motor generators on the cars which charge the batteries and supply the lighting circuits, and all other d-c output from the substations excepting energy used for heating of the cars.

The relation between average kilowatt-hours per car mile and temperature is shown in curve *A* of figure 1 and was drawn from the d-c substation output load records combined with a daily record of the movement of the cars including the car miles operated.

From the information obtained in the above manner it was found that the increase in kilowatt-hours per car mile over the summer requirement commenced at approximately 60 degrees and between 60 and 45 degrees the increase was due entirely to the heating in the cars. In the kilowatt-hours per car mile-temperature curve it will be noted that at 60 degrees the consumption is 4.30 kilowatt-hours per car mile and at 45 degrees it is 4.73 kilowatt-hours per car mile. For this range of temperature of 15 degrees the difference in consumption is 0.43 kilowatt-hour per car mile and the curve is a straight line. This difference is equivalent to an increase of 0.0286 kilowatt-hour per car mile per degree due to the heating of the cars.

Daily records of the train operations included total car miles operated during the morning and evening peak demand hours and also the length of time the cars were in service during these hours, which gave the total number of "car hours" in service. From this information it was found that with the heaters on continuously the maximum

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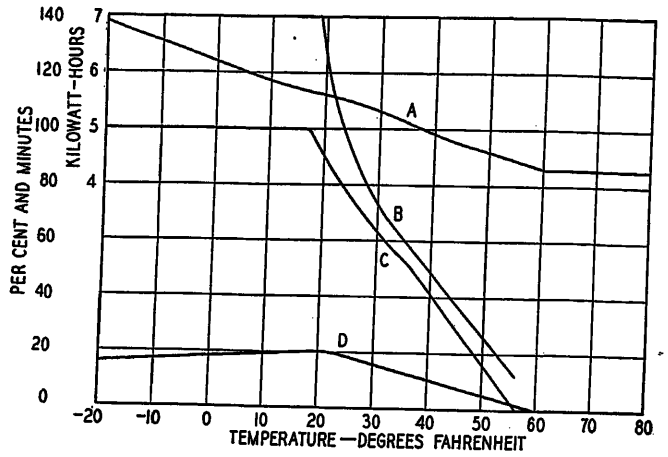



**Fig. 1. Curves showing effect of temperature on train heating and traction requirements in suburban service of the Illinois Central system**

*A*—Average kilowatt-hours per car mile

*B*—Average time in minutes elapsed before thermostat opens heater circuit when heating a cold car in storage yards

*C*—Per cent of time heater circuit is closed for trains in service and handling passengers

*D*—Per cent of the total energy consumption due to heating in the cars

possible heating that can be used would increase the consumption 1.13 kilowatt-hours per car mile over the consumption when no heat was being used.

Dividing this maximum possible heating of 1.13 kilowatt-hours per car mile by the increase of 0.0286 kilowatt-hour per degree of temperature obtained above we get a range of temperature of 40 degrees during which the energy for the heating of the cars increases. This increase is at the rate of 0.67 per cent per degree between 60 and 20 degrees. As the heating of the cars commences at approximately 60 degrees this means that at 20 degrees the energy required for heating is constant and at the maximum amount possible.

Curve *C* shows the per cent of the time the heater circuits are closed on trains in service and handling passengers after the cars have been heated previously a sufficient length of time to operate the thermostat if the weather conditions permit. This curve was drawn from the meter records obtained from the specially equipped unit and it will be noted that at approximately 17 degrees the heaters are on continuously.

The above statements regarding heating apply to cars in service.

It has been the practice on the Illinois Central to start heating the cars approximately one hour before departure from storage yards when the temperature is below freezing, and when the weather is more severe this preheating time is increased. When the temperature is colder than 10 above zero it has been found desirable to have the heat on continuously.

The energy required to heat the cars prior to their departure from the storage yards increases materially the average kilowatt-hours per car mile on days when the temperature is below freezing.

Curve *B* shows the elapsed time in minutes between the time the heat is turned on in a cold car standing in the storage yards until the thermostat operates to open the heater circuit.

The ventilation provided in the cars affects the energy consumption necessary for heating. The number of changes of air per hour in the cars is determined by the number of ventilators opened together with the frequency of stops requiring opening of the car doors. It is customary to provide more ventilation in smoking cars than in other cars in the train by opening more ventilators. In colder weather patrons remain inside the heated shelters provided on the elevated platform until the doors of the trains are opened causing congestion by not entering doors of the train farther away from the shelters. This causes longer loading and unloading time at stations which increases the length of time the doors are opened and resulting in the heat being dissipated more quickly.

Considering the heat emitted by the passengers themselves as it affects the energy consumption for heating the cars no definite conclusion could be arrived at. The indications are that the more passengers handled the more often the vestibule and diaphragm doors are opened by the passengers walking from one car to another which increases the ventilation in the cars and offsets the heat gained from the passengers themselves.

At temperatures below freezing it is noticeable that a majority of the passengers will close the doors between the vestibule and the body of the car, whereas, at more moderate temperatures these doors remain opened. This reduces slightly the percentage of the time the heat would be on at temperatures below freezing were these doors not closed and accounts for curve *C* not being a straight line.

After a car has been heated to a maximum according to the prevailing temperature there is considerable heat stored in the heaters themselves as well as other metal parts of the cars. To derive the maximum benefit from this stored heat the operating instructions to the trainmen provide for pulling the heater circuit switches in all cars at specified points before arriving at terminals on those trains that are to be tied up in storage yards. It has been found that no inconvenience is experienced in pulling heater switches from 15 to 20 minutes before arrival at destination. The economy resulting from this practice is worth while especially where it reduces the demand charges.

Referring to curve *A* it will be noted that the summer requirement is constant at 4.3 kilowatt-hours per car mile and starting at 60 degrees the consumption increases in a straight line at the rate of 0.67 per cent per degree to a temperature of 45 degrees due entirely to heating in the cars. Colder than 45 degrees the rate of increase is greater than that required for heating alone, until at 20 degrees above zero the total increase over the summer requirement is 1.3 kilowatt-hours per car mile as compared to a maximum possible increase due to heating alone of 1.13 kilowatt-hours per car mile. This additional increase or difference of 0.17 kilowatt-hour per car mile is due to the fact that these lower temperatures are experienced during

(*Concluded on page 366*)

# The Capacitance of a Parallel-Plate Capacitor by the Schwartz-Christoffel Transformation

By HARLAN B. PALMER
MEMBER AIEE

AN EXACT method of calculating the capacitance of a parallel-plate air condenser, taking into account its fringing effect, has been suggested by J. J. Thomson[1] and more completely worked out by A. E. H. Love.[2] The purpose of this paper is to promote familiarity with this mathematical technique by making it more readily accessible to American engineers. In addition to the exact method, a number of approximate methods are included.

The capacitance of a condenser consisting of a single pair of very long parallel plates in air is usually calculated by the formula

$$C = \frac{w}{4\pi d} \text{ statfarads per centimeter} \qquad (1)$$

This formula neglects the fringing of the flux and the flux which passes between the back sides of the plates, and consequently the true value may be several thousand per cent greater than indicated. An error of this magnitude would occur, for example, if equation (1) were applied to a pair of very long thin rectangular bus bars separated by many times their width.

## The Schwartz-Christoffel Transformation

The general problem of mapping polygons was first investigated by Schwartz[3] and Christoffel.[4] Since numerous explanations of this general method are available in English,[5,6] only a brief outline will be included here.

In the map of any electric field, the flux and potential lines intersect each other at right angles and, if the scales of flux and potential are made equal, the areas formed by the 2 families of intersecting lines are so-called curvilinear squares. If the field map, originally plotted in a complex plane $Z$, is replotted in a complex plane $W$, where $W$ is any analytic function of $Z$, the orthogonal intersections and curvilinear squares will be preserved. The Schwartz-Christoffel transformation consists of finding that particular functional relationship between $Z$ and $W$ which makes the transformed areas true straight-sided squares. In other words, the change of variable has the effect of warping the original boundary conditions or electrodes (between which the flux and potential lines are unknown curves) into new boundary conditions (between which the flux and potential lines are uniformly spaced straight lines) without changing the capacitance. The Schwartz-Christoffel transformation does not determine $Z = f(W)$ directly, but first determines both $Z$ and $W$ as functions of an auxiliary variable $\zeta$.

$$Z = f_1(\zeta) \qquad (2)$$

$$W = f_2(\zeta) \qquad (3)$$

In some cases it is possible to eliminate $\zeta$ between equations (2) and (3). In other cases the relation between $Z$ and $W$ must be kept in parametric form.

## $Z$ Plane

The ($Z = x + jy$) plane, in which the given boundaries of the parallel-plate condenser are plotted, is shown in figure 1*a*. The Schwartz-Christoffel transformation applies only to those 2-dimensional field problems whose boundaries are the straight sides of a polygon. The boundaries of this problem consist of the 2 plates which are equipotential surfaces, the zero flux line passing between the centers of the inside surfaces of the plates, and the maximum flux line passing (through $\infty$) between the centers of the back sides of the plates. This figure, resembling a double cross, is virtually a polygon whose sides have collapsed until they are contiguous, as examination of the slightly expanded view in figure 1*b* will reveal.

## $\zeta$ Plane

The auxiliary ($\zeta = \xi + j\eta$) plane is shown in figure 2. Due to symmetry, only the right-hand half of the $Z$ plane and the upper half of the $\zeta$ plane need be considered. The 6 vertices of the $Z$ polygon (lettered *a*, *b*, *c*, *d*, *e*, *f*) may be

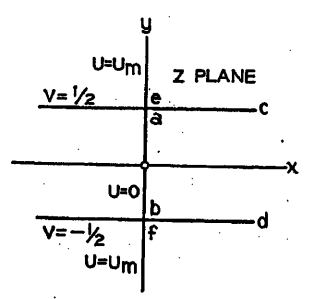



Fig. 1a

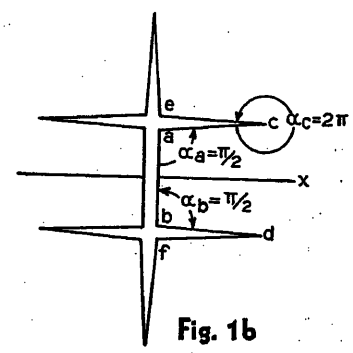



Fig. 1b

transformed into the similarly lettered points on the $\xi$ axis of the $\zeta$ plane. Furthermore the extremities of the $y$ axis become the extremities of the $\xi$ axis. Thus the problem has been resolved into finding the capacitance between 2 plates (shown by heavy lines *a-c-e*, and *f-d-b* in figure 2) lying in the same plane and having widths of $(1/k - 1)$ and being separated a distance of $(1/k + 1)$, center to center.

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1. For all numbered references, see list at end of paper

## W Plane

The $(W = U + jV)$ plane is shown in figure 3 and has co-ordinates $U$ (representing flux) and $V$ (representing potential). The area plotted in this plane is a rectangle bounded by the sides $(V = {}^1/_2)$, $(V = -{}^1/_2)$, $(U = U_m)$, and $(U = -U_m)$. Thus the problem has been further resolved into finding the capacitance of an equivalent parallel-plate condenser (shown by the heavy lines of figure 3) in which fringing is absent and all of the flux

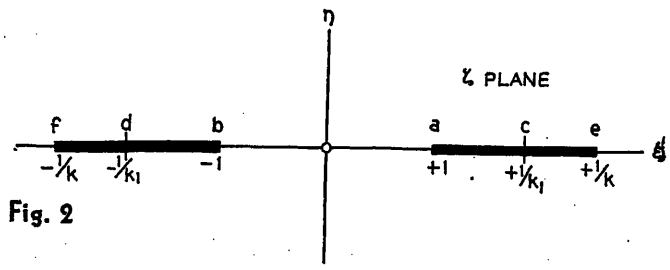



Fig. 2

passes with uniform density between the inside surfaces of the plates. Hence equation (1) may be applied. Since the capacitance of this equivalent condenser depends only upon the ratio $R$ of plate width to plate separation, the separation (equal to potential since the potential gradient is uniform) has been arbitrarily chosen as unity, while the width or $R$ (equal to flux) is as yet undetermined.

## Transformation Equations

The functional relationship transforming the vertices of any polygon in one complex plane into specified points all on one axis of another complex plane may be found by solving equation (4).

$$Z = A\int[(\zeta - \xi_a)^{m_a}(\zeta - \xi_b)^{m_b}(\zeta - \xi_c)^{m_c} \dots (\zeta - \xi_n)^{m_n}]d\zeta \qquad (4)$$

The $\xi_n$'s are the co-ordinates of the $n$ points into which the $n$ vertices are to be transformed. The exponents $(m_n)$ are given by $m_n = (\alpha_n/\pi) - 1$, where the $\alpha_n$'s are the angles of the polygon to be transformed. See figure 1*b*.

Transforming from $Z$ to $\zeta$ and referring to figures 1*a*, 1*b*, and 2,

$\xi_a = 1$ $\quad m_a = (\pi/2\pi) - 1 = -{}^1/_2$

$\xi_b = -1$ $\quad m_b = (\pi/2\pi) - 1 = -{}^1/_2$

$\xi_c = 1/k_1$ $\quad m_c = (2\pi/\pi) - 1 = 1$

$\xi_d = -1/k_1$ $\quad m_d = (2\pi/\pi) - 1 = 1$

$\xi_e = 1/k$ $\quad m_e = (\pi/2\pi) - 1 = -{}^1/_2$

$\xi_f = -1/k$ $\quad m_f = (\pi/2\pi) - 1 = -{}^1/_2$

$$Z = A'\int\frac{(\zeta^2 - 1/k_1^2)d\zeta}{\sqrt{(\zeta^2 - 1/k^2)(\zeta^2 - 1)}}$$

This is an elliptic integral and may be treated by formula 569, reference (7) to give the result,

$$Z = A[k_1^2E(\phi,k) - (k_1^2 - k^2)F(\phi,k)] + C$$

The arbitary constants $A$ and $C$ may be evaluated by inserting the boundary conditions,

$Z = 0$ when $\zeta = \sin\phi = 0$; therefore $C = 0$

$Z = \pm j$ when $\zeta = \sin\phi = \pm 1$; therefore $A = \dfrac{j}{k_1^2E - (k_1^2 - k^2)K}$

$$Z = j\frac{k_1^2E(\phi,k) - (k_1^2 - k^2)F(\phi,k)}{k_1^2E - (k_1^2 - k^2)K} \qquad (5)$$

Inserting in equation (5) the additional boundary condition,

$Z = 0 \pm j$ when $\zeta = \sin\phi = \pm 1/k$

the relation, $k_1^2 = k^2K'/E'$ results.

For the evaluation of elliptic integrals having upper limits greater than 1, see reference (8), page 43.

Inserting in equation (5) the final boundary condition,

$Z = R \pm j$ when $\zeta = \sin\phi = \pm 1/k_1$

the relation

$$R = \frac{K'E'(\beta,k) - E'F'(\beta,k)}{(E' - K')K + K'E} \qquad (6)$$

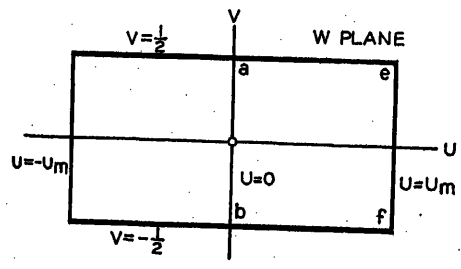
results

where

$$\sin^2\beta = \frac{K' - E'}{K'(1 - k^2)}$$

The combination of complete elliptic integrals in the denominator of equation (6) is identically equal to $\pi/2$, being the celebrated formula of Legendre. For a given value of the ratio $R$ it is impossible to determine $k$ except by trial and error. Values of $R$ have been calculated for

Fig. 3



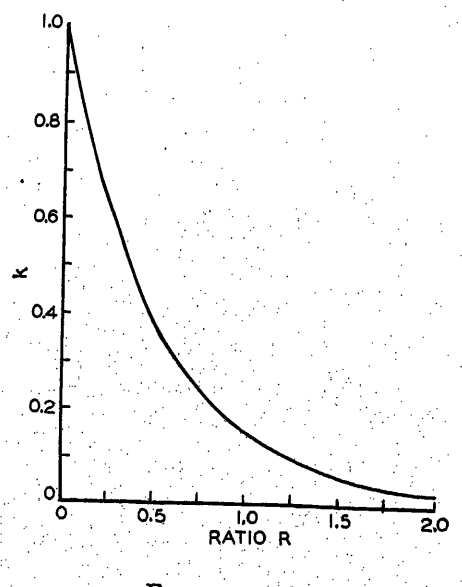




Fig. 4. Equation 6

many values of $k$ between 0.02365 and 1.0 with the results shown graphically in figure 4.

The transformation equation from $Z$ to $\zeta$ becomes, after evaluating all constants except $k$ which can only be expressed implicitly as in equation (6),

$$Z = j\,2/\pi\,[K'E(\phi,k) - (K' - E')F(\phi,k)] \tag{7}$$

Transforming from $W$ to $\zeta$ and referring to figures 2 and 3,

$\xi_a = 1$ $\qquad m_a = (\pi/2\pi) - 1 = -1/2$

$\xi_b = -1$ $\qquad m_b = (\pi/2\pi) - 1 = -1/2$

$\xi_e = 1/k$ $\qquad m_e = (\pi/2\pi) - 1 = -1/2$

$\xi_f = -1/k$ $\qquad m_f = (\pi/2\pi) - 1 = -1/2$

$$W = B' \int \frac{d\zeta'}{\sqrt{(\zeta^2 - 1/k^2)(\zeta^2 - 1)}}$$

$$W = BF(\phi,k) + C$$

Inserting the boundary conditions,

$W = 0$ when $\zeta = \sin\phi = 0$; therefore, $C = 0$.

$W = \pm j^{1/2}$ when $\zeta = \sin\phi = \pm 1$; therefore, $B = j/2K$

$$W = j\,\frac{F(\phi,k)}{2K} \tag{8}$$

Eliminating ($\zeta = \sin\phi$) between equations (7) and (8),

$$Z = 2/\pi\,[2(E' - K')KW + jK'E(am - j2KW,k)] \tag{9}$$

## Calculation of Capacitance

Corresponding to the given ratio $R$ of plate width to plate separation, determine the modulus $k$ from figure 4.

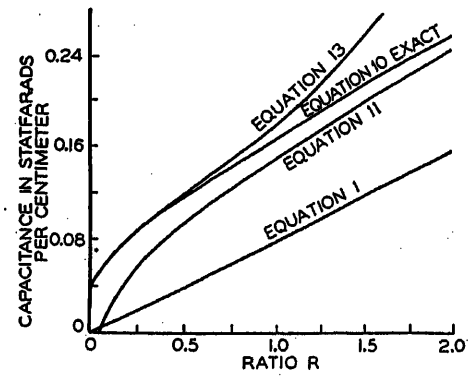



Fig. 5

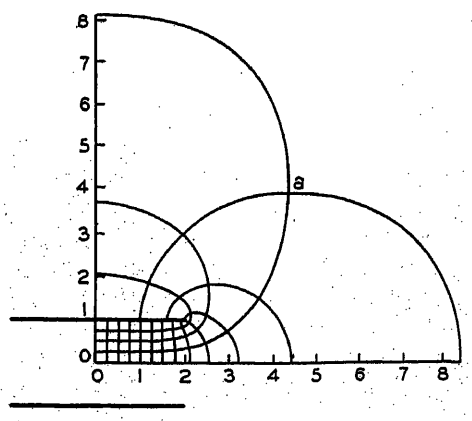



Fig. 6. Map of electric field of parallel-plate capacitor

From a table of elliptic integrals[7,9] determine the complete elliptic integral $K$ and the complementary elliptic integral $K'$.

Since the 2 axes drawn through the origin in figure 3 represent the zero-potential and zero-flux lines respectively, the point $e$ represents half of the total flux and half of the potential difference between plates. The value of $\zeta$ corresponding to point $e$ is $1/k$, and $\phi = \sin^{-1} 1/k$. Substituting this value of $\phi$ in equation (8),

$$W = U + jV = j\,\frac{K - jK'}{2K}$$

$$\begin{aligned} U_m &= K'/2K \\ V &= 1/2 \\ C &= U/4\pi V \\ C &= K'/4\pi K \end{aligned} \tag{10}$$

For example: when

$$\begin{aligned} R &= 2 \\ k &= 0.02365 = \sin 1.355 \text{ degrees} \\ k' &= 0.99972 = \sin 88.645 \text{ degrees} \\ K &= 1.571 \\ K' &= 5.131 \\ C &= 0.2599 \text{ statfarad per centimeter} \end{aligned}$$

By equation (1)

$C = 0.1592$ statfarad per centimeter

## Approximate Formulas

1. For very large values of $R$, there is an approximate formula due to Bromwich and given by Love,[2] as follows:

$$C = R/4\pi[1 + (1/\pi R)(1 + \log 2\pi R)] \tag{11}$$

For a value of $R = 2$, $C = 0.2486$ which is only 4.35% low.

2. Maxwell[11] obtained a result which is quite similar to equation (11) by using condenser plates of semi-infinite extent and investigating the field in the vicinity of the finite ends. This simplifies the transformation from $Z$ to $W$ by eliminating the 4 polygonal right angles at $a$, $b$, $e$, and $f$ in figure 1$a$ and substituting a zero polygonal angle where the plates meet at infinity. Maxwell's result, making certain other simplifications which are justified for large values of $R$, is as follows:

$$C = R/4\pi\{1 + (1/R\pi)\,[1 + \log\,(1 + \pi R)]\} \tag{12}$$

3. It has been found that for small values of $R$ (less than one), the capacitance of a parallel-plate condenser is approximately the same as for 2 round conductors having diameters of $1/2$ the plate widths and being separated center to center, by the same amount as the separation between the plates. The capacitance in this case is given by

$$C = \frac{1}{4\,\log\,(4/R)} \tag{13}$$

Although no mathematical justification for equation (13) has been discovered, it has been checked against the exact equation at many points and found to be surprisingly accurate.

Capacitances of parallel-plate condensers, for values of $R$ less than 2, have been calculated from equations (1), (10), (11), and (13). The results are shown in figure 5.

## Field Map

The Schwartz-Christoffel transformation, in addition to supplying an exact method for the calculation of the capacitance of a parallel-plate condenser, makes it possible to map the entire electric field. One quadrant of the field map, for $R = 2$, is shown in figure 6. The points of intersection of the flux and potential lines were calculated from equation (9). The increment for both flux and potential is $^1/_8$. There are 4 potential tubes and approximately 13 flux tubes, making the capacitance

$$C = \frac{13}{(4\pi)\ 4} = 0.2599 \text{ statfarad per centimeter.}$$

Any intersection such as point "$a$" in figure 6 may be calculated as follows:

$k$ = 0.02365 (See figure 4)
$k'$ = 0.99972
$K$ = 1.571018
$K'$ = 5.131306
$E$ = 1.570579
$E'$ = 1.001295
$U$ = $U_m - 1/8 = K'/2K - 1/8$ = 1.50812
$V$ = 1/8
$F(\phi,k)$ = $0.3927 - j4.7386$ (equation 8)
$F(\phi,k)$ = $0.3927 + j0.3927 - jK'$

$$\sin\phi = \frac{1}{ksn\ (0.3927 + j0.3927)} \qquad sn\ (u \doteq jK') \equiv \frac{1}{k\ sn(u)}$$

$\sin\phi$ = $56.5048 - j50.9732$ reference (10) equation 760.1
$E(\phi,k)$ = $1.5375 - j5.1456$ reference (8) pages 33, 34, 83
$Z$ = $4.37 + j3.99$ equation (9)

## Symbols Used in This Paper

$C$ = capacitance
$w$ = semiplate width
$d$ = semiplate separation
$R$ = ratio of plate width to plate separation
$Z,W,\zeta$ = complex variables
$x,y$ = co-ordinates of $Z$
$U$ = co-ordinate of $W$ denoting flux
$V$ = co-ordinate of $W$ denoting potential
$\xi,\eta$ = co-ordinates of $\zeta$
$A,A',B,B',C$ = constants of integration
$\alpha_n$ = angle of polygon in $Z$ plane
$a,b,c,d,e,f$ = vertices of polygon in $Z$ plane
$k_1$ = arbitrary constant
$k$ = modulus of ellipitc integrals
$k'$ = complementary modulus = $\sqrt{1 - k^2}$
$sn\ u$ = elliptic function
$F(\phi,k)$ = elliptic integral of first kind
$E(\phi,k)$ = elliptic integral of second kind
$K$ = complete elliptic integral of first kind
$E$ = complete elliptic integral of second kind
$K'$ = complete complementary integral of first kind
$E'$ = complete complementary integral of second kind.

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## Effect of Weather Conditions on Energy Required for Multiple-Unit Trains

(*Continued from page 362*)

the winter months when due to reduced hours of daylight an increased amount of lighting is used in the cars, the air compressors also do more work as the temperature lowers and in addition to this is the fact that inclement weather increases the standing time at stations requiring more traction energy to be used to maintain schedules.

Between 45 and 20 degrees the increase in kilowatt-hours per car mile due to traction which includes all auxiliaries, etc., other than heating appeared to be made up entirely of the above mentioned causes and there was little indication that increased bearing friction or wheel flange resistance entered into it.

Proceeding along the curve $A$ it may be assumed that at temperatures below 20 degrees any further increase in kilowatt-hours per car mile is due to traction and auxiliaries other than heating. Commencing at 20 degrees and colder the traction energy increases at the rate of 0.75 per cent per degree expressed as a per cent of the summer requirement.

Assuming that the energy required for heating increases at a uniform rate to the point where it is constant and at a maximum, the per cent of the total energy consumed which is due to heating may be calculated and this result is plotted as curve $D$. The difference between curve $D$ and 100 per cent is the percentage of the total energy used for traction and auxiliaries other than heating.

## An Analysis of Copper-Oxide Rectifier Circuits

(*Continued from page 360*)

is noticeable departure in wave form between the real rectifier and the approximation, as shown by the non-sinusoidal shape in figure 5*a*. However, in these cases, the assumption of a constant rectifier is a decided improvement over that of a perfect rectifier.

An equivalent circuit was established for this constant rectifier and its application to various types of loads discussed. A few standard circuit analyses were presented and the resulting computed wave-forms compared with observations. Thus this paper presents a method of obtaining the current forms present in a rectifier circuit,

which yields better results than the perfect rectifier idealization and yet is not much more difficult to use. By using the equivalent circuit as developed in equation 1 and shown in figures 4 and 8, the series method outlined by Stout[6] can be applied to the constant rectifier circuits.

## List of Symbols

$D$ = equivalent rectifier resistance to current in the direction $Cu_2O$ to Cu
$S$ = equivalent rectifier resistance to inverse currents
$P = \frac{2DS}{D+S}$, analogous circuit constants to replace constant rectifier in determining $i_L$
$\phi = \frac{S-D}{S+D}$
$Z_O$ = impedance of bridge with d-c terminals open
$Z_S$ = impedance of bridge with d-c terminals shorted
$e$ = $E_m \sin \theta$, applied voltage, ($\theta = \omega t$)
$e_L$ = load voltage during conduction
$e'$ = load voltage during cut-off
$q$ = condenser charge during conduction
$q'$ = condenser charge during cut-off
$i_L$ = $i_R + i_C$ total load current during conduction
$i_R$ = resistance branch current during conduction
$i_C$ = condenser branch current during conduction
$i_L'$, $i_R'$, $i_C'$ = currents during cut-off
$i_D$ = current through bridge leg acting as $D$
$i_S$ = current through bridge leg acting as $S$
$i_S'$ = current through bridge legs due to $e'$
$i_a$ = total line current

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# Discussions

## Of AIEE Papers—as Recommended for Publication by Technical Committees

ON THIS and the following 3 pages appear discussions submitted for publication, and approved by the technical committees, on papers presented at the general technical sessions of the AIEE South West District meeting Dallas, Texas, October 26–28, 1936. Authors' closures, where they have been submitted, will be found at the end of the discussion on their respective papers.

Members anywhere are encouraged to submit written discussion of any paper published in Electrical Engineering, which discussion will be reviewed by the proper technical committee and considered for possible publication in a subsequent issue. Discussions should be submitted to C. S. Rich, secretary, technical program committee, AIEE headquarters, 33 West 39th Street, New York, N. Y.

## A Disturbance Duration Recorder

**Discussion of a paper by C. H. Frier published in the September 1936 issue, pages 1025–8, and presented for oral discussion at the general technical session of the AIEE South West District meeting, Dallas, Texas, October 26, 1936.**

R. K. Honaman (Bell Telephone Laboratories, Inc., New York, N. Y.): Mr. Frier's paper offers an ingenious scheme for making a record of time durations of the order of magnitude of those ordinarily involved in voltage surges. As the author has pointed out, the ability to measure and record intervals of the order of magnitude of a few cycles to a few seconds is, particularly in certain cases, very desirable. It may be of interest, therefore, to present an alternative method for making such records which engineers interested in this problem might find helpful.

The possibility of initiating the operation of the recorder by means of an electron tube control instead of the contact-making voltmeter is one which suggests itself and is recognized by the author in the paper. Such a device would have the advantage not only of additional speed in operation to avoid part of the delay of 1 to 3 cycles inherent in the contact-making voltmeter, but also would be more rugged.

An arrangement for accomplishing this could be set up by means of tubes rectifying the 60-cycle current from the power line using the d-c output against a bias to trigger an electron tube with a relay in the anode circuit. Such an arrangement would necessitate the use of a resetting circuit for the tube but means of accomplishing this are available. A vacuum tube with a marginal relay operating in its plate circuit has also been suggested.

In the recording of the duration itself, another scheme, the principle of which has been suggested by Mr. L. K. Swart, is worth consideration. This depends upon the relationship between the voltage across the terminals of a condenser and the time during which the condenser has been charged. The practical working out of the suggestion is accomplished by having the initiating device, whether it be a contact-making voltmeter or electron tube trigger arrangement, connect a capacitor of appropriate size in series with a charging battery and a resist-

ance at the beginning of the period whose duration is to be measured. The size of the capacitor and the resistance and the voltage of the battery are so proportioned that the condenser will not be fully charged for the maximum interval to be measured. At the end of the interval the capacitor is disconnected from this circuit and switched by means of a relay to the grid of a high-impedance vacuum tube, in the plate of which is inserted a graphic voltmeter. The leakage can be made sufficiently small so that the graphic voltmeter swings to a point corresponding to the voltage of the capacitor which, in turn, bears a definite relation to the time interval during which it has been charged. Thus the graphic meter can be made to indicate the time at which the surge took place and by means of its deflection, the duration of the disturbance. The deflection would be calibrated in units of time. By means of electron-tube circuits and fast relays the delay in connecting and disconnecting the capacitor and the charging circuit can be made as low as the order of $^1/_2$ cycle (0.008 second).

If, in such an arrangement the charged capacitor were left connected to the grid of the low-leakage vacuum tube, the graphic meter would continue to read for a considerable period, this reading falling off slowly as the leakance of the circuit discharged the condenser. This falling off can be made so slow that the voltage will be reduced only a negligible amount in a minute. It is only necessary to maintain the charge long enough to permit the graphic meter to record the deflection, and relay circuits would be arranged to short circuit the capacitor after a sufficient interval has elapsed to give a satisfactory deflection. This interval can be arranged to suit the characteristics of the graphic meter itself.

It should be noted that the ability of this instrument to measure successive surges would depend upon the rate at which the graphic meter chart is moved. It could not differentiate between surges closer together than the time interval required to move the paper a distance sufficient to separate the pen traces.

## Electrical Features of the Texas Centennial Central Exposition

**Discussion and author's closure of a paper by John Fies published in the October 1936 issue, pages 1060–74, and presented for oral discussion at the general technical session of the AIEE South West District meeting, Dallas, Texas, October 26, 1936.**

**C. M. Cutler** (nonmember; General Electric Company, Cleveland, Ohio): The architecture is modern in character but still reflects some of the feeling of the old Spanish missions of Texas. The texture of the wall surfaces is similar. The effect depends principally upon mass, form, painted decoration, and sculpture. The fact that the majority of the buildings are to be used for subsequent state fairs and regional expositions made it desirable to use a method of illumination which would allow the equipment to be removed during the time the exposition is not in use and store it. The lack of maintenance and protection during the large part of the year when the buildings would be unoccupied made it rather impractical to use many of the newer forms of architectural elements, such as recesses, panels of translucent materials, etc., except in a few cases. Consequently, the logical method of illumination is principally floodlighting with the units located in specially designed pits, concealed behind landscaping, installed in setbacks, or placed in towers. In all cases however, lighting was particularly designed for each building.

**W. E. Folsom** (nonmember; Dallas Power and Light Company, Dallas, Texas): Interior lighting in Centennial areas of important buildings uses on the average, over 4 watts per square foot. This is in a combination of indirect and controlled direct lighting systems—the latter in the form of recessed reflectors with either flush louvers, silver-bowl lamps, or diffusing glass panels. Louvers are of either concentric or geometric types designed in general with light cut-off of about 30 degrees from vertical. Silver-bowl lamps are effectively used in shallow recessed reflectors with comparatively wide openings. The several thousand reflectors used in exposition areas are for the most part of special design, spun of aluminum with etched or specular reflecting surfaces made lasting by the Alzak treatment. Reflector units are of 5 general types with a large variety of assemblies possible and providing desirable interchangeability.

The effectiveness of the many types of interior and exterior lighting units was not left to chance—but tested in a lighting laboratory established for the purpose. Spectacular effects were experimented with thoroughly before final designs were determined.

**G. M. Buchanan** (nonmember; General Electric Company, Dallas, Texas): The absence of windows in the exhibit buildings is worthy of comment. An inspection of the Centennial in the daytime will reveal the desirable artificial lighting in the exhibit buildings. A much more pleasing effect is secured by all artificial lighting than could be secured by a combination of varying daylight and artificial lighting.

Mr. Fies stated for interior lighting 2 to 20 watts per square foot is used, giving a maximum of 40 foot candle. Some of you, not directly concerned with the application of good lighting, may not realize what this means in view of the fact that most of the lighting is indirect. You note the desirability and excellent lighting jobs on the interior of the exhibit buildings.

I want to call your attention to the 870 kw of mobile colored lighting on "Esplanade of State." This is an outstanding installation and the night show place on the Centennial grounds. A national expert in exposition lighting remarked as he viewed the "Esplanade of State" at night—"this, in my opinion, has never been equaled in any installation." I have often been asked how it is that the tower on the Federal Building is so evenly illuminated from top to bottom. The answer is 8 watts per square foot as mentioned in Mr. Fies' paper. The average intensity is 50 foot candle which is so high for floodlighting that any variation in intensity from top to bottom is not noticeable.

The parapet on the Ford Building has 15 watts per square foot or approximately 100 foot candle and is visible a great distance at night. In the Ford Building the daylight effect secured by the combination incandescent and mercury lamps used for the interior lighting is very interesting. The permanent street lighting system as installed by the city and exposition is unusual in that it is economical to maintain, yet has an entirely different appearance from the conventional street lighting standard, and this feature is particularly desirable in expositions. An opportunity to view the exposition grounds from a distance at night will show the desirable effect created by the battery of 24 36-inch searchlights. These searchlights make the exposition visible from a great distance at night and with the color screens offer a suitable climax to the lighting system when viewed from inside the grounds.

**R. W. Roessler** (Westinghouse Electric & Manufacturing Company, Dallas, Texas): The author is to be commended on his most interesting paper on the electrical features of the Texas Centennial Central Exposition. The exterior and interior lighting of all the buildings within the Centennial grounds definitely proves that full co-operation between the illuminating engineer and the architect is essential; and in this case, resulted in an outstanding lighting spectacle.

Illumination of the streets and grounds of the expositon indicates that careful study was given to provide adequate lighting and still blend in with the building architecture and other surroundings. It is interesting to note the clever manner in which the different street and grounds lighting fixtures were designed and placed, eliminating clashing effects. The lighting and power distribution system of the Centennial Exposition in itself shows thoughtful planning and good engineering. The magnitude of this system can only be realized when we note that the demand varies from 8,200 to 9,000 kw and that the system handles approximately 2,600,000 kilowatt-hours per month. The type of load served, the importance of uninterrupted service, and all other demands on this system are even more exacting than those of a fair sized municipality requiring the same kilowatt demand.

**A. E. Allen** (General Electric Company, Dallas, Texas): There is one point that seems worthy of additional emphasis, and that is the figure of 1.5 watts per square foot connected load for the entire exposition. This may not seem very much, but it is greater than for any previous world's fair. Some of this increase may be attributable to the large use of air conditioning by the major exhibitors, but lighting did not suffer by diversion of current for air conditioning, for this exposition, in my judgment, is outstanding in its lighting effects. Chicago's Century of Progress was remembered for its extensive use of gaseous tube lighting, and the Texas Centennial Exposition may be remembered for its large scale of mobile color lighting. The combination of the electronic valve with saturable core reactors makes possible a perfect control for blending

and changing color effects. The huge power loss formerly experienced in the use of resistance dimmers is avoided, and the control is so flexible that the colors may be changed without reducing the intensity of light on the building. The colors may be mixed to produce lovely pastel shades, and blended into innumerable combinations, or primary colors used as desired. There is little doubt that an even greater use of mobile color lighting will be made in the expositions planned for New York and for San Francisco in 1939.

**M. C. Hughes** (Texas Agricultural and Mechanical College, College Station): Unless I am mistaken, I believe that the incandescent electric lamp was not used at the Paris Exposition of 1881. I wonder whether or not Mr. Fies, in this connection, was referring to arc lights as incandescent lighting rather than the Edison carbon lamp which was generaly referred to as incandescent lighting. According to my information, illumination at the Paris Exposition of 1881, in so far as it was electrically lighted, was produced by the arc lamp.

If I am mistaken in this matter, I should like very much to be corrected, because it seems to me that the history of the early uses of light should be kept as straight as possible.

**John Fies:** These discussions, in the author's opinion, are all well founded and contribute materially to the value of the paper. The author herewith expresses his appreciation of all discussions submitted and offers the following comments as a closure to the discussions.

*a.* In Mr. Cutler's discussion reasons for the types of lighting and architecture are mentioned. These reasons should be of particular interest to those who may become associated with this field of lighting. We regret that space in the paper did not permit details of the interesting engineering problems.

*b.* In Mr. Folsom's discussion it is pointed out that the lighting as seen at the Exposition has proved to be a definite stimulus to the lighting business, particularly within the area of less than a day's ride from Dallas. This is important. It is a challenge to the builders of future fairs to provide lighting of types that will afford such a definite stimuli.

*c.* In Mr. Buchanan's discussion, reference is made to artificial versus natural light. We find some natural light on the Natural Resource Exhibit in the Transportation Building at the Exposition. This is an excellent exhibit but an illumination man in viewing it is well aware of how much more effective it would have been had it been presented in artificially lighted cases. No criticism is offered, as this exhibit is a remarkable exhibit, assembled quickly, and consequently was too late to be incorporated in the lighting plans.

*d.* In Mr. Roessler's discussion, reference was made to the importance of uninterrupted service. The local power company was given the responsibility of providing reliable electric service to the 38 points of delivery. From the beginning of the Fair to date there have been no primary interruptions of consequence. When we consider that all branch secondary feeders have their source at the mentioned points of delivery it becomes evident that if primary service is reliable then practically all service is reliable and troubles are necessarily restricted to small circuits and small areas. There have been, to date, no complaints relative to continuity of electric service.

*e.* In Mr. Allen's discussion, reference is made to the figure 1.5 watts per square foot. This figure is conservative and is based upon gross area. If we exclude from our figures certain areas used for stables for Cavalcade horses and for storage of miscellaneous material, that is, areas not accessible to visitors to the Exposition, we would have to propose a figure in excess of 2 watts per square foot for 145 acres.

*f.* Professor Hughes is his discussion mentioned that my reference to the use of incandescent lamps at the Paris Exposition in 1881 might be questioned. The author agrees with Professor Hughes that such a statement should be further supported when it pertains to past history and when it may not agree with generally accepted information on the subject. It may have been better had the paper stated that the incandescent lamp was "shown on a relatively large scale" rather than "used," yet the showing may also have constituted the using although the arc light was undoubtedly used extensively. The statement used in the paper was based upon a paragraph found in a very excellent and carefully written book "Electricity at the Columbian Exposition" copyrighted in 1894 and written by John P. Barrett, Chief of Department (probably electrical), Columbian Exposition, Chicago, 1893. It is reasonable to expect that Mr. Barrett had assembled by 1893 considerable authentic information relative to the use of electricity at expositions prior to that date, hence, we owe him our confidence in the credibility of the statement contained in his book as follows:

"Between 1878 and 1881 so many improvements had been made in the utilization of the electrical current for lighting purposes, and so great was the public interest in the subject, that the ever memorable electrical exposition of 1881 was held at the Palais de l'Industrie. It was then that incandescent lighting was first shown on anything like a large scale, and formed with the telephone the chief element of success for that exposition. Arc lighting was also indulged in commercially."

# Experiences With a Modern Relay System

**Discussion and author's closure of a paper by G. W. Gerell published in the October 1936 issue, pages 1130–6, and presented for oral discussion at the general technical session of the AIEE South West District meeting, Dallas, Texas, October 28, 1936.**

**Robert Treat** (General Electric Company, Schenectady, N. Y.): This paper brings out very convincingly the great value of records obtained by means of an automatic oscillograph to an operator who is determined to keep his system in the pink of condition, so to speak, without at the same time incurring large and unjustifiable expenditures. The many ways in which oscillographic records of accidental system disturbances can be of value to the operator, may roughly be classified into 5 groups.

## 1. Continuing Check on the Timing and Correct Operation of Relays and Circuit Breakers

Early in our studies of power system instability, it became apparent that a major improvement in stability could be obtained at relatively low cost by keeping the duration of short circuits to a minimum. As a result, high-speed clearing of faults began to be used on new projects; and many existing breakers and relays were speeded up in order to improve system performance during transients caused by short circuits. It was realized that if the stable operation of the system were to depend on high-speed clearing of faults, it would certainly be very desirable that the operator should have available a means for knowing absolutely that faults were actually being cleared in the expected times. There was no way of being sure that relays and breakers would perform in the same way during accidental short circuits that they did during periodic tests of individual devices. Hence it appeared desirable to secure a check on breaker and relay performance during actual operation. The time intervals which it was necessary to measure were very small, since the entire short circuit might last only 6–8 cycles. The only solution seemed to be an automatic oscillograph which should be capable of starting its record at the very beginning of a short circuit.

With some misgivings on the part of the commercial department, the General Electric Company undertook the development of such an oscillograph. The general specifications were in part as follows:

*a.* It must be capable of being put into operation automatically by a system disturbance.

*b.* It must furnish a clear, usable record, which began within 1/2 cycle of the incidence of the short circuit.

*c.* It must run for an adjustable predetermined time, but it must continue in operation if the initiating cause still existed at the end of that time.

*d.* It must be so designed as to obviate the necessity for changing the film or paper after each record was made; but it must also be possible to remove each record immediately if desired.

*e.* It must be so simple to operate, adjust, and maintain that it could be installed in power stations and substations, and operated and serviced by men who had no previous experience with oscillographs.

*f.* It must be priced so that operators would feel that they could afford to use it.

All these specifications were met. Although this device was not put on the market until early in the depression, nearly 50 of them made by one manufacturer alone are now yielding useful and valuable information of accidental system disturbances such as described by the author of this paper.

## 2. Evidences of System Instability, and of the Appropriate Remedy

Oscillograms of system disturbances are helpful in indicating any tendency of the system to become unstable during or subsequent to accidental faults. Since the likelihood of instability increases with system load, this should be very important now that

utility loads are again increasing so rapidly. When it becomes necessary to bolster up the system stability, oscillograms of part disturbances will often yield valuable information which aids greatly in making an intelligent decision as to which remedial measures will be the most effective per dollar of expenditure.

3. Check on Stability Calculations

Many calculations have been made of the probable performance of systems from the stability standpoint. Although the background of this phenomenon is now well understood, and the results of stability calculations made today contain little of the guess work which entered the computations made even as recently as 7 or 8 years ago, it is still desirable to obtain a check on the assumptions and calculations. Checks obtained by means of staged tests are not altogether satisfactory for the reason that it is undesirable that these tests should cause disturbances to service. This necessitates their being made, if at all, under artificial conditions (such as during light load or with considerable reserve generating capacity connected) which seldom, if ever, exist during normal operation. Oscillograms of accidental system disturbances, however, yield data which serve as a very satisfactory check on the results of stability calculations. Obviously a complete check cannot be obtained from any one disturbance and it is necessary to accumulate the data over a considerable period in order to get a fairly complete comparison of predicted with actual performance.

4. Information Concerning the Values and Phase Positions of the Voltages and Currents of the 3 Phases, and Concerning the Sudden or Momentary Changes in These Values

Practically every relay engineer is occasionally faced with seemingly inexplicable misperformance of his relays. Sometimes relays do not trip when they should; more frequently they trip when apparently they should not. Subsequent tests of the offending devices frequently reveal no reason for their apparent misbehavior. As pointed out by the author of this paper, the automatic oscillograph shows that the currents and voltages in individual phases sometimes jump around in magnitude and phase position during faults and subsequent breaker operations in a most unexpected and apparently erratic manner. From this information it is learned that some of the apparently incorrect relay operations were, in reality, absolutely correct under the conditions which existed; but that the conditions themselves were entirely different from those contemplated when the relay application was made. While this may be of only academic interest when the relay engineer has to explain to his boss why the relaying went haywire, it is of far more than academic interest when he has to decide what ought to be done about it.

5. Reduction in the Time of a Patrol Crew in Locating a Flashover After an Outage

Even though a line successfully returns to service immediately, some operating companies make a patrol after every outage, in order to determine whether the damage is sufficient to require maintenance at some convenient time. As pointed out by the author of this paper, his company and some others have found that it is possible from the information on the oscillograms to determine very closely where the failure occurred, and thus save much time of the patrol crew. Although the author gives no indication of the saving in patrol expense resulting from this practice, it is suspected that this item alone, which was quite unforeseen when the development was first undertaken, is sufficient to justify an automatic oscillograph. If this be true, all the other advantages are obtained for nothing.

Some companies have found that the damage from any single flashover is so slight that they do not feel warranted in patroling a line after each interruption; rather, a thorough inspection is made at the end of each season. It seems entirely probable that if these companies had this means of sending the patrol crew right to the point of flashover, they would feel justified in availing themselves of the additional security of an inspection after each line outage.

The prominence given to the value of oscillograms of accidental system disturbances in this paper is indeed gratifying to one who was partially instrumental in encouraging the original development, and who has strongly felt that the information yielded by an automatic oscillograph was worth far more than its cost. Although many companies which have not yet installed automatic oscillographs are inclined to look upon them as luxuries, which, however desirable, can ill be afforded when they can hardly get money enough for necessary bread and butter, I do not know of a single operating company which has ever bought an oscillograph, that could be induced to part with it for several times the price paid, if it could not be replaced. I suppose the psychology is the same as with an electric refrigerator, or an automobile—it is a luxury until you get your first one; after that, it is a necessity which you are ever after at a loss to understand how you did without, so long.

G. W. Gerell: Concerning Mr. Treat's remarks it might be noted that automatic oscillographs, as available today, are quite reliable, and in general do meet the specifications which he imposed.

In regard to system instability, records obtained from the oscillograph have shown definitely that a number of incorrect operations have resulted from instability and have further indicated remedial steps necessary in the relay equipment to prevent its repetition.

It may be well to mention here that the case of trouble described in connection with the oscillogram of figure 3 of the paper was included, to open up this important subject of, "how fast a relay may operate and still give a correct tripping impulse." It is suggested that considerable thought should be given to this.

As Mr. Treat mentions, the location of line faults from data supplied by the oscillograph has been of great assistance to the patrol crews. But, it will not necessarily reduce patrol expense, inasmuch as the patrol crews cannot be reduced in number. In many instances patrol crews have inspected a line, finding nothing. Later the location was given them from the data secured from the oscillograph. A second patrol was invariably successful.

## Steinmetz Painting Presented to High School



AN oil painting of Doctor Charles P. Steinmetz (A'90, M'91, F'12, past-president, deceased October 26, 1923) has been presented by the General Electric Company to a new $3,000,000 high school in Chicago, Ill., that has been named for the scientist. The painting shows Doctor Steinmetz at his desk about 3 months before his death, and is the work of H. M. Mott-Smith. It was presented by E. W. Allen (A'03, F'22) vice-president of the General Electric Company, who is shown at the extreme left with Mayor Edward J. Kelly of Chicago at his side. At the right is Daniel F. O'Hearn, principal of the school, and Theodore Luga, a student and son of an immigrant, who accepted the gift for the school.

# News

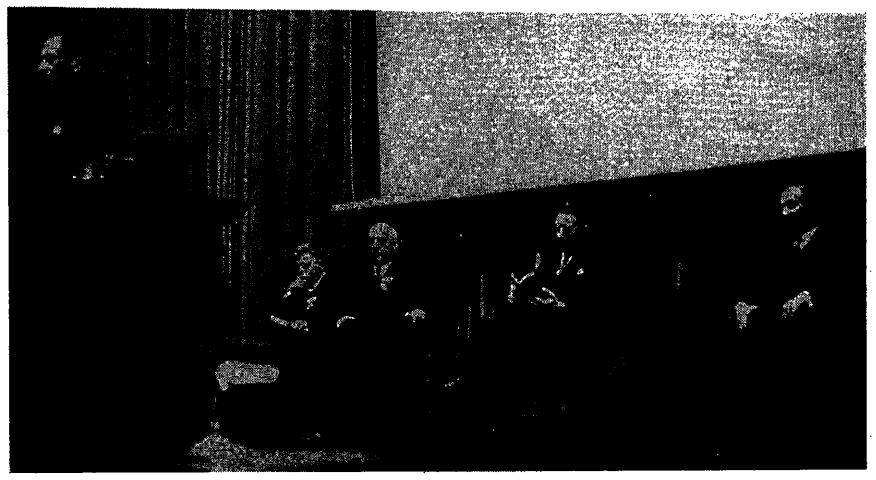
## Of Institute and Related Activities

# The Institute's 1937 Winter Convention

TERMED by President A. M. MacCutcheon, "one of the busiest, most stimulating, and most interesting" conventions that he had ever attended, the Institute's 1937 winter convention drew to a close with a total registration of 1,165. Perhaps one of the busiest attendants at the convention was President MacCutcheon himself. An unusually large number of committee meetings was held, and for the first time the board of directors met on 2 successive afternoons during convention week.

Details concerning registration and attendance are given in the accompanying tabulations. Although the total registration was somewhat less than last year's total, the attendance at various sessions and activities was good and in some cases exceeded last year's attendance. The drop in registration, as may be noted from an accompanying tabulation, was primarily among those from the New York Section territory for which the registration was 68 less than last year. Another interesting fact, shown by another tabulation is that the attendance at the smoker, which is believed to have set a new record, was higher than the number registered. This is evidence of the fact that many attended the convention who did not register, so that the actual total attendance was somewhat higher than the registration figures show.

Details concerning the various features of the convention are given in the following paragraphs and on subsequent pages.



H. S. Osborne, chairman, technical program committee, speaking on the technical sessions at the opening session of the convention. Seated on the platform, left to right, are Director R. W. Sorensen, of Pasadena, Calif., President A. M. MacCutcheon of Cleveland, Ohio, H. R. Beardsley of Brooklyn, N. Y., chairman of the winter convention committee, and A. G. Oehler, chairman of the New York Section

### Noble Prize Presented at Opening Session

The convention was officially opened at 2 p.m. on Monday, January 25, by C. R. Beardsley, chairman of the general winter convention committee, who extended a very cordial welcome to all those attending. Following his remarks, President MacCutcheon announced that the Alfred Noble prize for 1936 had been awarded to Abe Tilles, instructor in electrical engineering at the University of California, Berkeley, and counselor of the Institute's University of California Branch. (Details of this award and a biographical sketch of Doctor Tilles appeared in the news pages of the January issue.) President MacCutcheon outlined briefly the details of the award and sketched the recipient's career.

In Doctor Tilles's absence, the prize was presented to R. W. Sorensen, professor of electrical engineering at the California Institute of Technology, Pasadena, and a director of the AIEE, who accepted it in behalf of Doctor Tilles.

### President MacCutcheon's Address

Following presentation of the Noble prize, Chairman Beardsley introduced President MacCutcheon, who spoke on the subject "The Challenge of 1937." In this address, President MacCutcheon amplified his message to the membership published in the February issue. He emphasized particularly the importance of increased activity on the part of the Sections and Branches during 1937, urging that each Section appoint at least one technical committee. "Such Section technical committees," he said, "can develop subjects of unusual interest, and recommend authors of unusual ability, reporting to the national technical committee having jurisdiction. Among our membership are many potential authors who would be willing to devote their time to the preparation of a paper desired by the profession and asked for by fellow Section members. Such papers, when published, would be accompanied by proper recognition to the Section submitting the paper. By this means the technical activities could be made more widely representative, and more fully meet the desires of the membership.

"I feel that the Institute has reason to be truly proud of the fine work being carried on through the Branch organization, but still more can be accomplished in 1937. With the young men in the Branches lies the future of the profession and the future of the Institute. . . .

Concerning the movement under way to broaden the activities of the Institute, President MacCutcheon said: "In 1936, many devoted Institute members, several special committees, and the board of directors have canvassed possibilities in connection with broadening the scope of Institute activities. Should papers be prepared and presented dealing with the relations of the engineer to society, with the engineer's relation to war, with the engineer's relation to the distribution of electrical products, with the engi-

### Analysis of Registration at 1937 Winter Convention, New York, N. Y.

| Classification | Dist. 3 | Dist. 1 | Dist. 2 | Dist. 4 | Dist. 5 | Dist. 6 | Dist. 7 | Dist. 8 | Dist. 9 | Dist. 10 | Totals |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Members | 532 | 190 | 178 | 17 | 35 | 2 | 10 | 7 | 1 | 14 | 986 |
| Men guests | 40 | 9 | 11 | 1 | 2 | | 1 | | | 1 | 65 |
| Women guests | 48 | 21 | 23 | 3 | 1 | | 1 | | | 2 | 99 |
| Students | 9 | 2 | 4 | | | | | | | | 15 |
| Totals | 629 | 222 | 216 | 21 | 38 | 2 | 12 | 7 | 1 | 17 | 1,165 |

neer's relation to unemployment, with the engineer's relation to natural resources? Personally, I feel that there should be a sane and intelligent broadening of our activities, provided that in so doing we are following the fundamental principles for which the society was organized. . . ."

He closed by urging "each member . . . to join with the vice-presidents, the other directors, and myself, in the resolve to do all in our power to meet the inspiring challenge of 1937."

### Doctor Osborne's Remarks

Following President MacCutcheon's address, H. S. Osborne, chairman of the Institute's technical program committee, spoke as follows on the technical sessions of the convention:

"In preparation for such a convention as this, the technical committees and the technical program committee consider the whole wide range of the professional activities of Institute members. From the various suggestions which are developed by this review a program is adopted, based upon the combined judgment of these committees regarding what at the moment will be of greatest interest and value.

"One feature of this convention, as well as other recent conventions, to which I should like to call your attention is the technical conferences. As you will note there are 4 of these on the present program. The technical conference might be defined as a meeting without the publication of papers. Since these conferences involve very little expenditure, it would be practicable to hold a large number of them in connection with our conventions if they are desired by the membership. Many such conferences might lead up to the future publication of papers summarizing the outcome of the conference or of a series of conferences. The appearance of these conferences on the program is an illustration of the fact that the technical program committee is experimenting with new methods of expanding and enriching the technical activities of the Institute.

"The fact is that the field of activity which is described in our Constitution as "the theory and practice of electrical engineering and of the allied arts and sciences" is rapidly growing. As a result of this vitality it is natural that there should always be a problem of how best to meet the varied interests and desires of the Institute membership. It has been suggested that some members would like to see more attention given in Institute programs to subjects of broad general interest, particularly to subjects in which engineering and the social sciences are both involved. Also, we know that some members would like to have more opportunity for discussion at the Institute meetings of specific subjects on the frontier of technological advance. While such subjects from their nature would often, taken individually, be of immediate interest only to a relatively small number of members, taken in the aggregate they may be of interest to a large number.

"These considerations illustrate the desirability of a careful review of the Institute program having in mind the wide scope of interest of the Institute membership and also the limitations in the amount of money which can be spent. This whole question is being carefully studied by the committees most directly concerned. I speak of these matters here to ask your help as members of the Institute. If you have ideas regarding the programs of future meetings which you think will help the Institute to meet in the broadest and most satisfactory way the needs of the membership, please give these suggestions to any member of a technical committee or of the technical program committee. I know that these will be helpful to them. It may not be possible to apply all such suggestions but I assure you that they will all be gratefully received and carefully considered."

Following Doctor Osborne's remarks, the first technical sessions of the convention assembled.

**Analysis of Registration at Recent Winter Conventions**

| District | 1934 | 1935 | 1936 | 1937 |
|---|---|---|---|---|
| New York City and Foreign (3) | 812 | 694 | 697 | 629 |
| North Eastern (1) | 179 | 194 | 219 | 222 |
| Middle Eastern (2) | 161 | 153 | 222 | 216 |
| Great Lakes (5) | 40 | 38 | 43 | 38 |
| Southern (4) | 5 | 6 | 15 | 21 |
| Canada (10) | 16 | 21 | 11 | 17 |
| South West (7) | 11 | 5 | 11 | 12 |
| Pacific (8) | 1 | 1 | 4 | 7 |
| North Central (6) | 2 | 1 | 6 | 2 |
| North Western (9) | 0 | 1 | 3 | 1 |
| Totals | 1,227 | 1,114 | 1,231 | 1,165 |

### Technical Sessions

With the exception of the sessions on electric welding and tensor analysis, reports of the technical sessions are not given here since all papers presented have been published in Electrical Engineering, and since all written discussions approved by the technical program committee will appear in subsequent issues. At the session of welding, only one previously published paper was presented, the remainder of the program including a demonstration lecture and a special address. The tensor sessions, included several informal discussions by invited nonmember guests. Brief reports of these 2 sessions are given on succeeding pages.

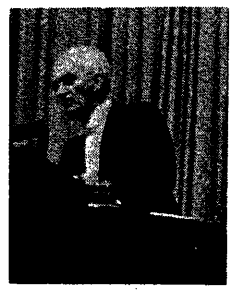
Attendance at the technical sessions, as reported by the technical program committee, is given in an accompanying tabulation. The count in each case was an instantaneous one taken about 1½ hours after the session began. The total attendance at any one of the sessions may have been somewhat greater, if those who stayed for only a brief interval were included.

### Technical Conferences

As mentioned by Doctor Osborne in his remarks at the opening session of the convention, 4 technical conferences were held on the following subjects: education; network analysis and synthesis; sound; and performance standards and test codes for rotating machinery. All these conferences were featured by interesting informal discussions. At some of them official actions were taken by the sponsoring committees. Brief reports of these conferences are given on succeeding pages.

### Address "Power and People"

Following the Edison Medal presentation ceremonies, which took place at a special session of the convention on Wednesday evening, January 27 (reported in succeeding pages), an address entitled "Power and People" was delivered by John C. Parker, vice-president, Consolidated Edison Company of New York, Inc., to those assembled for that occasion. Doctor Parker pictured the place of power, particularly electric power, in the lives of people. Speaking of the work of engineers, who provide the mechanisms necessary for the furnishing of power in usable forms, he said: "The engineer does not live a life of isolation, but on the contrary works with and through other men. His work, . . . involves understanding of, and adjustment to and co-operation with other men . . . His work is definitely more social than that of the physician or of the lawyer or of the minister of souls or of the exponent of the creative arts, each of whom, in a large degree, works as an individual. In that very fact, however, the engineer has at once a satisfaction and a limitation of his social contacts. With



**Doctor Parker speaking on "Power and People"**

**Attendance at Technical Sessions and Conferences**

| Time | | Attendance |
|---|---|---|
| Monday | | |
| 2:00 p.m. | Opening of convention | 250 |
| **Technical Sessions** | | |
| 2:30 p.m. | Communication | 200 |
| 2:30 p.m. | Selected subjects | 100 |
| Tuesday | | |
| 10:00 a.m. | Power transmission | 250 |
| 10:00 a.m. | Tensor analysis | 125 |
| 2:00 p.m. | Tensor analysis | 115 |
| 2:00 p.m. | Power distribution | 125 |
| Wednesday | | |
| 10:00 a.m. | Induction machinery | 50 |
| 10:00 a.m. | Protective devices | 350 |
| 2:00 p.m. | Synchronous machinery | 70 |
| 2:00 p.m. | Electronics | 100 |
| Thursday | | |
| 10:00 a.m. | Electrical machinery | 85 |
| 10:00 a.m. | Electrophysics | 125 |
| 2:00 p.m. | Instruments and measurements | 100 |
| 2:00 p.m. | Electric welding | 110 |
| **Technical conferences** | | |
| Wednesday | | |
| 10:00 a.m. | Committee on education | 50 |
| 2:00 p.m. | Network analysis and synthesis | 75 |
| 2:00 p.m. | Noise conference | 20 |
| Thursday | | |
| 2:00 p.m. | The performance standards, synchronous machinery, induction machinery, and d-c machinery test codes | 18 |
| Total registered convention attendance | | 1,165 |

other men, largely of identical or at least of closely related interests and limitations, he finds satisfaction for his desires for human contact and such satisfaction easily enough so preoccupies his time that he can easily fail of social understanding of the people whom his profession serves or of the social significances of his own work. . . ."

"In consequence of engineering remoteness, we perhaps become obsessed with the technical beauties and interests of our work and with the human problem of co-ordination with our fellows in creation and miss some perspective of how our works touch on the larger interests of society. . . ."



E. R. Thomas, chairman of the inspection trips committee

Concerning the public's interest in power, Doctor Parker said in part: "There is a general public interest in the problems of power production and distribution that is way out of proportion to any significance that even so important an art has in the affairs of men. This would be puzzling if it were only a recent phenomenon. It is not the less disturbing because of the fact that it has been developed over a period of years by an ill-considered but perfectly honest enthusiasm which has mistaken simultaneity of occurrence for a relation of cause and effect."

Speaking of power in industry, he said: "American industry did not set out with the idea of trying to apply power to industrial production and thereafter discover the means for utilizing power. . . . The power industry saw a commercial opportunity and observed a social responsibility. . . ." Later, he compared the importance of power in industry with that of design for production, modern materials, machine tools, use of tolerance limits, interchangeability of parts, standardization, the use of limit gauges. "All of these elements put together," he said, "might have accomplished nothing had it not been for the superb achievements of distribution which have brought the end results of industry to the final user.

"Note well that every one of these elements. . . has been essential to modern industrial life as we know it; even more than that, has been essential to modern non-industrial living. Our enthusiasm for one of these elements in which we may happen to be particularly interested—let us say, power—should not run away with our sense of proportion. On the contrary, it seems to me that our pride in our own service becomes greater if we have an adequate picture of where it fits in as an essential and considerable element of something enormously bigger than itself."

Regarding the place of electricity in home and farm life, Doctor Parker said in part: "We need not be at all deprecatory of the importance of our power developments as service to the home or to the farm merely because we may be realistic in our apprehension of the fact that many other things enter into life and that the life is more than meat and the body more than raiment. It is understandable, though not by virtue of that at all defensible, that the specialist should develop an unrestrained enthusiasm for his particular field of human endeavor and that his extreme loyalty might communicate his zeal to others. What is not perhaps quite so clear is that economic, social, and political injuries may result from these widespread and exaggerated enthusiasms. Not alone as a matter of humane consideration, but in self defense against the reactions of disappointed hope, we must be at pains not to arouse desires that we cannot gratify or which, gratified, will be found not all that the body or the soul of man craves."

"Important as is power as an adjunct to factory, farm and home," he concluded, "it, in and of itself, will not revolutionize life. We are, in our most profound relations, biologic creatures and all the conscious mechanical and technical efforts in the world are small factors in determining the essential well-being of our lives. To the extent that we have made our lives in their superficial details depart from our biologic origins, we find the mechanisms of living important. They will be the more important if our perspective keeps them in the proper relation to the other elements of living and to life itself."

Full text of Doctor Parker's address appears on pages 305–11 of this issue.

**Attendance at Special Features of Recent Winter Conventions**

| Feature | 1935 | 1936 | 1937 |
|---|---|---|---|
| Total registration | 1,114 | 1,231 | 1,165 |
| Smoker | 550 | 1,025 | 1,175 |
| Dinner dance | 442 | 486 | 500* |
| Inspection trips | 815 | 1,753 | 926 |

* Estimated.

## Future AIEE Meetings

**North Eastern District Meeting**
Buffalo, N. Y., May 5–7, 1937

**Summer Convention**
Milwaukee, Wis., June 21–25, 1937

**Pacific Coast Convention**
Spokane, Wash., Aug. 30–Sept. 3, 1937

**Middle Eastern District Meeting**
Akron, Ohio, Fall 1937

### Inspection Trips

As in previous years, the last day of the convention was reserved entirely for inspection trips. Trips were held also on other days of the convention. As a special attraction, a post-convention trip to Bermuda was offered at special rates. About 28 people took advantage of this opportunity to enjoy a mid-winter trip to this popular resort. With the exception of the trip to inspect the mercury turbine of the Public Service Electric and Gas Company at Kearny, N. J., all trips were held as scheduled. Registration for the various trips is indicated in an accompanying tabulation.

The excellent variety of trips, together with the orderliness with which arrangements were made and carried out, elicited many favorable comments. The success of this part of the convention program reflected the efforts of the hard-working chairman of the committee, E. R. Thomas, and of his colleagues: H. C. Anderson, H. M. Case, P. T. Coffin, G. E. Dean, Henry Kurz, W. J. Quinn, H. O. Siegmund, H. B. Stoddard, R. H. Twiss, and W. Y. Vedder.

**Registration for Inspection Trips**

| Trip | Registration |
|---|---|
| Anaconda Wire & Cable Company, Hastings-on-Hudson mill | 107 |
| General Electric Company sponsored broadcast, "Hour of Charm," NBC studios | 95 |
| Warner Bros. moving picture studios | 77 |
| S.S. "Monarch of Bermuda" | 66 |
| New York Stock Exchange | 65 |
| The Associated Press | 60 |
| Brooklyn Navy Yard | 59 |
| Columbia Presbyterian Medical Center, Sloan radio frequency X-ray generator | 56 |
| Westinghouse Lamp Works, Bloomfield, N. J. | 52 |
| RCA Manufacturing Company, Inc., Harrison, N. J. | 51 |
| National Broadcasting Company studios | 45 |
| Independent Subway System, power control board and cable testing equipment | 41 |
| Weston Electrical Instrument Corporation | 39 |
| New York Museum of Science and Industry, hall of motion | 34 |
| Mackay Radio & Telegraph Company, ultra high frequency transmitter | 26 |
| The M. W. Kellogg Co., Jersey City, N. J., electric welding | 21 |
| S. H. Kress & Company, special lighting and air conditioning installation | 17 |
| Edison Wonder House, Brooklyn, N. Y. | 15 |
| Public Service Electric & Gas Company, Kearny generating station, mercury turbine | (Cancelled) |
| Total | 926 |

### Smoker

The success of this year's smoker can be judged best by the attendance, 1,175, which is believed to be a record for winter convention smokers. The affair was held in the Grand Ballroom of the Hotel Commodore. An excellent dinner was served, followed by a stage show featuring a pleasing variety of entertainment by well-known radio and motion-picture stars. Ray Perkins, well known for his work on the radio, was master of ceremonies.

E. S. Banghart was chairman of the smoker committee; he was assisted by W. H. Farlinger, H. E. Farrer, P. G. Fredericks, W. H. Harden, W. Jordan, J. E. McCormack, E. J. D. Paterson, R. E. Powers, T. D. Reimers, T. O. Rudd, H. C. Schlaikje, D. W. Taylor, and E. F. Thrall.

### Dinner-Dance-Buffet Supper

As usual, the dinner-dance proved to be the social high light of the convention. It was held at the Hotel Astor, and was followed by a buffet supper, a feature that has become popular in recent years. A total of

335 attended the dinner-dance, and 250 the dance-buffet supper; some of these attended both, but it is estimated that about 500 were present at the combined affair. Those serving on the dinner-dance committee were: C. M. Gilt, *chairman;* F. L. Aime, T. S. Bacon, L. W. Codding, H. E. Farrer, L. P. Ferris, J. E. Goodale, S. B. Graham, Thomas Maxwell, J. A. McHugh, J. H. Pilkington, and Tomlinson Fort.

### Women's Activities

A program of special entertainment was arranged for the women attending the convention. On Tuesday a group of about 50 visited the Van Gogh Exhibition at the Museum of Modern Art, after which the group inspected the Pedach Exhibition of Decorating Arts and Crafts, at Radio City. This was followed by tea at 4:00 p.m. in the British Empire Exhibition Room at Radio City, after which the group visited the Museum of Science and Industry. After dinner, there was a back-stage tour of the Radio City Music Hall, followed by attendance at the show in that theater. The most popular single event on the women's program was the luncheon and bridge held at the Engineering Woman's Club on Wednesday afternoon.

In addition to the foregoing, some of the women attended some of the regularly scheduled inspection trips, particularly those to the New York Stock Exchange and to the Steamship "Monarch of Bermuda." Serving on the women's committee were: Mrs. George Sutherland, *chairman;* Mrs. E. S. Banghart, Mrs. C. R. Beardsley, Mrs. O. B. Blackwell, Mrs. H. C. Dean, Mrs. Tomlinson Fort, Mrs. C. M. Gilt, Mrs. H. H. Henline, Mrs. A. H. Kehoe, Mrs. E. B. Meyer, Mrs. A. G. Oehler, Mrs. G. S. Rose, and Mrs. H. R. Woodrow.

### Directors and Committees Meet

The Institute's board of directors met during the convention, as is the usual custom. A meeting of the national nominating committee also was held, at which nominees for election to Institute officers for the year 1937–38 were selected. Reports of both these meetings appear in succeeding pages.



**C. M. Gilt (left) chairman of the dinner-dance committee, and E. S. Banghart, chairman of the smoker committee, comparing notes**

Many of the Institute's committees also met during the convention; these were as follows: technical program; research; power generation; production and application of light; standards; electrochemistry and electrometallurgy; automatic stations; Sections; electronics; electrophysics; membership; Group III of the subcommittee on conductors, towers, and wood poles of the power transmission and distribution committee; transformer subcommittee of the electrical machinery committee; and the protective devices committee and its subcommittees on (1) lightning arresters, (2) relays, (3) circuit breakers, switches, and fuses, and (4) fault-current-limiting devices. A scheduled meeting of the committee on electric welding was not held. A luncheon meeting of Student Branch counselors was held, and the newly appointed special committee on broadening of Institute activities also met. Reports of most of these meetings are presented in succeeding pages.

Much credit is due the general committee for the success of the 1937 winter convention. C. R. Beardsley was chairman of this committee; other members were: T. F. Barton, O. B. Blackwell, H. E. Farrer, E. E. Dorting, A. G. Oehler, C. S. Purnell, S. A. Smith, Jr., George Sutherland, and F. P. West.

## AIEE Directors Meet During the Winter Convention

THE regular meeting of the board of directors of the American Institute of Electrical Engineers was held at Institute Headquarters, New York, at 2:00 p.m., on Tuesday, January 26, 1937, adjourning at 5:35 p.m. until 2:00 o'clock the following afternoon, January 27.

There were present: *President*—A. M. MacCutcheon, Cleveland, Ohio. *Past-President*—J. B. Whitehead, Baltimore, Md. *Vice-Presidents*—O. B. Blackwell, New York, N. Y.; C. V. Christie, Montreal, Que.; R. H. Fair, Omaha, Neb.; C. F. Harding, Lafayette, Ind.; W. H. Harrison, Philadelphia, Pa.; N. B. Hinson, Los Angeles, Calif.; A. C. Stevens, Schenectady, N. Y. *Directors*—F. M. Farmer, New York, N. Y.; N. E. Funk, Philadelphia, Pa.; H. B. Gear, Chicago, Ill.; F. E. Johnson, Columbia, Mo.; C. R. Jones, New York, N. Y.; P. B. Juhnke, Chicago, Ill.; W. B. Kouwenhoven, Baltimore, Md.; Everett S. Lee, Schenectady, N. Y.; K. B. McEachron, Pittsfield, Mass.; L. W. W. Morrow, Corning, N. Y.; C. A. Powel, East Pittsburgh, Pa.; R. W. Sorensen, Pasadena, Calif. *National Treasurer*—W. I. Slichter, New York, N. Y. *National Secretary*—H. H. Henline, New York, N. Y.

Minutes of the board of directors meeting of October 20, 1936, were approved. The minutes of the executive committee meeting held on December 10, 1936, were approved with an amendment changing the name of the special committee on broadening of Institute activities, which was appointed by the executive committee, to "special committee on Institute activities," this committee to prepare for a discussion at the 1937 summer convention of the subject of desirable topics for presentation at Institute meetings and for publication, and to be discharged upon presentation to the board of directors of its report on this session.

Actions of the executive committee under date of November 2, 1936, on applications were reported and approved, as follows: 3 applicants transferred to the grade of Fellow; 1 applicant elected to the grade of Fellow; 19 applicants transferred and 13 elected to the grade of Member; 69 applicants elected to the grade of Associate; 905 Students enrolled.

A report of a meeting of the board of examiners held on January 20, 1937, was presented and approved. Upon the recommendation of the board of examiners, the following actions were taken: 1 applicant was elected to the grade of Fellow; 31 applicants were elected and 5 were transferred to the grade of Member; 97 applicants were elected to the grade of Associate; 204 Students were enrolled. The finance committee reported monthly disbursements as follows: December, $17,647.61; January, $25,368.21; report approved.

The final report of the special committee to consider Associate dues and related matters was submitted, with the recommendation that the present constitution and bylaws be unchanged. The board voted that the committee's report be accepted and published in Electrical Engineering, and that the committee be discharged. (The report appears elsewhere in this issue.)

Upon the recommendation of the committee on co-ordination of Institute activites, the following schedule of meetings in 1938 was adopted: winter convention, New York, N. Y., January 24–28; North Eastern District meeting, Pittsfield, Mass., in the spring; summer convention, Washington, D. C., June 20–24; Pacific Coast convention, Portland, Ore., dates to be determined later.

Approval was given to the dates of August 30 or 31 to September 3 for the 1937 Pacific Coast convention, already scheduled to be held in Spokane, Wash.

Upon the recommendation of the committee on student Branches, the board authorized the organization of student Branches of the Institute at Columbia University, New York, N. Y., Northwestern University at Evanston, Ill., and Tulane University, New Orleans, La.

The president was empowered to appoint 2 representatives of the Institute upon the council of the American Association for the Advancement of Science for the year 1937.

G. G. Post was appointed a representative of the Institute upon the Commission of Washington Award for the unexpired term, ending August 1, 1938, of William B. Jackson, deceased.

The committee on award of Institute prizes reported its recommendations on various suggestions for modifications in the rules for the award of Institute prizes. The board voted its approval of the recommendations, which involved the following changes in the rules and the reprinting of

the pamphlet containing the rules:

(1) Provision that the national prize for branch papers will be based upon the student year July 1 to June 30, inclusive, rather than the calendar year as at present. This is in accordance with the recommendation of the conference of officers, delegates, and members held in Pasadena, Calif., in June 1936. It is recommended that this change be brought about by the adoption of the following specific changes in the present rules.

Page 3, paragraph at the bottom of the page beginning "Only papers presented. . . ., etc."—Modify to read as follows:

"For the national best paper prize and the national prize for initial paper, only papers presented during the calendar year shall be considered except those for the best paper prize in the class of public relations and education. In this class all papers presented subsequent to those considered at the time of the last previous award in this field and prior to the end of the last calendar year will receive consideration. For the national prize for Branch papers only papers presented during the preceding academic (college) year shall be considered.

"All papers approved by the technical program committee . . ., etc."

Page 6, paragraph 6—Modify to read as follows: "Only papers presented during the calendar year shall be considered for the prize for best paper and for initial paper. Only papers presented during the preceding academic (college) year shall be considered as eligible for the Branch paper prize. They must be submitted in duplicate by authors, or by officers, of the Section, Branch, or District concerned to the District secretary on or before the following dates: best paper and initial paper, February 15; Branch paper, July 15."

If this recommendation is adopted, it is understood that the committee on award of Institute prizes will this year consider for the national Branch paper prize only papers presented between January 1 and July 1, 1936.

(2) Provide for a District prize for a graduate student paper. This is in accordance with a previous recommendation of the prize award committee, approved by the board of directors on May 25, 1936, but not heretofore incorporated in the rules for national and district prizes.

At the top of page 6, add item 4, prize for graduate student paper.

"4. The District prize for graduate paper may be awarded for the best paper based upon graduate work and presented at a national, District, Section, or Branch meeting of the Institute. At the time of presentation, the author must be a graduate student and either a member or an enrolled Student of the Institute. In the case of co-authors, the graduate requirement applies to all and the membership requirement applies to at least one of the coauthors."

Page 6, paragraph 6—Modify the revision set forth under item 1 above to read as follows:

"Only papers presented during the calendar year shall be considered for the prize for best paper and for initial paper. Only papers presented during the preceding academic (college) year shall be considered for the prize for Branch paper and for graduate student paper. They must be submitted in duplicate by authors, or by officers of the Section, Branch, or District concerned to the District secretary on or before the following dates: best paper and initial paper, February 15; Branch paper and graduate student paper, July 15."

A report of the Institute policy committee on recommendations of the committee on safety codes for an expansion of that committee's scope was presented and approved. The report included the statement: "It is the feeling of this committee that there are many types of activity looking to increased safety, which lie beyond the normal purposes of the AIEE. It is felt that any expansion of the Institute's work on safety should be limited strictly to the technical and engineering aspects of safety, and particularly should not conflict with the safety work of any other organization." It recommended that "the chairman of the committee on safety codes be informed that the board of directors is interested in the possibility that the Institute, within its proper scope, may make further contributions to the cause of safety than it is now doing, and will welcome any specific suggestions to this end from the committee on safety codes."

The publication committee reported that it is making a thorough study of publication policy, and certain recommendations, including increases in the budget for ELECTRICAL ENGINEERING for the present year, were approved. The committee may submit additional recommendations after further consideration and discussion of the matter at the conference of officers, delegates, and members during the summer convention.

President MacCutcheon presented abstracts of reports which he had received, upon his request, from the technical committees and several of the general committees. The board referred these reports to the chairman of the committee on co-ordination of Institute activities for a survey of committee activities and any recommendation he may have for the Board.

The final report of the special committee to revise Section territories was presented. The board voted that the committee's report be accepted, that the actions recommended be adopted, the changes to become effective August 1, 1937, and that the committee be discharged with the thanks of the board.

Reference was made to the publication in the December 1936 issue of ELECTRICAL ENGINEERING of a report of the committee on professional recognition of Engineers' Council for Professional Development, which had not yet been approved by ECPD, and comments on which were invited. This report was referred to the committee on economic status of the engineer, with the understanding that a notice would be published in ELECTRICAL ENGINEERING that the report had been referred to this committee, the chairman of which has requested that Institute members send to him their comments on the subject. (This notice appears elsewhere in this issue.)

Other matters were discussed, reference to which may be found in this or future issues of ELECTRICAL ENGINEERING.

## Nominating Committee Announces Candidates

A complete official ticket of candidates for the Institute offices that will become vacant August 1, 1937, was selected by the national nominating committee at its meeting held at Institute headquarters, New York, N. Y., January 26, 1937. This committee, in accordance with the constitution and by-laws, consists of 15 members, one selected by the executive committee of each of the 10 Geographical Districts, and 5 selected by the board of directors from its own membership.

The following members of the committee were present: A. W. Berresford, New York, N. Y.; O. B. Blackwell, New York, N. Y.; C. V. Christie, Montreal, Canada; N. E. Funk, Philadelphia, Pa.; E. E. George, Chattanooga, Tenn.; K. L. Hansen, Milwaukee, Wis.; R. E. Kistler, Seattle, Wash.; H. S. Lane, San Francisco, Calif.; T. H. Morgan, Worcester, Mass.; J. W. Ramsay, Austin, Tex.; R. W. Sorensen, Pasadena, Calif.; A. C. Stevens, Schenectady, N. Y.; A. L. Turner, Omaha, Neb.; J. B. Whitehead, Baltimore, Md., and W. E. Wickenden, Cleveland, Ohio; also H. H. Henline, New York, N. Y., secretary of the committee.

The following is a list of the official candidates selected by the committee:

FOR PRESIDENT

W. H. Harrison, assistant vice-president, department of operation and engineering, American Telephone and Telegraph Company, New York, N. Y.

FOR VICE-PRESIDENTS

I. Melville Stein (Middle Eastern District, number 2) director of research, Leeds & Northrup Company, Philadelphia, Pa.

Edwin D. Wood (Southern District, number 4) general superintendent, Louisville Gas & Electric Company, Louisville, Ky.

L. N. McClellan (North Central District, number 6) chief electrical engineer, U.S. Bureau of Reclamation, Denver, Colo.

J. P. Jollyman (Pacific District, number 8) hydroelectric and transmission engineer, Pacific Gas & Electric Company, San Francisco, Calif.

M. J. McHenry (Canada District, number 10) manager, Toronto district, Canadian General Electric Company, Ltd., Toronto, Ont.

FOR DIRECTORS

C. R. Beardsley, superintendent of distribution, Brooklyn Edison Company, Inc., Brooklyn, N. Y.

V. Bush, vice-president and dean of engineering, Massachusetts Institute of Technology, Cambridge, Mass.

F. H. Lane, manager, engineering division, Public Utility Engineering & Service Corporation, Chicago, Ill.

FOR NATIONAL TREASURER

W. I. Slichter, professor of electrical engineering, Columbia University, New York, N. Y.

The constitution and by-laws of the Institute provide that the nominations made by the national nominating committee shall be published in the March issue of ELECTRICAL ENGINEERING. Provision is made for independent nominations as indicated in the following excerpts from the constitution and by-laws:

CONSTITUTION

Sec. 31. Independent nominations may be made by a petition of twenty-five (25) or more members sent to the National Secretary when and as provided in the By-Laws; such petitions for the nomination of Vice-Presidents shall be signed only by members within the District concerned.

BY-LAWS

Sec. 23. Petitions proposing the names of candidates as independent nominations for the various offices to be filled at the ensuing election, in accordance with Article VI, Section 31 (Constitution), must be received by the secretary of the National Nominating Committee not later than March twenty-fifth of each year, to be placed before that committee for inclusion in the ballot of such candidates as are eligible.

On the ballot prepared by the National Nominating Committee in accordance with Article VI of the Constitution and sent by the National Secretary to all qualified voters during the first week in April of each year, the names of the candidates shall be grouped alphabetically under the name of the office for which each is a candidate.

(Signed) National Nominating Committee
by H. H. Henline, *Secretary*

BIOGRAPHIES OF NOMINEES

In order that those not personally acquainted with the nominees may know something of them and their qualifications for the Institute offices for which they have been nominated, brief biographical sketches are given in the "Personals" columns of this issue.

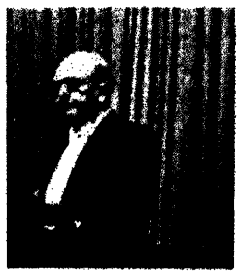
# Edison Medal for 1936 Presented to Alex Dow

FOR "outstanding leadership in the development of the central station industry and its service to the public," the 1936 Edison Medal, highest award of the AIEE, was presented to Doctor Alex Dow, president, Detroit (Mich.) Edison Company, at a special session of the Institute's 1937 winter convention, on the evening of January 27. Doctor Dow has been a member of the Institute for 44 years, having been elected an Associate in 1893, and transferred to the grade of Fellow in 1913. He has been president of the Detroit Edison Company since 1913.

A. M. MacCutcheon, president of the Institute, presided over the ceremonies, introducing first H. P. Charlesworth, past-president of the Institute, and chairman of the Edison Medal committee, who briefly outlined the history of the medal and the terms of its presentation. Mr. Charlesworth's remarks follow:

## Past-President Charlesworth Outlines History of Medal

"The Edison Medal was founded by an organization of associates and friends of Thomas A. Edison who desired to commemorate the achievements of a quarter of a century in the art of electric lighting with which Edison had been so prominently identified.



Past-President Charlesworth outlining history of medal

"It was decided that the most effective means of accomplishing this object was by the establishment of a gold medal which could serve 'as an honorable incentive to scientists, engineers, and artisans to maintain by their works the high standard of accomplishment' which had been set by Edison. The American Institute of Electrical Engineers was invited to undertake the responsibility of making the awards. The Institute accepted and organized the Edison Medal committee, or board of award, composed of 24 members.

"Three of these members are appointed each year by the president of the Institute to serve for a term of 5 years each; 3 are elected each year by the board of directors from its own membership to serve for a term of 2 years each; the other 3 members are *ex-officio*, the president, the national treasurer, and the national secretary of the Institute.

"The by-laws of the committee provide for making one award each year, and the deed of gift specifies that the award shall be made to some one resident in the United States or Canada, for meritorious achievement in electrical science, electrical engineering, or the electrical arts.

"The medal was designed by James Earle Fraser, and carries on the obverse the portrait of Thomas A. Edison, and on the reverse an allegorical conception of the genius of electricity crowned by fame."

## Louis H. Egan Eulogizes Doctor Dow

Following Mr. Charlesworth's remarks, President MacCutcheon introduced Louis H. Egan (A'08, M'15) president, Union Electric Light and Power Company, St. Louis, Mo., a long-time friend, close associate, and great admirer of Doctor Dow. Mr. Egan outlined some of Doctor Dow's accomplishments as president of the Detroit Edison Company, and related many interesting anecdotes demonstrating his fine personal characteristics.

Going back 35 years, Mr. Egan told of his first meeting with the medalist, on which occasion he (Mr. Egan) was seeking employment (which he obtained). Speaking of these early associations, he said in part: "Mr. Dow was beyond belief in his method of treatment and in the rare privilege that came to be mine of being welcomed into their home. There I came to understand one of the reasons for his success, and she is here tonight; I would indeed be derelict if I didn't mention and give full credit to the very delightful and lovely hospitality that she offered to me at that time—Mrs. Dow."

"I am not going to undertake," Mr. Egan continued, "to tell you here tonight very much, if anything, about the big boilers, or about the unusual transmission system, and the substations, and the stores department, and how we handled the meters, and all the rest of this, our public relations, and so forth. You will hear those from others, possibly, and if you don't, you can find them out very readily. They have been published many times.

"I should like to tell you just a little of the human side of this gentleman that we are honoring here tonight. I will mention just in passing, if I may, something about this company that he runs, and, rather than going to one of his intimate friends, or refreshing my own recollection on the subject, I should like to take a chapter out of the book of...the Public Utilities Commission of the State of Michigan. It is paraphrased a little, because I think I write it better than they do. It may be briefed in spots, but it is designed to serve its purpose here and the basis of it can be found in the decision of that commission; it says this:

" 'The Detroit Edison Company was organized in 1903 under the laws of the state of New York. At that time Michigan did not have corporation laws suitable to the operations of the Detroit Edison Company, which they proposed to conduct.

" 'At the time of its organization, the Detroit Edison Company took over the Edison Illuminating Company, Detroit and Michigan corporation, which had been organized under the Michigan laws, and also the Peninsula Electric Light Company, a Michigan corporation which had been organized in 1898.

" 'The Eastern Michigan Edison Company was incorporated July 24, 1906, under the laws of the state of New York, as a subsidiary of the Detroit Edison Company, for the purpose of doing certain classes of business, most of it privately owned. Electrical properties in the southeastern part of the state have since been consolidated in the Detroit Edison Company. Briefly, it covers practically all of Michigan within 50 or 60 miles of the city of Detroit, and recently it purchased the property, plant, and facilities of the Michigan Electric Power Company, operating in what is known as the thumb of Michigan. The territory served by the company has a population of approximately 2,500,000 people.

" 'The growth of the company since its organization in 1903 has been phenomenal. At the close of that year it had, according to its books, total fixed capital of less than $7,000,000. At the end of 1935, its total fixed capital was something like $290,000,000. Thus we see that in 33 years, beginning with 1903, the total fixed capital of this utility was multiplied by more than 42 times.

" 'In addition to serving electric light and power in the territory above described, the company supplies an extensive steam heating service, principally in Detroit. The investment which might properly be allocated to the steam-heating business approximates $15,000,000. It also has a small amount of manufactured-gas business.

" 'The Edison Company has grown greatly with the growth of the southeastern part of Michigan. When the company began business in 1903, the population of its territory was only about 300,000. It is now about 8 times that amount. During its existence it has purchased and taken over about 50 electric light and power plants previously owned by municipalities or by small utility companies.



Louis H. Egan sketching high lights in life of medalist

" 'It owns and operates some 7 or 8 rather small water powers on the Huron River; although most of its energy is generated in steam plants located in the vicinity of Detroit, it has one rather large steam plant near its gas utility at Marysville.

" 'The Utility under consideration has always taken care of the interests of the public. It has been a very important factor in the phenomenal growth of the territory it serves. It was one of the first utilities in the country to begin the electrification of rural territory, and at the present time about 75 per cent of the farms in its territory that it has occupied for a considerable period of time have been electrified.

" 'The stock of the company is widely distributed. It has almost 14,000 stockholders. There is no doubt about the fact that the Detroit Edison Company is one of

the outstanding electric utilities in this country. It is not owned by any holding company. It is an independent concern. Ever since its organization it has been most efficiently managed and operated. Its head during its entire history has been Alex Dow, one of the foremost electric light and power men in the United States.'

"I think probably that is the greatest tribute that has ever been paid by a regulating body to the electric light and power industry, to the man who headed a company, in this whole country, since regulation began. It is merited beyond belief. For over 40 years he has been the guiding factor and the principal factor in the creation of this company. It is recognized both in the United States and abroad as a model example of its kind."

Mr. Egan next spoke of Doctor Dow's broad general interests, mentioning specifically several widely divergent subjects with which he is conversant.

Speaking of Doctor Dow's achievements in the electric power industry, Mr. Egan said: "Would you like to know somebody who thought of most of the things that come to your minds about the light and power industry today, thought of them 25 years ago, and forgot them? If you think that you are about to develop something new in this industry, I warn you, because I have made the mistake, you had better go back and dig up the proceedings of the National Electric Light Association, and of the Association of Edison Illuminating Companies, and there you will find them expounded about a quarter of a century ago by Mr. Dow. It doesn't make any difference whether it deals with customer relations, whether it deals with street lighting, whether it deals with the contacts of municipalities, or government control; it is all there. I have looked them up and read them.

"What a great treat it must be to all these thousands and thousands of young men and women, just as it was to me, to come in contact with a mind of that kind in this business! I can't begin to tell you the thankfulness that is in my heart for the things that he did to me, sound, true, sane, stable principles that he has followed and preached since he started.

"You talk about there being no romance in business! Only careless, foolish people say that. A young boy in Scotland—nobody to help him—an orphan in his early years, people to assist; he starts out by just sheer industry, perseverance, the will to make good, he comes to this country, takes half a dozen simple jobs of one kind or another, all the time storing up in this retentive memory of his the things that are going to be to his advantage in the future.

"Finally he lands in Detroit to put in a municipal street lighting system, and, after he did it, the local company said: 'There is the type man we want.'

"He has been there 41 years doing that job. Why, it is an inspiration beyond belief! It is the kind of thing that is the United States of America at its best."

Concerning Doctor Dow's humanitarian activities, Mr. Egan said: "What he has done for people all over this country will never be known." He then mentioned several specific instances in which Doctor Dow had rendered personal assistance to people in need.

"His breast is shining with unseen medals for the goodness that he has done," Mr. Egan concluded. "I could continue this eulogy for a long, long time It has been said and said well that a big enterprise is a shadow of a man. Perhaps those who don't think well imagine it becomes trite, but it is true; it never was more fully exemplified than it was in this case.

"But the sun is setting, and the shadow becomes long. It isn't a dark shadow. It is a shadow that shines with a roseate light, a white shadow, if you will, the kind of shadow that will last forever in the district where it has first fallen, and that is what his shadow will be on his chosen state and his chosen city."



**President MacCutcheon (right) presenting medal and certificate to Doctor Dow**

## Doctor Dow Responds

Immediately following Mr. Egan's address, President MacCutcheon presented the medal and certificate to Doctor Dow, who responded, in part as follows:

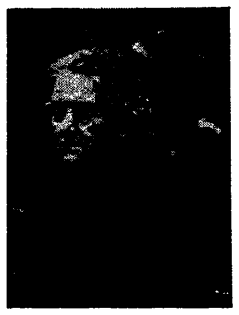


**Doctor Dow responding**

"...I plead guilty to having contributed to the development of the central station industry. I found myself in that industry, to my own great surprise, dealing with, to begin with and for several years almost continuously, properties that had been failures, trying to put them on their feet, succeeding quite a bit; at other times saying that in this particular case what was wanted was not a diagnosis and medication but a postmortem. These things happened, and that experience, I know, was exceedingly valuable to me in teaching me the things that just could not be done in that industry....

"By the time that I got through listening to the...remarks of Louis...I came to the conclusion that I must have failed in my vocation; instead of being an electric-light man doing the day's work as it came along, the best I knew how, glad when the day was done, I ought to have been a missionary or a member of a settlement, preaching the gospel... I am glad that that destiny... miscarried. I am afraid that I should have been even more weary of it than I have been at times of the day's work as it is.

"...I wish you would think of me as somebody who has just, as I have already said, done the day's work as it came to him, looked ahead, saw what could be foreseen, sometimes having a vision that was almost prophetic... At times it has been given to me to see what was coming and to see the possibilities of meeting the on-coming event in such manner as would conduce to the welfare of the service for which I was responsible; that I have taken that service seriously I wish you would think of as being assured of.



**Mrs. Dow after the ceremonies**

"As far as investment goes, it is rather a serious matter to be responsible for $300,000,000 of other people's money. As far as the care and welfare of employees go, for groups that have ranged in the last few years, even during the depression period up to about 8,000 people, and as far as service to the public goes, that Mr. Egan has stated to you; and it is a service that is unusual, exceptionally comprehensive, covering and trying to reach, everybody.

"We have been able there to have accepted by our authorities the doctrine of the economic area, separating out from individual municipalities, each insisting upon having its own accounting and its own particular rate schedule...and we have an integrated area there that is willing to be dealt with as a whole. That is the correct theory, we believe. I know that I was one of the first to point out that that was how it should be, that a service such as the central station service is, could not be congeries of local services, but must be a broad service extending over the area which was economically one area; and that is what has been sought by my people and by myself.

"Now...I have by example as well as by precept shown what may be done, shown that it is possible to get along peacefully, shown that it is possible to have no labor trouble (and I speak for myself personally, and I am touching wood when I say that in these troublesome days—touching wood and making a little prayer that it will continue). I began to boss men when I was a 14-year old boy. The men never bothered me because they were all quite willing to be bossed—it saved them from doing any thinking; but the boys of my own age, or a little older, I had to fight it out with every confounded one of them before I could get peace. I don't know any other way to get peace either in business or in politics, but to fight it out when you have to—to avoid it as long as you can but to fight it out when you have to.

"So it has gone, and, to play fair with these divergent interests and interests that may become divergent, has been my job in life—that much more than any choice in engineering matters or any development of new principles or any application of established principles.

"Let me confess here...that I have almost forgotten what it is to be an electri-

cal engineer.... I have to tell them [electrical engineers] when they come and talk to me about something new: 'Now that is all right, but settle down and tell it to me in words of one syllable.' Usually it is possible to do that and I, having no facilities whatever in the language of the mathematician and the symbols in which he expresses an idea concisely and clearly,...am glad to revert to the one-syllable plan.

"...Forty-five or 50 years ago I knew all there was to know about telegraphy, but now I don't even know the language. And it is so with many, many matters of electrical engineering nowadays... Still, I have an understanding mind; still, I am glad to have a new problem brought to me, glad to hear how it has been solved, and glad to settle down and think about it and think how that is going to fit into my day's work, into the problem of serving 600,000 customers scattered over 6,500 square miles, and that is what engineering means to me; but as for being an electrical engineer—no....

"...I found the United States, when I came to them, more than 50 years ago, a place that welcomed the youngster who was willing to take it as he found it, who had no call to show it the error of its ways, and was not only willing to take things as he found, but also willing to work hard at whatever work Providence put before him. I turned my hand to a good many things. I had a certain facility at mechanical employments.

"Before I was 20 years old I came to the United States, and I ultimately landed... into the electric light and power industry, and have stayed with it, grown up with it, was an early operator in that industry and have seen it become what it is. That has taken above all things an understanding of the American people. It has taken an infinite patience. It has taken that foresight with which I thank the Lord He has given me a certain amount of. It has taken the judgment as to what should be done when one felt what was coming. So far I have had good fortune. I hope it will continue. I trust it will continue....

"Still, after all, in these matters for which I have been given much praise tonight, I have tried to understand, I have tried to make it easier for those who needed help, and tried when it was necessary to speak the truth without malice. I have tried to be patient. I have tried even to suffer fools gladly, although that has been perhaps the most trying thing that I have had to do....

"As it is, it is anything but engineering. I wouldn't unless I were an engineer by thought and by a certain amount of training be where I am, but it is anything but engineering in the day's work; it is finance, it is management, it is law, it is politics—which I don't approve of at all. You know, you need a big sense of humor to keep your patience with politics....

"As for taking care of my people, well, and other people—things that have been wished upon me: I never believed in welfare systems—no welfare system that I know of, and that applies to a little bit of an organization...right up to the wonderful scheme for the betterment of 15 or 20 million people that we now have on our lists, so many of them capitalized with 3 or 4 initials...As to these things, I admit having done what came to my hand, and I have summed up my philosophy of such matters in a very, very few words: ...Do what you can, what is within your powers, what is within your duty, if it may so happen, for ...,the person—man or woman—who does need help; do it quietly and kindly, without any fuss and botheration. Don't do it mechanically. Do it personally. If you cannot do it personally yourself, at least see that the job is done. Delegate it to someone that is light of hand and will not try to make people feel grateful. That kind of gratitude I don't much like. It reminds me of that definition of gratitude: 'Gratitude is a lively sense of favors to come.' Do it quietly, as I have said; do it patiently and kindly; thank God that you have had the chance to do it; and, forever afterward, keep your mouth shut about it.

"I think I have said a plenty. Thank you for listening, and this [the medal] I am highly honored by."

# Reports of 15 Committee Meetings Held During the Winter Convention

BRIEF reports of the meetings of 16 Institute committees and subcommittees held during the Institute's recent winter convention are presented herewith, as prepared by the committee chairmen or from notes submitted by them. These reports cover meetings of 2 general committees, 6 technical committees, and 7 subcommittees of technical committees. Reports of the meetings of 4 subcommittees of the protective devices committee have been combined with that of the parent committee.

No report of the meeting of the committee on electrophysics was submitted, but according to Chairman R. C. Mason that committee "met to consider plans for future activities." In addition, no report of the standards committee meeting is included here, but actions of this committee on items of interest to the membership are reported in the "Standards" columns elsewhere in this issue. A scheduled meeting of the committee on electric welding was not held.

## Membership Committee

By G. A. Kositzky, Chairman

Some 21 of the members of the national membership committee attended the meeting of the committee held January 27, 1937, at national headquarters in New York during the recent winter convention. The several matters of routine business that were discussed have been reported to all members of the committee through the medium of the minutes of the meeting.

Special attention was called to the new pamphlet containing an article by E. S. Lee, former national membership chairman, entitled "Membership in the American Institute of Electrical Engineers." This article is highly informative concerning Institute activities, and has been distributed by mail to all Institute members. These booklets are available from national headquarters.

## Sections Committee

By W. H. Timbie, Chairman

The Sections committee is unanimous in believing that a thoroughgoing survey should be undertaken immediately of the activities of the Sections. The majority believes that a "field survey" should be made by a competent investigator; the rest are of the opinion that a questionnaire survey is all that is necessary. Consequently, it is proposed that a special survey be made, the committee sending to the chairman of each Section a "self-analysis blank," by means of which each Section chairman, assisted by his Section secretary, may analyze the activities of his Section stating specifically:

*A.* Aims or objectives of the Section.

*B.* Activities now carried on to attain these objectives.

*C.* Critical examination of the results of these activities.

*D.* Necessary or desirable change in activities.

The objective of this survey is: first, that the Sections examine themselves in order to crystallize their objectives and reasons for and results of their activities; second, from a study of the returns the Sections committee hopes to obtain facts and data that will enable it to assist the several Sections in reaching a clearer understanding of the aims and in more effective methods of obtaining them.

It is especially desired that ways may be opened up for: (*a*) further co-operation between a Section and other community-minded groups that would profit by the help of the engineer; (*b*) more effective co-operation between the Sections committee and the various Sections; (*c*) greater co-operation between Sections. This preliminary survey should likewise give a fair indication as to whether a "field survey" is necessary or desirable.

The committee plans to co-operate to the fullest extent with the newly appointed special committee on the broadening of Institute activities.

## Automatic Stations Committee

By M. E. Reagan, Chairman

Because of the enthusiastic reception that has been accorded the subcommittee's report on supervisory control and telemetering, by operating people, it was decided to bring this report up-to-date and request its publication in ELECTRICAL ENGINEERING. The subcommittee appointed to follow this program is as follows: Chester Wallace, American Telephone and Telegraph Company, New York, N. Y.; P. A. Borden, Bristol Company, Waterbury, Conn.; M. E. Reagan, Westinghouse Electric & Manufacturing Company, East Pittsburgh, Pa.; and A. E. Anderson, General Electric Company, Philadelphia, Pa.

It was suggested that the committee undertake a study of operating practice on short-circuiting or open-circuiting of neutral-grounding resistances in case of circuit

breaker failure on ground faults. It was believed, however, that this was a function of the committee on power transmission and distribution. It was decided to offer the assistance of the automatic stations committee to the committee on power transmission and distribution in co-ordinating any investigation of this problem.

A request for a round-table discussion on automatically controlled hydroelectric generating stations at the Institute's 1937 summer convention was discussed at some length. It was decided that the committee would sponsor such a meeting if the convention committee considers that there is enough general interest in the subject. At the request of the summer convention committee, the automatic stations committee will co-operate in a general discussion on "control" to be held at that convention.

Preliminary reports were made by 2 subcommittees on the general subjects of:

(*a*) Battery-charging methods in unattended stations.

(*b*) Reclosing of breakers on bus-differential operation.

AIEE Standards No. 26, which is now undergoing consideration by the American Standards Association, was again reviewed.

## Committee on Electrochemistry and Electrometallurgy

By F. O. Schnure, Chairman

On the subject of electrolytics, the committee is now formulating plans for a round-table conference to be held in connection with the Institute's forthcoming summer convention. It is the committee's plans to broaden the scope of the intended discussion by inviting to participate in it, members of other technical societies interested in the various aspects of the general subject of electrolytics. As chairman of the committee to plan this conference, N. R. Stansel of the industrial engineering department, General Electric Company, Schenectady, N. Y., and former chairman of the committee on electrochemistry and electrometallurgy, was appointed. Looking forward to the 1938 winter convention, the committee also is considering the possibility of developing for the program of that convention a symposium on the subject of electrolytics, or some other subject growing out of the intended summer-convention round-table conference.

There was considerable discussion on the question of a "definition of the committee's function." As this is now "defined" or understood, the scope of the committee's activities can include either the thermal applications of electricity, the electrolytic applications of electricity, or both. To study the subject and report later to the committee a recommended definition of function and scope of activity, a subcommittee has been appointed.

Brought forth during the committee's general discussion were strong suggestions to the effect that the Institute membership should be "classified according to interests and professional work."

## Committee on Protective Devices

By J. P. McKearin, Chairman

Rules were adopted to govern the standing subcommittees of this committee in the preparation of their annual reports. These reports are to show the extent of the subcommittee programs and to give all members of the protective devices committee and all members of all the subcommittees the benefit of a record of the work that has been done, so as to maintain the continuity of subcommittee work from year to year.

A resolution was adopted, recommending to the Institute's standards committee that the revised AIEE Standards No. 22, on "air switches," be published in report form.

Arrangements were made to obtain improvements in the report on Standard No. 23, for "relays," to bring these Standards up to date.

Plans were made for participation by this committee with the committees on power transmission and distribution and electrical machinery in a proposed joint session at the Institute's 1937 summer convention on "lightning protective equipment and insulation co-ordination." Considerable interest has been shown in this type of session.

### Circuit Breakers, Switches, and Fuses

The subcommittee on circuit breakers, switches, and fuses, H. J. Lingal, chairman, made further plans for its work on recommendation for improvements in AIEE Standards No. 19, for "oil circuit breakers," and proposed Standards No. 25, for "fuses above 600 volts." This work is the result of suggestions received from the industry at large in response to the invitation for opinions, criticisms, and suggestions printed on the recently published reports on these 2 standards.

### Relays

The subcommittee on relays, E. E. George, chairman, reviewed its program, which includes: "application of electronics to relay protection," "trend of distribution relay protection," "standardization and simplification of relay design and application," and "high-speed protection and reclosing."

### Fault-Current-Limiting Devices

The subcommittee on fault-current-limiting devices, J. O'R. Coleman, chairman, reviewed its program and made further plans for its work which includes "a survey of grounding practices," "mutually-coupled reactors," and preparation of new standards for "fault current limiting devices for neutral grounding."

### Lightning Arresters

The subcommittee on lightning arresters, J. R. North, chairman, gave further consideration to arrangements for the proposed joint session at the summer convention and discussed its work on other projects which include: "testing procedure for lightning arresters," "performance characteristics of lightning arresters," "performance characteristics of the various forms of protective gaps," "application of lightning arresters," "specific lightning arrester protection problems," and the preparation of a new standards for "protective gaps."

Chairman North says that the lightning arrester subcommittee has a rather extensive program outlined for the year. He has prepared the following report of the meeting of that subcommittee from reports presented by the sponsors of each of the "sub-groups" on the scope and status of their work.

*Testing Procedure for Lightning Arresters—Herman Halperin.* This group is determining proper methods and test procedure for ascertaining the condition of lightning arresters in service and as received from the manufacturers. Both station and line type arresters are included. Suitable


## Membership—

Mr. Institute Member:

The young engineer looks to the leaders in his profession for guidance and inspiration—for leadership. The American Institute of Electrical Engineers is leadership in organized form; it represents and speaks for all electrical engineers as a group.

An interested and inclusive membership assures you of a strong, representative, and effective organization. You can do yourself and your associate engineers, who are not members, a service by securing their applications or by sending their names to your membership committee.

Vice-Chairman, District No. 5
National Membership Committee

test procedures are being drafted, and arrangements are being made for disseminating this information.

*Performance Characteristics of Lightning Arresters—K. B. McEachron.* This group is assembling specific and comparative information regarding the 60-cycle and protective characteristics of modern lightning arresters. Present published data regarding arrester characteristics is not on a uniform basis and is, therefore, not directly comparable. It is planned to have the results of this work in shape for submitting as a tentative report at the Institute's 1937 summer convention.

*Rod Gaps, Expulsion Gaps, and Deion Gaps—J. J. Torok.* The possibility of developing AIEE Standards for gaps and the performance of different types of protective gaps was discussed in considerable detail, and it was decided that the preparation of standards should await the results of the "Manufacturers' Inter-Company Laboratory Group" studies which are now in progress. In the meantime, a summary outlining the status of protective gaps generally is to be prepared so that this information may be readily available for use.

*Application of Arresters and Influence of Station Equipment—J. R. North.* This sub-group is dealing particularly with the proper application of lightning arresters and the standardization of terminology regarding arrester connections as used with distribution transformers. A memorandum covering this work will be sent out to the members of the subcommittee for consideration within the next few months.

*Specific Protection Problems—A. H. Sweetnam.* The proper means of protecting various equipment, including constant current transformers, regulators, line switches in open position, etc., is being studied by this sub-group and a memorandum summarizing current practices is to be prepared and distributed as a matter of information.

*Proposed Institute Papers.* Several papers proposed for presentation before the Institute were discussed. Three papers were proposed as part of a joint symposium on the subject of "Protective Equipment and Insulation Co-ordination," and it was decided that every effort should be made to insure the placing of this joint session on the program for the 1937 summer convention.

## Committee on Production and Application of Light

By A. L. Powell, Chairman

Following a review of the work of the committee for the year to date, the chairman pointed out that one technical paper* and several brief contributions† on recent advances in the field of illumination are now awaiting publication in ELECTRICAL ENGINEERING. Inasmuch as the Institute's publication committee has decided that it is expedient to publish more items of general interest, the committee decided to re-establish its policy of supplying a series of short illumination notes so that the editor might have these on hand for use as filler material when occasion arises. Members of the committee were urged to prepare such items on current advances in illumination that come to their attention and submit them to the chairman.

Plans for the session on lighting to be held during the Institute's 1937 summer convention were discussed, and the desirability of avoiding a parallel session was emphasized. There was some discussion also of the various papers proposed for presentation at that session.

* See pages 319–24.
† See pages 302–04.

## Committee on Power Generation

By G. M. Armbrust, Chairman

Recent developments in subjects pertaining to the work of the committee were discussed.

It is the opinion of the committee that sufficient new material for papers is available for a session on power generation at the Institute's 1938 winter and the following summer conventions.

The committee will endeavor to arrange symposia covering 2 or 3 subjects such as "superimposed units, their economic advantages and justification," and "parallel operation of power plants and interchange of power over transmission systems."

## Committee on Research

By W. B. Kouwenhoven, Chairman

This meeting was attended by 18 members. F. M. Farmer reported that funds had been raised for carrying on the investigation on the "stability of impregnated paper insulation" under the direction of Doctor J. B. Whitehead of Johns Hopkins University. He also reported that the work had been started December 1. The supervisory committee co-operating in this investigation consists of H. H. Race, *chairman*, General Electric Company, Schenectady, N. Y.; R. W. Atkinson, General Cable Corporation, Perth Amboy, N. J.; W. F. Davidson, Brooklyn (N. Y.) Edison Company; R. J. Wiseman, Okonite Company, Passaic, N. J.; and K. S. Wyatt, Detroit (Mich.) Edison Company. This committee reported that it had met with Doctor Whitehead and had unanimously agreed to a definite plan of procedure in carrying out the investigation. Mr. Farmer then reported on the status of the funds for the "investigation in the field of electric shock." He stated that the necessary funds had not been fully raised and that the balance is expected to be available within a short time.

Mr. Farmer also reported on the list of research projects that the research committee has circulated in the past, which list he is now revising. He especially requested the members of the committee to furnish him with suggestions; suggestions from others also are welcome. He reported that the previous lists had proved very useful.

A discussion followed of the methods by which members of the committee could best co-operate with their local Institute Sections. It was decided that each national committee member should offer his services to the chairman of his local Section.

The Committee decided to hold a session at the Institute's 1937 summer convention; 4 papers were proposed for this meeting.

The committee also discussed the question of rural electrification and the problems that exist in that field. K. K. Paluev presented an excellent summary of the economic features of rural electrification. The chairman was instructed to present this to the newly appointed special committee on Institute activities.

## Electronics Subcommittee

By H. M. Turner, Chairman

At the meeting of this subcommittee, which is a joint subcommittee of several of the Institute's technical committees, further consideration was given to plans for the 1937 summer convention. It is hoped that the electronics subcommittee will have at least one formal paper (preferably from the Milwaukee, Wis., region) and a conference on electronics with emphasis on industrial applications. The details will be worked out with the convention committee in the near future.

Preliminary plans were made looking toward a rather ambitious program for the AIEE winter convention in 1938. It seems likely that 2 sessions will be required to cover adequately the various phases of electronics, and there probably will be a conference which will permit a more complete and informal discussion of points brought out in the formal presentation. The electronics subcommittee will work with other committees in bringing into focus electronic developments and applications and in unifying them for the benefit of the Institute membership. It will continue the symposium idea that was so successful 2 years ago, but on a somewhat different basis.

Several subjects that have been proposed were considered from the standpoint of their suitability for discussion at the Institute's 1938 winter convention.

## Group III of Subcommittee on Conductors, Towers, and Wood Poles

By Edwin Hansson, Chairman

This was a routine meeting of this group, which is one of 3 groups of the subcommittee on conductors, towers, and wood poles, of the Institute's power transmission and distribution committee. Group I is concerned with towers; group II with wood poles, and group III with conductors. Group III was established for the purpose of studying particularly the question of vibration in transmission line conductors, and to establish satisfactory endurance limits. This work is progressing.

## Transformer Subcommittee

By I. W. Gross, Chairman

Transformer standards came up for extensive discussion at the meeting of this group, which is a subcommittee of the Institute's committee on electrical machinery. The sectional committee on transformers of the American Standards Association for some time has been preparing, and now is about to issue, a report on a proposed American Standard on power transformers that is scheduled to embrace the AIEE standard "transformers, induction regulators, and reactors (AIEE No. 13), the AIEE publication "Recommendations for the Operation of Transformers" (AIEE No. 100), and the AIEE proposed "Test Code

for Transformers." The AIEE transformer subcommittee is keeping closely in touch with this development, co-operating with the ASA sectional committee on transformers, and expects to keep in touch with the situation until such time as the expected reports shall have run the gamut of evolution and emerged in final form.

With reference to present impulse tests, the subcommittee unanimously agreed to alter the method of designating impulse voltages as used in the impulse testing of transformers—from inches-of-gap to kilovolts—without in any way changing the magnitude or character of the tests. This is a change in terminology only, leaving test procedure unchanged.

To study and later to recommend practical methods for the drying out of transformers in the field, a subcommittee group has been set up. Recognizing that circumstances frequently prevent the shipment of damaged apparatus from the field to laboratories, repair shops, or other concentration points fully equipped with rehabilitation equipment, and recognizing also the limitation of equipment and specially trained personnel in the field, the subcommittee's desire is to establish specifications of practical procedure that will obviate the possibility of damage to transformers that would result from exceeding safe temperature limits during the dry-out period.

To bring up to date the information concerning impulse strength of transformers, a subcommittee technical paper was proposed to give full consideration to this as well as to other related phases of the general problem of insulation co-ordination.

Methods of making front-of-wave impulse tests on transformers were discussed at some length. Consensus of opinion, however, was to the effect that further study is required before any standard could be promulgated.

The problem of establishing, in terms of the normal clearance of the bushing alone, minimum limits of acceptable (or safe) mechanical clearance between bushing terminals and case or other nearby integral parts of a transformer was discussed and assigned to a sub-group for further study and later report.

Comments and suggestions pertaining to any of the foregoing points are solicited by the subcommittee.

# Reports of 4 Technical Conferences Held During the Winter Convention

TO PROVIDE opportunity for the informal "round-table" discussion of technical subjects of a specialized nature, 4 "technical conferences" were held during the Institute's 1937 winter convention, under sponsorship of 3 technical committees and 1 subcommittee. Brief reports of these conferences are presented here. These reports have been prepared by the presiding officers of the respective conferences, except for the conference on test codes for rotating machines, which was prepared by the chairman of the sponsoring technical committee.

## Education

By O. W. Eshbach, Chairman

This morning-long round-table conference sponsored by the Institute's committee on education drew an attendance of more than 40 committee members and other interested persons, taxing the facilities of the board room where the meeting was held.

Although several different subjects pertaining to the committee's work were entered for discussion, the major portion of the time was devoted to a general discussion concerning some of the many factors involved in the current program of the Engineers' Council for Professional Development incident to the accrediting of engineering curricula in the principal educational institutions in the United States. Recent experiences incident to this accrediting program in the New England and Middle Atlantic areas were discussed at length, and special attention was given to an informal outline and explanation presented by Doctor A. B. Newman covering the long-established accrediting practice of the American Institute of Chemical Engineers.

Concerning the question of what constitutes adequate and otherwise acceptable "minimum standards" of engineering education, the general consensus of opinion was that this highly ramified subject presented many related aspects such that there can be no written specification but the judgment of experienced people must prevail.

The committee discussed its plans for participation in the program of the Institute's forthcoming summer convention, and laid definite plans for a 1938 convention program appointing a "steering committee" consisting of O. W. Eshbach, chairman of the committee on education; Dean J. W. Barker of Columbia University; and Professor Robin Beach, head of the department of electrical engineering, Brooklyn Polytechnic Institute.

## Network Analysis and Synthesis

By Edward L. Bowles, Chairman

At this conference, which is the second of its type to be sponsored by the Institute's committee on communication, the subject of special network problems that have arisen in connection with the design of radio receivers was presented for discussion as follows:

1. SIDELIGHTS ON THE MULTIPLEX ANTENNAPLEX SYSTEM, by V. D. Landon (this subject deals with filters, amplifiers, and transformers involved in the operation of an antenna system over a wide range of frequencies).
2. CONSTANT-$k$ MULTITRANSFORMER FILTERS FOR COVERING A WIDE RANGE OF FREQUENCIES, by H. A. Wheeler.
3. DRIVING A FILTER FROM A REACTIVE GENERATOR, by H. A. Wheeler.
4. THE USE OF THE MU-BETA DIAGRAM IN THE ANALYSIS OF FEED-BACK CIRCUITS, by H. F. Mayer.
5. THE PROPERTIES OF DIRECTIVE MUTUAL REACTANCE OBTAINED BY THE USE OF VACUUM TUBES, by H. A. Wheeler.

The presentation elicited a very wholesome discussion which was entered into freely by the many individuals whose work dealt with problems in or relating to the field of radio receiver design. From the observers point of view, it was gratifying to see such freedom of discussion and apparent lack of hesitation in the expression of opinion.

The subject of the program quite naturally led to the conclusion that very soon the field of network theory will be generally recognized to include active circuit elements, such as vacuum tubes, and other general circuit elements as, for example, the already applied piezo-electric crystal, and



A group of alumni of the University of Illinois attended the smoker held during the Institute's 1937 winter convention, including 11 members of the class of 1909 all of whom had not been together at one time since graduation. Left to right, seated: H. A. McCrea (A'23, M'30) Boston, Mass.; E. C. Nein, New York, N. Y.; D. A. Henry, New York; P. M. Farmer (M'19) New York; and R. E. Doherty (A'16, M'27, past-chairman of committee on education) Pittsburgh, Pa.; standing: H. C. Dean (A'26, M'29, chairman of board of examiners) New York; E. D. Doyle (A'09, F'27) Philadelphia, Pa.; A. B. Campbell (A'20, M'24) New York; H. D. Braley (A'18) New York; B. M. Fast, New York; I. W. Fisk (A'10, M'13) New York; W. C. Nein (A'08, M'25) New York; M. E. Reagan (A'20, M'30, chairman of committee on automatic stations) East Pittsburgh, Pa.; H. G. Wood (A'23, M'28) Harrison, N. J.; E. S. Lee (A'20, F'30, past-chairman of membership committee) Schenectady, N. Y.; H. O. Siegmund (A'19, M'27) New York; and H. H. Henline (A'19, M'26, national secretary) New York

that future applications of these newer circuit elements will lead to great departures from what may be termed conventional selective network design.

The substantial attendance at both this conference and the one held during the 1936 winter convention is, it appears, an indication of the worth-while nature of meetings of this character which, if they are continued in a vigorous manner, should serve a very useful purpose in aiding the development and application of network theory through personal contact and free and liberal interchange of ideas.

## Sound Measurement

By P. L. Alger, Chairman

Specialists of other organizations, as well as Institute members attended this conference, which was sponsored by the subcommittee on sound of the Institute's standards committee. A draft of a proposed test code for the measurement of apparatus noise was reviewed and approved in final form for submission to interested individuals and organizations for approval and subsequent printing by the Institute. This new code is based upon the already published American Standards for acoustic terminology, sound measurements, and sound level meters (*Z*24.1, *Z*24.2, and *Z*24.3). These standards, however, only define means of measuring the sound level at any single point in space and give no information on how to describe the noise produced by apparatus, which involves taking a number of sound-level readings at different locations around the apparatus, and evaluating the effects of ambient sound level, sound reflections from walls and other parts of the environment, and transmitted vibrations. The new code describes both factory and field test procedures necessary for these purposes, but leaves to the individual manufacturer, industry, or user of apparatus the specification of the number of measurements, distances, and other factors, which may be most suitable in any particular circumstances.

The code should serve a useful purpose in educating both makers and users of apparatus to their separate responsibilities for securing quieter living conditions, and in enabling the various causes of unsatisfactory noise conditions to be more quickly traced and remedied.

Following the discussion on this test code, the question of further activity of the subcommittee on sound was considered briefly. It was decided that the subcommittee should continue its work, chiefly for the purposes of education and organized discussion of noise problems. In this connection, it was suggested that a joint round-table session might be held with the Institute's committee on electrical machinery to discuss questions related to the use of elastic mountings for electric motors and transmitted noise problems.

## Test Codes for Rotating Machinery

By J. L. Hamilton, Chairman, Committee on Electrical Machinery

This report gives a brief résumé of the development of test codes for rotating electrical machinery, and presents an outline of the discussion and action taken at this conference, which was sponsored by the committee on electrical machinery. G. A. Waters, chairman of the induction machinery subcommittee, presided. Future activities of the committee in connection with each of the codes are indicated.

In May 1929, the board of directors of the Institute approved a proposal of the standards committee calling for the development of test codes for the principal types of electrical machinery and apparatus. The actual formulation of a series of such codes was then placed by the standards committee in the hands of the committee on electrical machinery. In July 1931 that committee made its first report, submitting "Test Code for Transformers." The "Test Code for Synchronous Machines" was the second, and "Polyphase Induction Machines" the third of the proposed series. A test code for d-c machines is being developed at the present time. That the electrical industry might become fully cognizant of the work that has been undertaken and at the same time obtain a clear picture of the proposed contents of such codes, the standards committee arranged for their publication as reports in pamphlet form.

In order to determine the performance characteristics of electrical machines, methods of testing, or test codes, have been developed and are in common usage. It is the purpose of these test codes to provide in convenient reference form the more generally applicable and accepted methods of conducting and reporting tests of a commercial nature, which apply to the fulfillment of performance guarantees and to acceptance tests. It is not intended that the codes shall cover all possible tests or those of a research nature. It must be recognized that the selection of the most suitable test depends upon local conditions and the degree of precision desired.

The subcommittee on synchronous machines has prepared another preliminary report on a proposed test code for synchronous machines which was printed January 1937 and is available for distribution.

The discussion of test codes for synchronous machines developed some suggested changes which were referred to the chairman of the subcommittee on synchronous machines for consideration and action.

The first preliminary test code on polyphase induction machines was printed and distributed in January 1935. Many valuable suggestions for changes and improvements in this preliminary code have been received and considered; these were incorporated in a report by the subcommittee on polyphase induction machines and were considered at this round-table conference. The conference approved the releasing for publication of the code for polyphase induction machines after the editing committee has completed its work. It has not yet been decided as to whether this test code will be recommended to the standards committee as a second preliminary report or otherwise.

The work on the test code for d-c machines had developed to the point where a few copies of a preliminary report on the proposed code were distributed in January 1937 for use at this conference. Suggested improvements in the preliminary report were referred to the chairman of the subcommittee for consideration and action. The subcommittee's final report will probably be printed as a preliminary report on a proposed test code for d-c machines.

The committee on electrical machinery takes this occasion to draw attention to the value of criticisms based upon experience. Any suggestions looking toward improvement in these codes will be welcome for guidance in the preparation of future editions.

# ASTM Standards on Insulating Materials

A compilation of all the standards of the American Society for Testing Materials pertaining to electrical insulating materials has been issued in a 1936 edition which includes a number of revised test methods covering the following: varnishes, solid filling and treating compounds, sheet and plate materials, natural mica, untreated paper, insulating oils, and varnished cloths and tapes. Revised specifications cover friction tape, black bias-cut varnished tape, and asbestos yarns, tape, and roving.

In addition, standards are given also for rubber gloves, rubber matting, electrical cotton yarns, silk and cotton tapes, pasted mica, and slate; also rubber insulating tape, flexible varnish tubing, and electrical porcelain. Test procedures cover thickness testing, impact resistance, thermal conductivity, and resistivity. The 1936 report of committee *D*-9 on electrical insulating materials is included; this report outlines the extensive research and standardization work being carried on by the committee. Copies, in heavy paper cover, can be obtained at $2 each from ASTM headquarters, 260 South Broad Street, Philadelphia, Pa.

# Springfield Section Offers Electronic Course

A course of instruction in electron theory, tubes, and circuits is being given under auspices of the AIEE Springfield Section in order to provide an opportunity for acquiring knowledge of an increasingly important subject at reasonable cost. Classes meet weekly, the course covering approximately 18 weeks, and each class is limited to 25. Preference is given to members of the AIEE, but nonmembers are admitted upon the payment of $1 in addition to the regular $10 fee for the course. For the additional fee, nonmembers become local members of the Section for the remainder of the Section year.

The course is planned for beginners in the study of electron theory, but students are expected to have a working knowledge of a-c and d-c theory and electrical-engineering terminology. D. E. Noble (A'32) assistant professor of mechanical engineering at Connecticut Agricultural College, has been chosen as instructor for the course.

# Doctor Elihu Thomson Honored at Welding Session

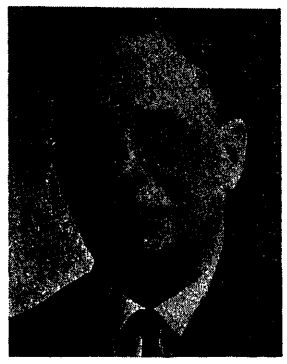
PRESENTATION and discussion of the paper "Resistance Welding Circuits" by C. L. Pfeiffer (A'21, M'27) constituted the first item on the program of the session on electric welding held during the Institute's recent winter convention. This paper was published in the August 1936 issue of ELECTRICAL ENGINEERING, pages 868–73. At the conclusion of the discussion, a demonstration lecture entitled "Some Fundamental Phenomena of the Electric Arc" was presented by Doctor C. G. Suits of the research laboratory, General Electric Company, Schenectady, N. Y. Following Doctor Suits's lecture and the ensuing discussion, Herman Lemp (A'89, F'13) consulting engineer of the Ingersoll-Rand Company, New York, N. Y., presented reminiscences of Professor Elihu Thomson's fundamental invention of electric resistance welding. His address was supplemented by remarks by Albert L. Rohrer (A'87, M'88) retired, Maplewood, N. J., who is said to be the only living witness of Professor Thomson's early efforts to develop the resistance-welding art. H. M. Hobart, chairman of the Institute's committee on electric welding, presided at the session; he was assisted by K. L. Hansen, ex-chairman of the committee on electric welding, and W. E. Crawford, a member of the committee for the past 5 years.

### LECTURE BY DOCTOR SUITS

Doctor Suits has supplied the following abstract of the material used in his demonstration lecture:

*Contemporary Arc Theory.* The Compton theory of the electric arc serves as the foundation for the development of the modern thermal concept of the high pressure discharge. Measurements of arc-core temperatures made by several methods, such as (1) from gas density, by X ray absorption (VonEngel and Steenbeck), (2) spectrographic observations (Ornstein), or (3) by the velocity of sound waves (Suits), show that the arc core is a body of gas ionized to a degree determined by its temperature of approximately 5,000 degrees Kelvin. In this high-temperature arc core the current conduction is by a thermal ionization process in quantitative agreement with Compton's theory in cases where the measurables are known. On the basis of this picture the core of an arc in air has the following properties: Its temperature lies in the range of from 4,000 to 7,000 degrees Kelvin; its composition is of the order of 20 per cent $N_2$, 25 per cent O, 55 per cent N; partial pressure of electrons is $10^{-4}$ atmospheres; the mean density is 0.00003 or approximately $^1/_{30}$th that of air at the same pressure and at room temperature; the gas viscosity is approximately 0.0016, which is nearly as great as that of water at the boiling point; the effective ionization potential lies in the range between 8 and 15 volts.

*Arcs at Very High Pressures.* New arc data presented in the practically unexplored field of very high gas pressures. To cover this range several experimental chambers are employed. Transient arc stability is studied in a very small chamber up to pressures of 50 atmospheres. A second chamber, which employs a window, allows measurements of current, current density, and electric gradient up to 200 atmospheres. A third hydraulic-ram chamber allows measurements of current, voltage, and light quality up to 3,500 atmospheres. It has actually been used with nitrogen up to 1,275 atmospheres (18,800 pounds per square inch). In general, it is found that the current density, electric gradient, and arc luminosity increase with pressure. Probably the most important result of this study is the following correlation: Arcs in various gases and at various pressures develop the same current density and electric gradient at the pressures for which the heat transfer is the same. Thus the arc in hydrogen at one atmosphere should have the same current density and electric gradient as the arc in nitrogen at approximately 100 atmospheres, in agreement with experiment. Using this correlation law, arc properties can be predicted in a pressure range for which the measurements may be difficult or impossible. The generality of the theory awaits more complete measurements, but in the cases of nitrogen and hydrogen the agreement with experiment is as good as the knowledge of heat transfer allows.



**Doctor Thomson**

Following his talk, Doctor Suits demonstrated some of his results by throwing an enlarged image of an experimental electric arc onto a ground-glass screen so that those in the audience could see.

*Experiment 1.* This showed the arc between pure carbon electrodes, with an arc length of 3 millimeters, and an arc current of 6 amperes (d-c). From the image projected on the screen, the arrangement and position of the electrodes and the dimensions of the arc column could be seen for comparison with the following experiments.

*Experiment 2.* For the same electrodes, arc length, and arc current, the arc in hydrogen at a pressure of 1 atmosphere was shown. The much smaller diameter of arc column with resultant increase in current density appeared from the reduced size of the image.

*Experiment 3.* For the same conditions as for experiments 1 and 2, the arc was shown in commercially pure nitrogen at a pressure of 1 atmosphere. This arc appeared to have characteristics quite identical with those of the arc in air.

*Experiment 4.* For the same electrode arrangement and current the arc was burned in nitrogen at a pressure of 80 atmospheres. At this pressure the arc cross-section decreased and the current density was nearly as great as in hydrogen at 1 atmosphere. When the pressure was reduced from 80 atmospheres to 1 atmosphere, the continuous increase in arc diameter with decrease in pressure was visible.

In the discussion that followed, the opinion was expressed that the results presented by Doctor Suits are of fundamental importance in the study of the electric arc, and that a published paper reporting those results would prove highly valuable for reference purposes.

### TALKS BY MESSRS. LEMP AND ROHRER

The following summary of remarks by Herman Lemp and Alfred L. Rohrer was prepared by Doctor G. E. Claussen of The Engineering Foundation, who attended the session.

Mr. Lemp referred to the Franklin Institute lectures in 1878 by Professor Thomson, in which electrical discoveries were discussed. It was at this time that Professor Thomson commenced experiments leading to the development of electric resistance welding. He discharged a Leyden jar through the secondary of a Ruhmkorff coil. The ends of the primary, being close together, were found to have stuck together as a result of the discharge. Following the lead provided by this experiment, Professor Thomson was able in 1885, to make practical applications of electric resistance welding, as it is now known.

Mr. Lemp then interrupted his remarks to introduce Mr. Rohrer, another former associate of Professor Thomson. Mr. Rohrer made a verbal sketch of the qualities that characterized all of Professor Thomson's work and made him a supreme experimentalist and scientist. Professor Thomson was among the first to become convinced that all metals and alloys are weldable by the resistance process. The Ruhmkorff coil used by Professor Thomson in his early experiments, and having a capacity of 2,000 to 3,000 amperes is still in existence at Thomson's laboratory, Lynn, Mass. Mr. Rohrer concluded his remarks by contrasting the experimental equipment for resistance welding used by Professor Thomson in the eighties with present-day resistance-welding machines of several types used extensively in industry.

After Mr. Lemp had shown slides of resistance-welding equipment, he resumed his reminiscences of the early developments of the Thomson electric resistance welding concern. He presented brief biographies of several engineers who made noteworthy contributions to that development, including the following Institute members: Walter S. Moody (A'06, F'12), Russell Robb (A'93, M'95), G. F. Sever (A'94, F'12), A. R. Everest (A'04, M'04); Messrs. Robb and Everest are deceased. Mr. Lemp referred particularly to several of the outstanding achievements of the Thomson concern in the field of transformer and rotary convertor construction. Among other in-

teresting anecdotes, he recounted the experiences he had in applying electric resistance heating to the local annealing of hardened steel, such as armor plate, for the United States Navy. The process was first applied in the construction of the famous battleship "Oregon" shortly prior to the war of 1898. Mr. Lemp also made it plain that the scope of the activities of the Thomson concern was international.

At the conclusion of Mr. Lemp's talk, those in attendance voted to send the following telegram to Professor Thomson:

"We, members and guests of the American Institute of Electrical Engineers, here assembled, in reviewing the past, present and future of an art created by your vision and perseverance, send greetings to you and the assurance of our appreciation of what your work has meant to industry and the arts, and which in the hands of capable young engineers is bound to become more valuable as time goes by on the foundation laid down by you."

Before the meeting was adjourned, President MacCutcheon spoke briefly, stressing especially the importance of resistance welding to electrical engineers, first, because the process is fundamentally electrical, and second, because the process is very widely used in the construction of electrical machinery.

# Usefulness of Tensors Probed at Convention Session

WITH E. E. Dreese (M'25) chairman, electrical engineering department, Ohio State University, Columbus, presiding, more than 100 attended both the morning and afternoon sessions on tensor analysis, held on Tuesday, January 26, during the Institute's recent winter convention. The following 5 papers, all published in ELECTRICAL ENGINEERING, were presented:

1. THE TENSOR—A NEW ENGINEERING TOOL, A. Boyajian. April 1936 issue, pages 856–62.

2. TENSOR ALGEBRA IN TRANSFORMER CIRCUITS, L. V. Bewley. November 1936 issue, pages 1214–19.

3. TENSOR ANALYSIS OF MULTIELECTRODE TUBE CIRCUITS, Gabriel Kron, November 1936 issue, pages 1220–42.

4. DYADIC ALGEBRA APPLIED TO 3-PHASE CIRCUITS, A. Pen-Tung Sah, August 1936 issue, pages 876–82.

5. COMPLEX VECTORS IN 3-PHASE CIRCUITS, A. Pen-Tung Sah, December 1936 issue, pages 1356–64.

Following the formal presentation of the papers, the sessions were featured by enthusiastic discussions by members and some guests who were invited, because of their particular qualifications, to present informal discussions on the papers. Among the invited discussers was Doctor Banesh Hoffman, of the Institute for Advanced Study, Princeton (N. J.) University, who discussed the papers from the point of view of the mathematician, showing the simplicity of the tensor method by assuming a simple hypothesis in the physics of motion and developing it into a tensor expression. He pointed out the advantages of tensors in distinguishing physical phenomena by avoiding the use of specific coordinate axes and reference frames; however, he expressed the belief that at present electrical engineers are not using tensors as they are known in the realm of pure mathematics, but are using a modified form of tensor theory.

Doctors Oswold Veblen and H. W. Tucker, also of the Institute of Advanced Study, Princeton University, continued the discussion of the purely mathematical aspect of tensors. Doctor Veblen spoke briefly about the controversial aspect of tensor analysis and its introduction as an engineering tool, comparing the present controversy to the disputations aroused by the introduction of quaternions as an analytical aid. He stated that tensor analysis is very valuable to certain branches of science, but that it should not be forced upon the engineer as a universal instrument of analysis, for it is not the most easily applicable method for all types of problems. Doctor Tucker demonstrated the applications of some of the abstract processes of topology to the analysis of electrical circuits.

Professor Karl L. Wildes (A'21, M'29) associate professor of electrical engineering at Massachusetts Institute of Technology, Cambridge, compared the methods of symmetrical components and dyadic algebra in the analysis of unbalanced polyphase circuits, pointing out an advantage in the use of dyadic algebra for solving 3-phase



**After 2 sessions on tensors: E. E. Dreese (left) of Columbus, Ohio, who presided, and K. L. Wildes of Cambridge, Mass., one of the discussers**

circuits with unbalanced impedances. Professor Wildes asserted that engineers should not be too eager to adopt the method of tensors until its field of usefulness is more clearly defined, because the general application of method may be more obscure and devious than the methods now in use.

W. E. Byrne, of Virginia Military Institute, outlined briefly his experiences in attempting to teach the theory of tensors to a special class of senior students. He expressed a need for closer co-operation between the teacher of mathematics and the practicing engineer.

W. H. Ingram, New York, N. Y., based his discussion upon 2 premises: (1) tensors have not been introduced in electric-circuit theory to date; and (2) there is no necessity for using tensors in circuit analysis. He contended that the term "tensor analysis," as used in electrical-engineering literature, is a misnomer and, moreover, that tensors have no direct application in electrical-engineering problems.

Professor M. G. Malti (M'34) of Cornell University, Ithaca, N. Y., discussed briefly the need for new methods of analysis to deal with the complexities of modern electrical-engineering problems and the suitability of tensors in filling that need. He predicted that the tensor method will be found useful in so many branches of electrical science that its universal adsoption is inexorable, although it may be slow in finding such acceptance. Professor Malti recalled that many engineers bitterly contested Heaviside's operational methods at the time of their introduction, but that those methods have become so widely useful that they can be ignored no longer.

L. V. Bewley (A'27) in his closing discussion emphasized an opinion expressed in his paper: that the tensor method, although extremely flexible, is an inefficient engineering tool, because most problems do not require the mathematical power obtainable by means of tensors. By way of substantiating this assertion, Mr. Bewley described the results obtained by a group of advanced engineering students in determining the best method of analysis in the solution of a great variety of electrical-engineering problems. Each problem was first analyzed to determine the most suitable method of attack, solved by the method chosen, and recorded. Most problems were found to be most easily solved by the conventional vectorial methods; only a relatively small number were advantageously solved by the use of the tensor method.

Following a brief closing talk by P. L. Alger (A'17, F'30) of the General Electric Company, Schenectady, N. Y., who was one of the chief promoters of the tensor sessions, the afternoon session was adjourned by Chairman Dreese; however, several informal conferences were formed for the further pursuit of unfinished problems and arguments. According to Chairman Dreese, the sessions were notably combined meetings of engineers and mathematicians, in which the free interchange of ideas served to inform the mathematicians of new applications of a method of reasoning with which they are already familiar, and to suggest to the engineers some further applications of the tensor method, some necessary revisions in nomenclature and symbols used in engineering papers, and some improvements to provide a more rigorous mathematical treatment of problems involving the use of tensors.

**IES Moves Offices.** General offices of the Illuminating Engineering Society have been moved from the Engineering Societies' Building to the New York Life Insurance Company Building, 51 Madison Avenue, New York. All communications to the society should be sent to room 2100 at the new address.

## Conference Held by Student Branches Committee

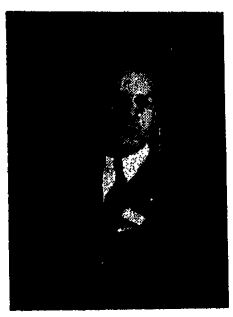
Some 40-odd committee members, Student Branch counselors, and other interested persons attended a luncheon conference of the Institute's Student Branches committee, held at the Town Hall Club in New York, N. Y., January 27, 1937, during the recent winter convention. Among those present were Past-President (1902–03) Charles F. Scott of New Haven, Conn.; Past-Vice-President W. H. Timbie of Cambridge, Mass.; Vice-President C. Francis Harding of Lafayette, Ind.; Director R. W. Sorensen of Pasadena, Calif.; and Director F. Ellis Johnson of Columbia, Mo., who as chairman of the Student Branches committee presided.

Chairman Johnson reported that the organization of 3 new Branches had been authorized on January 26, by the Institute's board of directors in accordance with the recommendation of the committee on Student Branches: Tulane University, New Orleans, La.; Northwestern University, Evanston, Ill.; and Columbia University, New York N. Y.

With reference to the organization of future Student Branches, a question was raised concerning the possible influence of the current program of the Engineers' Council for Professional Development in accrediting engineering curricula. Two schools of thought on the subject were evident: (*a*) That the authorization of Branches should not be dependent upon the accrediting of certain technical curricula; and (*b*) that no Branch should be authorized in institutions where electrical engineering curricula had not been accredited. The consensus of opinion was to the effect that for the present, and until ECPD's accrediting program has been carried further, there would be no change in the committee's basis for considering the organization of new Student Branches.

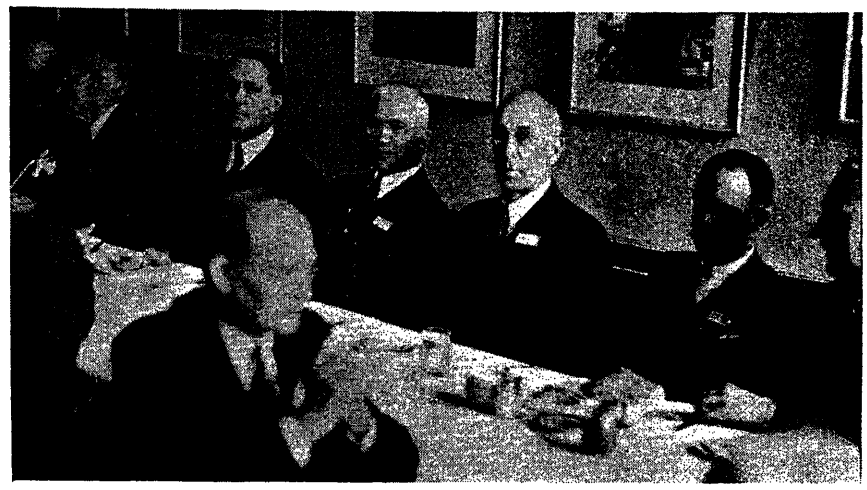
The perennial subject of student technical papers, particularly with reference to District and national prize competition and rules governing such competitions, came up for extended discussion. The general consensus of opinion seemed to be that the question of a proper basis for national grading of student papers "is not yet satisfactorily settled."

Student Branch counselors came in for self-discussion, in connection with successful and effective conduct of Branch activities. Emphasized during the discussion was the fact that the Branch counselorship is "an important position involving certain definite responsibilities as well as certain privileges," and that the office should not be held by any one man for any great length of time, but should be passed around among available faculty members so that full benefit might be derived from "new blood."



**Director F. Ellis Johnson, of the University of Missouri, Columbia, chairman of Student Branches committee presiding**

Student leadership, and the training of students for leadership, was believed by many to be one of the most important functions and opportunities of the Student Branch. It was strongly opined that the Branch "should be operated as a training ground for leadership," and that consequently as many students as possible should have the opportunity of serving as Branch officers and otherwise actively participating in the development and conduct of Branch affairs.



**Group at head table at conference of Student Branch counselors, left to right: Past Vice-President W. H. Timbie, Massachusetts Institute of Technology, Cambridge; Past-President Chas. F. Scott, Yale University, New Haven, Conn.; Director F. Ellis Johnson (chairman) University of Missouri, Columbia; W. E. Wickenden, Case School of Applied Science, Cleveland, Ohio; Past Vice-President H. V. Carpenter, State College of Washington, Pullman; T. F. Ball, University of South Carolina, Columbia; A. B. Newman (member of American Institute of Chemical Engineers) Cooper Union, New York, N. Y. In the foreground is W. R. Work, Carnegie Institute of Technology, Pittsburgh, Pa.**

## Executive Committee of Southern District Meets

A meeting of the executive committee of the Institute's Southern District (Number 4) was held at Chattanooga, Tenn., December 5, 1936. The following attended:

W. W. Hill, counselor, Alabama Polytechnic Institute Branch
K. L. Dillon, secretary, Alabama Section
C. W. McCracken, Birmingham, Ala.
J. M. Flanigen, secretary, Atlanta Section
Stanley Warth, chairman, Louisville Section
W. A. Smith, chairman, Florida Section
E. A. Corum, chairman (now past-chairman), Memphis Section
J. E. Jackson, chairman, Virginia Section
A. P. Farrow, secretary, East Tennessee Section
Chase Hutchinson, chairman, East Tennessee Section
E. E. George, vice-chairman, East Tennessee Section
F. E. Johnson, secretary, New Orleans Section
W. J. Seeley, student counselor, Duke University Branch
Mark Eldredge, vice-president, Southern District
R. F. Crenshaw, secretary, Southern District

The District co-ordinating committee to function according to section 33 of the AIEE by-laws was selected as follows: Mark Eldredge and R. F. Crenshaw, *ex-officio;* F. W. Russell, Louisville, Ky.; H. N. Pye, Atlanta, Ga.; W. W. Hill, Auburn, Ala.; C. W. Ricker, New Orleans, La.; and K. L. Dillon, Birmingham, Ala.

Activities of the Sections were discussed by Vice-President Eldredge, following which the delegates representing the various Sections in the District gave brief outlines of the activities of their respective Sections. Mr. Hill summarized the student Branch activities, and mentioned that a District student conference is to be held in April at Auburn, Ala., with representatives from other colleges attending.

Members of the committee next partook of a delightful luncheon, arranged by Mr. George, as guests of the Tennessee Electric Power Company. Following the luncheon, Edwin D. Wood, director and general superintendent of the Louisville (Ky.) Gas and Electric Company, was unanimously nominated as the District candidate for vice-president to succeed Mr. Eldredge. E. E. George was chosen to represent the District on the national nominating committee.

The monthly publication of the Institute, ELECTRICAL ENGINEERING, was the next topic for discussion. After considerable discussion of various phases of the publication, it was unanimously voted that the committee send the following resolution to headquarters:

That in order to increase interest and value to the students and memberships at large, the journal should include a summary of each article being approximately 10 per cent of the length of the article and written by the technical staff of the journal, which would outline the paper or article for most readers without including the subject matter in a theoretical nature. Also that more illustrations and practical applications be presented whenever possible.

Vice-President Eldredge gave a brief account of the discussion at a recent meeting of the Institute's board of directors on the branching out of electrical engineers into fields beyond electrical engineering, such as economics, to encourage electrical engineers to study and be actively engaged in other subjects of world interest. It was suggested that every effort be made to stimulate employers to consider an applicant's activity in engineering organizations

when evaluating his qualifications in addition to education and practical experience. The importance of engineers in executive positions in actively engaging in the affairs of engineering organizations was emphasized.

Following discussion of other routine matters, the committee was taken on an inspection tour through the dispatching headquarters of the Tennessee Electric Power Company.

## Acoustical Terminology Standard Completed by ASA

A standard acoustical terminology for engineers which is intended to eliminate confusion in motion picture, radio, and building fields has just been completed, according to an announcement by the American Standards Association. This standard is the work of engineers, musicians, manufacturers, and scientists, and has been 4 years in development. According to Leopold Stokowski, a member of the committee in charge: "In the America of the future radio and motion pictures will be important in developing our civilization. For this we need a complete understanding between engineers and musicians." The new standard is expected to achieve this "understanding."

The committee gives a broader meaning to the word "noise," now defined in terms of the listener as an "unwanted" sound rather than in terms of the sound itself. A section of the standard deals with architectural acoustics. Another section that provides standard terms for the measurement of hearing will be useful to the medical profession and to manufacturers of aids for the partially deaf. Other parts dealing with the conversion of sound to electrical energy and with acoustic transmission systems will be of particular value in motion picture and radio work.

A separate section for music brings engineers and acoustical experts into agreement with musicians on a basic standard pitch, the importance of which can be judged by the fact that an increase of only 4.14 per cent in pitch carried out through the entire keyboard of a piano would throw an additional strain of approximately half a ton on the framework of the instrument.

Standards for reference and intensity levels for sound measurement and for characteristics of measuring instruments have already been completed.

## Lamme Medal Awarded to Frank Conrad

The 1936 Lamme Medal of the AIEE has been awarded to Doctor Frank Conrad (A'02) assistant chief engineer of the Westinghouse Electric & Manufacturing Company, East Pittsburgh, Pa., "for his pioneering and basic developments in the fields of electric metering and protective systems." The medal and certificate will be presented to him at the annual summer convention of the Institute, to be held in Milwaukee, Wis., June 21–25, 1937. A biographical sketch of Doctor Conrad may be found in the "personals" columns of this issue.

The Lamme Medal was founded as the result of a bequest of Benjamin G. Lamme, chief engineer of the Westinghouse Electric & Manufacturing Company, who died on July 8, 1934; this bequest provides for the award by the Institute of a gold medal (together with a bronze replica thereof) and a certificate annually to a member of the AIEE "who has shown meritorious achievement in the development of electrical apparatus or machinery," and for the award of 2 such medals in some years if the accumulation from the funds warrants. A committee composed of 9 members of the Institute awards the medal. Previous recipients of the award have been: 1928, A. B. Field (A'03, F'13); 1929, R. E. Hellmund (A'05, F'13); 1930, W. J. Foster (A'07, F'16); 1931, Guiseppe Faccioli (A'04, F'12, deceased); 1932, Edward Weston (A'84, M'84, past-president, deceased); 1933, L. B. Stillwell (A'93, M'92, F'12, member for life, past-president); 1934, H. E. Warren (A'02), and 1935, Vannevar Bush (A'15, F'24).

Mr. Lamme made similar bequests to the Society for the Promotion of Engineering Education and Ohio State University, providing in the former for the annual award of a medal "for accomplishment in technical teaching or actual advancement of the art of technical training," and in the latter for the annual award of a medal to a graduate of Ohio State University in any branch of engineering for meritorious achievement in engineering or the technical arts. The 3 organizations adopted a common obverse for their medals, and each prepared a suitable reverse.

## Special Committee on Dues Recommends No Change

FOR several years a special committee of the AIEE has studied the matter of dues and membership grades with particular reference to the dues of Associates.

A final report was presented to the AIEE board of directors on January 26, 1937, recommending that no changes be made in dues or in membership grades at this time. The report was acted upon favorably by the board at this meeting.

An intensive study over a long period forced the committee to come to this conclusion. Any endeavor to place a time period in any membership grade with a change of dues involved the same fundamental criticisms that have been applied to the present rules. Any endeavor to make one fee for each grade without a time period involves increasing the dues in other grades or a penalty on the admission of young engineers.

An endeavor to get uniformity in grades and dues for the founder societies was made without success and a study of the accompanying tables shows that dues and grades for the AIEE are in line with the practices of these societies.

A statistical study of dues and members and of the effect of the increase in dues for 6-year Associates gives no evidence that this increased fee acts to deprive the Institute of members.

The membership on May 1, 1936 (including those who were in arrears for only one year on that date) developed dues charges to a total of $192,085, and the grade classifications were as follows:

| | |
|---|---|
| 691 Fellows @ $20 | $ 13,820 |
| 3,829 Members @ $15 | 57,435 |
| 5,258 6-year Associates @ $15 | 78,870 |
| 4,196 less-than-6-year Associates @ $10 | 41,960 |
| Total | $192,085 |

To revert to the former practice of charging all Associates $10 dues would have reduced the above total to $165,795, a difference of $26,290.

The membership committee of the New York Section recently made a recommendation that the dues of all Associates, without regard to length of membership, be fixed at $12.50. If this provision had been in effect on May 1, 1936, the total dues charges would have been $189,430 or $2,655 less

**Table I—Entrance Fee and Dues of Engineering Societies**

| Grades | ASME | | ASCE | | AIME | | AIEE | |
|---|---|---|---|---|---|---|---|---|
| | Entrance Fee | Dues | Entrance Fee | Dues | Entrance Fee | Dues | Entrance Fee | Dues |
| Fellow | $30 | $25 | $ | $ (b) | $ | $ | $20 | $20 |
| Member | 25 | 20 | 30 | 20 | 20 | 15 | 15 | 15 |
| Associate member | | | 25 | 20 | | | | |
| Associate | 25 | 20 | | | 20 | 15 | 10 | (f) 10 |
| Affiliate | | | 30 | 20 | | | | |
| Junior member | 10 | (a) 10 | 10 | (c) 10 | | | (e) 10 | |
| Junior foreign affiliate | | | | | | | 5 | |
| Student members | | 3 | | (d) | | | 2 | 3 |

(a) Dues of junior member grade increased to $20 after 6 years of membership.
(b) All members located within district number 1 (i.e., territory within 50 miles of New York City) pay $5 more than the amount indicated for each grade.
(c) Membership ceases at 33 years of age, unless previously transferred to grade of associate member.
(d) Membership in a student chapter includes privileges of special subscription rates to society publications.
(e) Dues charge of $10 obtains only for first 6 years after election or until reaching age of 33; thereafter charge is $15.
(f) Increased to $15 after completion of membership term of 6 years.

**Table II—Associates Resigned and Dropped From May 1, 1927 to May 1, 1930**

| | 6-Year Associates | | Associates | |
|---|---|---|---|---|
| | Number | Per Cent | Number | Per Cent |
| May 1, 1927: | 6,101 | | 8,664 | |
| Dropped | 425 | 7.0 | 739 | 8.5 |
| Resigned | 205 | 3.3 | 234 | 2.7 |
| Total | 630 | 10.3 | 973 | 11.2 |
| May 1, 1928: | 6,037 | | 8,401 | |
| Dropped | 395 | 6.5 | 707 | 8.4 |
| Resigned | 156 | 2.6 | 173 | 2.1 |
| Total | 551 | 9.1 | 880 | 10.5 |
| May 1, 1929: | 6,303 | | 7,756 | |
| Dropped | 295 | 4.7 | 566 | 7.3 |
| Resigned | 197 | 3.1 | 167 | 2.1 |
| Total | 492 | 7.8 | 733 | 9.4 |
| May 1, 1930 | 6,664 | | 7,069 | |

**Table III—Associates Resigned and Dropped From May 1, 1933 to May 1, 1936**

| | 6-Year Associates | | Associates | |
|---|---|---|---|---|
| | Number | Per Cent | Number | Per Cent |
| May 1, 1933: | 6,671 | | 5,747 | |
| Dropped | 861 | 12.9 | 801 | 13.9 |
| Resigned | 315 | 4.7 | 188 | 3.3 |
| Total | 1,176 | 17.6 | 989 | 17.2 |
| May 1, 1934: | 6,140 | | 4,659 | |
| Dropped | 731 | 11.9 | 775 | 16.6 |
| Resigned | 174 | 2.8 | 88 | 1.9 |
| Total | 905 | 14.7 | 863 | 18.5 |
| May 1, 1935: | 5,632 | | 4,225 | |
| Dropped | 326 | 5.8 | 379 | 9.0 |
| Resigned | 137 | 2.4 | 107 | 2.5 |
| Total | 463 | 8.2 | 486 | 11.5 |
| May 1, 1936 | 5,679 | | 4,299 | |

than the total actually charged in our records. It seems to the committee that the establishment of dues of all Associates at $12.50 would materially reduce the number of recent graduates applying for admission.

In table I data are shown regarding the dues, and special arrangements applicable to them, of the 4 large national engineering societies. In this tabulation it may be noted that the dues of the American Institute of Mining and Metallurgical Engineers do not differ greatly from those of the AIEE, and that the dues of the American Society of Civil Engineers and The American Society of Mechanical Engineers are materially higher. It is also significant to note that both the AIME and ASME have adopted provisions similar to that of the AIEE, adjusting the dues charge to the junior member grade after 6 years or after the age of 33 in the AIME. The ASME no longer terminates membership in the junior grade at the age of 35 as was the practice until a few years ago. It seems obvious that on the basis of any comparison with the dues of the other societies the Institute's arrangements appear favorable.

In tables II and III is information regarding the numbers of Associates who resigned and who were dropped during 3 fiscal years beginning May 1, 1927, and in 3 fiscal years beginning May 1, 1933, in order that the results both during and before the depression may be noted.

The percentages of Associates of less than 6 years standing who were dropped are higher in all 6 years than those of Associates of more than 6 years standing. The percentages of Associates of more than 6 years standing who resigned were higher in 5 of the years than the percentages of those of less than 6 years, but, of course, the figures for resignations are far below those of the numbers dropped. Hence, the total percentages dropped and resigned are higher for the less-than-6-year Associates in 5 of these 6 years.

Table IV is included to give some very recent figures regarding Associates who were delinquent. These do not indicate any adverse effects of the change in dues.

The committee has had opportunities to study during the past few years a great many tables dealing with these matters. The tables presented herein seem to be representative. After watching with the greatest care the results of the change in dues of Associates since the adoption, the committee concludes that the increase has had no appreciable effect upon the losses from the membership.

It seems essential to offer some reduction in dues to recent graduates for a few years. Since they constitute a high percentage of Associates admitted, it seems unnecessary and undesirable to make provisions for different dues for 2 groups, one including the recent graduates and the other including any other Associates admitted.

Some members have said that on account of the psychological effects of the present arrangements some kind of a change should be made. Any other plan involving a change in dues after the lapse of a certain period of time would, in the opinion of the committee, cause fully as much dissatisfaction as does the present plan. The types of members who will be a credit to the Institute seldom object, and we should not be unduly influenced by the "kicker" class. The committee has not heard any good reason why Associates should not after 6 years pay their fair share of the cost of conducting Institute activities.

A printed sheet has for 5 or 6 years been sent to all Associates at the time they reach the end of the 6-year period and are called upon to pay the dues of $15. Since headquarters has been supplying this information directly to the individuals concerned there have been fewer complaints than before.

It seems to the committee that there are obvious advantages in the flexibility of the provisions for Associates who are in the 3 large groups mentioned in paragraph 6 of the printed information.

In view of the thorough study made of the effects of the present system and of all possible suggestions for changes, the committee agreed to the conclusion that no changes be made at this time.

The special committee to consider dues of associates and related matters was appointed in 1932; the following served on the committee: L. W. W. Morrow (chairman 1935–37), H. H. Barnes, Jr. (chairman 1932–33), H. Goodwin, Jr., W. H. Harrison, J. Allen Johnson (deceased, chairman 1933–35), E. S. Lee, and E. B. Meyer (deceased).

**Table IV—Associates Delinquent on July 1, 1935 and on July 1, 1936**

| | 6-Year Associates | | Associates | |
|---|---|---|---|---|
| Membership on | Number | Per Cent | Number | Per Cent |
| July 1, 1935 | 5,499 | | 4,472 | |
| Including members who owe dues to | | | | |
| May 1, 1934 | 370 | 6.7 | 373 | 8.4 |
| May 1, 1935 | 562 | 10.2 | 455 | 10.2 |
| July 1, 1936 | 5,571 | | 4,650 | |
| Including members who owe dues to | | | | |
| May 1, 1935 | 228 | 4.1 | 263 | 5.7 |
| May 1, 1936 | 485 | 8.7 | 400 | 8.6 |

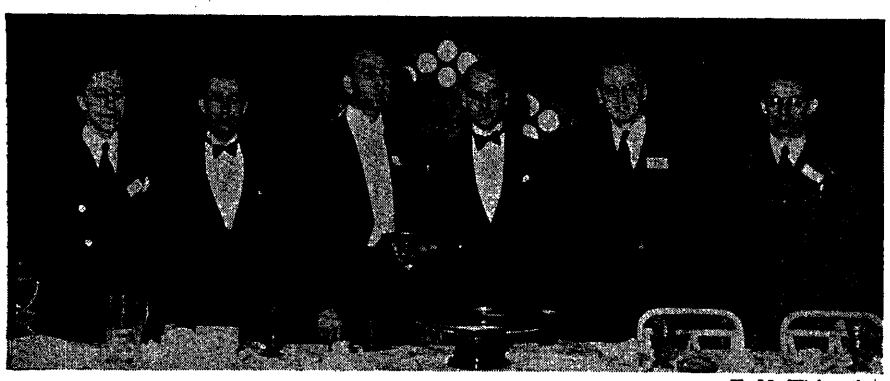
## Comments Invited on ECPD Recognition Report

The report of the committee on professional recognition of Engineers' Council for Professional Development, presented at the annual meeting of that organization held on October 6, 1936, was published in the December 1936 issue of ELECTRICAL ENGINEERING, pages 1390–92, with a statement that official action by ECPD on the recommendations included in the report had been deferred pending further consideration at a future meeting, and that comments on these recommendations were invited.

This report was discussed briefly at the meeting of the AIEE board of directors held during the Institute's 1937 winter convention, and was referred to the committee on economic status of the engineer for report to the board. Professor R. W. Sorensen, California Institute of Technology, Pasadena, chairman of that committee, requests that AIEE members read the report and send their comments directly to him.

## AIEE Members Receive Eta Kappa Nu Awards

Many prominent members of the AIEE were present at a meeting of the Eta Kappa Nu Association on January 25, 1937, at New York, N. Y., when F. M. Starr (A'30) central station engineer of the General Electric Company, New York, N. Y., received the award in the 1936 Eta Kappa Nu recognition of "outstanding young electrical engineers." His name will be engraved on a trophy to be placed at AIEE headquarters; a small replica of the trophy was presented to Mr. Starr. Certificates of honorable mention were presented to P. L. Bellaschi (A'29, M'34) Westinghouse Electric & Manufacturing Company, Sharon, Pa.; E. W. Boehne (A'29) General Electric Company, Philadelphia, Pa.; A. C. Seletzky (A'29, M'35) Case School of Applied Science, Cleveland, Ohio; and C. G. Veinott (A'28, M'34) Westinghouse Electric & Manufacturing Company, Springfield, Mass. An announcement of the awards and biograph-



K. M. Winkworth

**A group at the presentation of the Eta Kappa Nu awards as "outstanding young electrical engineers"; from left to right, A. C. Seletzky and E. W. Boehne, 1936 honorable mention; F. M. Starr, 1936 winner; C. A. Faust, president of Eta Kappa Nu Association; C. G. Veinott and P. L. Bellaschi, 1936 honorable mention**

ical sketches of those receiving them were published in the January 1937 issue of ELECTRICAL ENGINEERING.

Charles F. Scott (A'92, F'25, HM'29, past-president) spoke on "Opportunity and Young Engineers," calling on F. M. Feiker (M'34) of American Engineering Council for a few words. Vladimir Karapetoff (A'03, F'12, Life Member), to illustrate his subject "Art and Culture for the Engineer," played selections on the piano. Other Institute members taking part in the ceremonies were C. A. Faust (A'35) toastmaster, R. I. Wilkinson (A'35), M. S. Mason (M'31), E. S. Lee (A'20, F'30, director), and Morris Buck (A'05, F'23).

Mr. Starr delivered an address, "Let's Take a Look at Ourselves." Other addresses were "The Young Engineer and His Success" by Mr. Bellaschi, "Engineering Appreciation" by Mr. Boehne, "Broken Bones" by Doctor Seletzky, and "Achievement, Perspective, and Balance" by Mr. Veinott. Doctor Seletzky described apparatus, developed in collaboration with Doctor W. McGaw of Western Reserve University, that is intended for use in studying the progress of "knitting" or healing of fractured bones. An inertia-operated crystal vibrator driven by an oscillator is applied to one end of the fractured member, and an inertia-operated pickup of the crystal type, connected through an amplifier to an output meter, is applied to the other end of the fractured members so that the fracture is between them. The sound-intensity measurement obtained is compared with the measurement obtained on the "symmetrical mate" of the fractured member (that is, the right leg if the left leg be the broken member), and the ratio indicates the degree of "knitting," unity being perfect. The method is said to be of exceptional value in so-called "delayed unions" where the X ray may not reveal the true condition.

**Federal Power Commission Report.** In the sixteenth annual report to Congress, submitted by Frank R. McNinch, chairman; *Basil Manly*, vice-chairman; Herbert J. Drane, Claude L. Draper, and Clyde L. Seavey, commissioners, the Federal Power Commission reports "increased activity in the various functions which have been performed for 16 years, and marked progress in the new activities entrusted to the commission by Congress in the Federal Power Act of 1935." The report, which is for the fiscal year ended June 30, 1936, and with additional activities to December 1936, consists of a 68-page paper-covered pamphlet, 6 by 9 inches, and may be obtained at 10 cents per copy from the Superintendent of Documents, Washington, D. C.

## North Eastern District to Meet in Buffalo May 5-7

Buffalo, N. Y., will be host to a 3-day meeting of the North Eastern District with headquarters in the Statler Hotel, May 5–7, 1937. Tentative arrangements indicate that an interesting program, consisting of 3 or more technical sessions, a student technical session, entertainment, and inspection trips, will take place. Arrangements are to be made for a dinner on Thursday evening with a popular lecture afterward; there will also be a dance in the hotel on that evening.

Buffalo and its environs offer opportunities for many inspection trips among a variety of industries. There are the various steel mills, the Ford Motor Company, and the Huntley station as well as several other stations of the Buffalo General Electric Company. In addition, arrangements may be made for a golf tournament, and the city offers many attractive types of amusement.

Further details will be announced when made available.

**Consulting Engineer Dies.** J. F. Max Patitz, chief consulting engineer of the Allis-Chalmers Manufacturing Company, Milwaukee, Wis., died January 3, 1937. He was associated with the company for more than 51 years, during nearly 26 of which he served as consulting engineer. Mr. Patitz was born at Mugeln, Saxony, in 1866, and entered the employ of the E. P. Allis Company in Milwaukee in 1885. In 1901, when that company became part of the Allis-Chalmers Company, he was placed in charge of the building of steam engines and compressors. Mr. Patitz began his studies of parallel operation of a-c generators as early as 1900. He also made studies of critical speeds and of vibration in high-speed machines, and was an authority on intricate mathematical calculations connected with the design of machinery. Mr. Patitz was a member of The American Society of Mechanical Engineers, the Society of Automotive Engineers, and the Verein Deutscher Ingenieure.

## Tour of European Laboratories Planned

Industrial leaders to the number of 100 from all parts of the United States are expected to participate in a tour of European scientific laboratories which is being planned by the division of engineering and industrial research of the National Research Council. An advisory committee to co-operate in the planning has been appointed.

The tour will provide an opportunity to observe methods of outstanding research laboratories in Europe representing 18 major fields, under the guidance of such organizations as the Department of Scientific and Industrial Research in England, Verein Deutscher Ingenieure in Germany, the Sorbonne in France, and others. According to present plans, the group is scheduled to sail on May 14 from New York on the S. S. "Champlain." The tour comes as the culmination of 3 highly successful educational tours made to industrial and university laboratories in the United States in 1930, 1931, and 1935, under the direction of Maurice Holland (A'23, M'30) director of the division of engineering and industrial research of NRC.

## Prizes for Papers on Arc Welding

The James F. Lincoln Arc Welding Foundation, according to information released by that newly created organization, will distribute $200,000 among the winners of 446 separate prizes for papers dealing with arc welding as a primary process of manufacture, fabrication, or construction in 11 major divisions of industry in order to stimulate intensive study of the subject. The principal prize winner will receive not less than $13,700. Other prizes range from $7,500 to $100, the latter sum to be awarded each of 178 contestants who receive no other prize but whose papers are adjudged worthy of honorable mention.

In order to assure equal competitive opportunity, similar prizes are offered in the 11 major divisions of industry covered by the contest. These divisions are: automotive, aircraft, railroad, watercraft, structural, furniture and fixtures, commercial welding, containers, welderies, functional machinery, and industrial machinery. Wide diversification of awards is effected by further dividing each major industry into various subclassifications; with entrants required to select in advance the particular

subclassification to which their papers will relate.

When accepted by the jury of awards as properly classified, each paper will be in competition, in its particular subclassification, for 5 initial prizes established for that group. These are worth, respectively, $700, $500, $300, $200, and $100. From among these subclassification winners 4 papers will be selected in each major industry to receive additional prizes of $3,000, $2,000, $1,000, and $800. Thus these 44 semifinalists will be awarded a total of $74,800. In addition, the semifinal winners in the various divisions will be considered as possible recipients of the 4 main prizes. These range from $10,000 to $3,500, with the winner of the grand prize receiving not less than $13,700 for his paper.

Contestants, it has been announced, must have papers in duplicate on file with the secretary of the foundation at Cleveland, Ohio, not later than June 1, 1938. Prospective entrants should communicate promptly with A. F. Davis, box 5728, Cleveland, for complete details of the rules and conditions covering awards.

# Standards

## Proposed Standards for Transformers

The sectional committee on transformers working under the rules of procedure of the American Standards Association has practically completed its work in drawing up a new set of standards for transformers, regulators, and other induction apparatus, according to V. M. Montsinger, chairman of the AIEE standards committee. These will be submitted to the sectional committee for final approval in the near future.

These new standards, having as their basis the present AIEE Standards No. 13, have incorporated in them not only the latest practices but a considerable amount of material from standards of the National Electrical Manufacturers Association. In the appendixes have been placed a new set of guides for the operation of transformers, a development of the AIEE recommendations on operation giving for the first time permissible short-time overloads for both power and distribution transformers. Also, an enlarged and revised test code for transformers will be included in an appendix.

It is planned after approval by the committee and the ASA to publish these as American Tentative Standards for distribution to all interested societies for comments and suggestions for improvement before they are published as final American Standards. It is expected that the tentative drafts will be published within the next few months.

**Test Code for Synchronous Machines.** An extensive revision of the "Preliminary Report on a Proposed Test Code for Synchronous Machines" came up for general discussion at one of the informal conferences held during the recent winter convention of the Institute. Copies are now available in pamphlet form and can be obtained gratis by writing H. E. Farrer, secretary AIEE standards committee, 33 West 39th Street, New York, N. Y. The AIEE committee on electrical machinery under whose auspices all of the test codes on rotating machinery are being developed hopes, as a result of the open discussion of the report at the conference and possible criticisms which may develop through wide circulation of the printed pamphlet, to be able shortly to make available a final approved synchronous code satisfactory to all.

**Test Code for D-C Machines.** At the same informal conference at which the synchronous code referred to in the preceding paragraph was discussed, there was also presented a preliminary draft of a proposed "Test Code for D-C Machines." This has not yet reached the stage where it is ready for general distribution in printed pamphlet form as several important points are still open to argument. As soon as these are cleared up, publication will take place and copies will then be available to all for further criticism and suggestion.

**Test Code for Induction Machines.** The second step toward the development of a finally approved "Test Code for Induction Machines" was also taken at the winter convention conference to which previous reference has been made. This code first appeared in preliminary report form in December 1934. When the revised and approved code will become available is impossible to predict just at present, but it is expected that the electrical machinery committee will shortly be in a position to ask the approval of the standards committee of this induction machinery code.

**Test Code for Sound Level Measurements.** At the meeting on January 25, 1937, of the standards committee a report was received from P. L. Alger, chairman of its subcommittee on sound, advising that the subcommittee is preparing a "Test Code for Sound Level Measurements on Apparatus." It is intended for use as a guide in the measurement of sound levels and the investigation of the various elements that contribute to the total noise produced. The standards committee agreed to issue the code in pamphlet form when completed.

**Rotation, Connections, and Terminal Markings for Electric Power Apparatus.** A new American Standard for "Rotation, Connections, and Terminal Markings for Electric Power Apparatus" has just been issued in pamphlet form by the National Electrical Manufacturers Association, the sponsor organization. This project, known as *C*–6, has been going forward in a sectional committee working under the rules of procedure of the American Standards Association, the Institute being one of the organizations represented on the committee. The first edition of the standard received approval in 1925 and this revision was approved by American Standards Association in June 1936. Copies of the standard may be obtained at 90 cents each by addressing National Electrical Manufacturers Association, 155 East 44th Street, New York, N. Y.

**Revised Dry Cell Standards.** A revision of "Specifications for Dry Cells and Batteries," approved as an American Standard in 1930 and issued as "Bureau of Standards Circular 390," has just been approved by the American Standards Association. The new edition will be issued shortly by the sponsor, the Bureau of Standards, under the official designation of *C* 18–1937.

**Proposed Revision of National Electrical Safety Code.** The National Bureau of Standards, the sponsor under ASA procedure for the sectional committee on national electrical safety code, is taking the preliminary steps calling for a reorganization of the committee which when completed will consider a revision of the safety code as approved by ASA in 1927.

**Proposal for International Standardization of Photometric Units.** The National Bureau of Standards will propose in the near future the international adoption of fundamental photometric units which, if adopted, will involve a slight change in the units in use in this country. Essentially the proposal will be as follows: That the primary standard of light shall be the black body radiator operated at the temperature of solidification of pure platinum; that the brightness of the primary standard shall be taken as 60 candles per square centimeter, thus fixing the magnitude of the unit of intensity, the candle, for the color of light given by the primary standard; that standards for light of colors different from that of the primary standard shall be established by applying the "visibility factors" which have been adopted by the Illuminating Engineering Society, the American Standards Association, the International Commission on Illumination, and the International Committee on Heights and Measures. The Institute will appoint a representative on the subcommittee which will consider the full proposal and its effect upon American practice.

**Power and Rate Terms.** There has just been issued by the Federal Power Commission, Electric Rate Survey, a "Glossary of Important Power and Rate Terms, Abbreviations, and Units of Measurement." This pamphlet, which should be of considerable interest to those in the power generation field, has as its purpose the development of a uniform terminology for the reports and correspondence of the commission. Quite a number of the definitions of electrotechnical terms appearing in the glossary have been developed in co-operation with the interested subcommittees of the sectional committee on electrical definitions, of which the Institute is sponsor. Copies of the glossary may be obtained from the Superintendent of Documents, Washington, D. C., at 5 cents each.

# Letters to the Editor

CONTRIBUTIONS to these columns are invited from Institute members and subscribers. They should be concise and may deal with technical papers, articles published in previous issues, or other subjects of some general interest and professional importance. ELECTRICAL ENGINEERING will endeavor to publish as many letters as possible, but of necessity reserves the right to publish them in whole or in part, or reject them entirely.

ALL letters submitted for consideration should be the original typewritten copy, double spaced. Any illustrations submitted should be in duplicate, one copy, to be an inked drawing but without lettering, and other to be lettered. Captions should be furnished for all illustrations.

STATEMENTS in these letters are expressly understood to be made by the writers; publication here in no wise constitutes endorsement or recognition by the American Institute of Electrical Engineers.

## Effective Resistance of Synchronous Machines

*To the Editor:*

It is well known that the effective resistance of a synchronous machine is greater than the d-c resistance due to eddy current and hysteresis losses caused by the armature leakage flux, proximity effects due to armature current, and additional losses due to the distortion of flux under load. An approximate value of these losses may be obtained from the short-circuit loss and the armature $I^2R_{dc}$ loss.[1] This method gives values which are too low, since under dead short circuit, the flux in the machine is small. Robertson[2] gives a complete discussion of the subject, and his figures 1 and 2 show the errors to be expected. In computing the machine efficiency, it is customary to make an approximate correction in which the core loss is taken corresponding to the internal voltage.[1] It is the writer's opinion that more accurate results will be obtained using the effective resistance determined from the V-curve test,[3] and an improved method which includes the increase in core loss under load will be described in the paragraphs following.

The effective armature resistance is defined as the ratio of the power per phase consumed in the armature windings to the square of the current. The power (using the per unit system throughout) consumed with the motor running light and all shaft load disconnected, may be expressed:

$$P = I^2R + b$$

where

$P$ = power consumed with machine running light

$I$ = armature current

$b$ = sum of constant losses (windage, friction, and iron)

$R$ = effective armature resistance

With the machine terminal voltage held constant, values of total power and armature current are obtained by varying the field current. The curves of figure 1 of this letter show typical results obtained from a 3-phase 6-pole 15-kva 1,200-rpm 220-volt 39.4-ampere generator. The power was measured by the 2-wattmeter method.

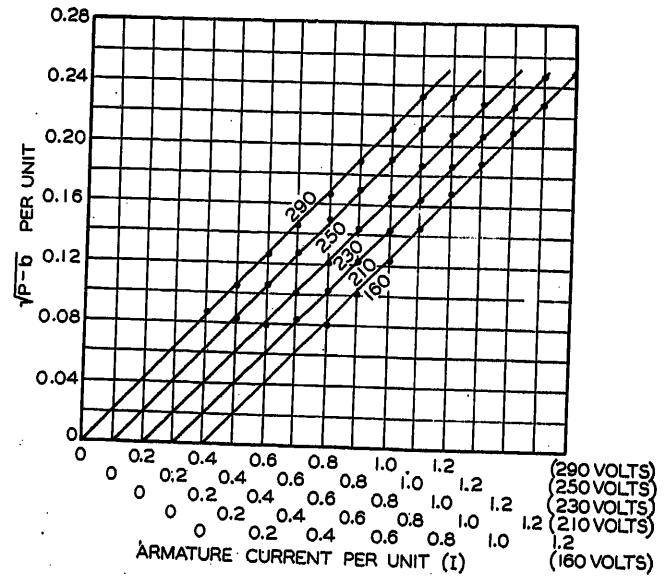



**Fig. 2. Determination of effective armature resistance**

Terminal voltages held constant at values shown on curves

Subscripts will be used to refer to 2 widely separated points on the same power-current curve.

$$P_1 = I_1^2R + b \qquad P_2 = I_2^2R + b$$

Solving for the constant losses

$$b = (I_1^2P_2 - I_2^2P_1)/(I_1^2 - I_2^2)$$

Transposing the original equation and taking the square root gives

$$\sqrt{P - b} = I\sqrt{R}$$

Values of $\sqrt{P - b}$ and $I$ were plotted to give straight lines passing through the origin; see figure 2. For a given terminal voltage, the effective resistance equals the square of the slope of the line.

The method is simple and effective, as the constant losses are evaluated without difficulty. If the value of $b$ is larger than the correct value, the curve will depart from a straight line and be concave downward, while if it is smaller than the correct value the converse will be true. The value $b$ can be conveniently corrected by plotting 2 widely separated points on the $\sqrt{P - b}$ versus $I$ curve. A straight line is drawn connecting the larger value with the origin. If the second point does not fall on this line, $b$ can be changed slightly to make it do so.

The method assumes that the effective resistance is constant and independent of current. The correctness of this assumption is verified by an examination of the drift of points from the $\sqrt{P - b}$ versus $I$

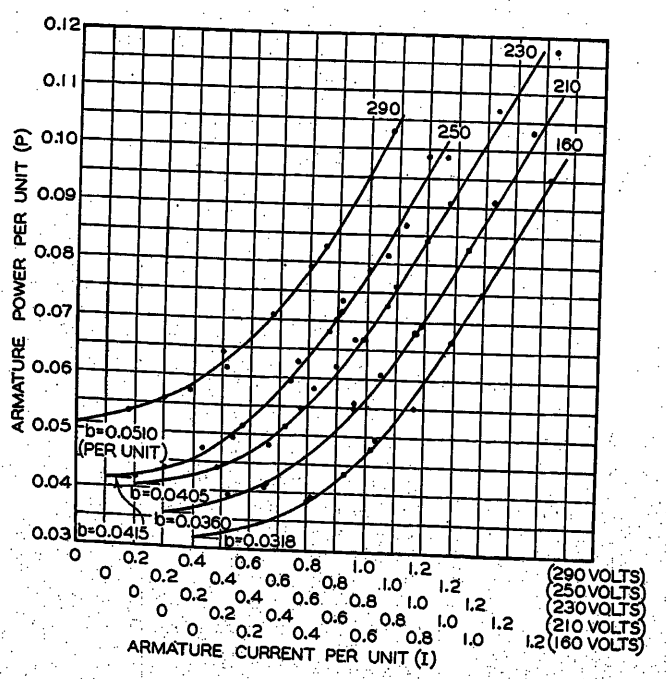



**Fig. 1. Determination of effective armature resistance**

Terminal voltages held constant at values shown on curves

curve. The results for 5 independent tests at various terminal voltages indicate that there is no appreciable variation with voltage. The effective resistance was taken as the average value, $R = 0.044$.

The ohmic resistance of the armature winding was determined by the d-c volt-ammeter method. The average resistance was $R_{dc} = 0.035$. It is apparent that the stray losses may be expressed as a resistance.

If it is desired to determine the machine performance at temperatures different from test, the corrected effective resistance is found as follows:

$$R_s = R_{t0} - R_{dct0} \quad \text{and} \quad R_{t1} = R_s + R_{dct1}$$

in which

$R_{t0}$ = effective resistance at temperature $t_0$
$R_{t1}$ = effective resistance at temperature $t_1$
$R_{dct0}$ = ohmic resistance at temperature $t0$
$R_{dct1}$ = ohmic resistance at temperature $t1$
$R_s$ = stray losses expressed as a resistance.

In using this method, the core loss should be taken corresponding to the terminal voltage, since the variation in core loss is taken into account in the effective resistance. It is believed that this method of determining the effective resistance is more accurate than the conventional procedure of determining the d-c resistance and the stray load losses from a short circuit test, since the additional losses due to flux distortion, and the increase in core loss under load, are taken into account. The advantages of the method are that the effective resistance may be considered constant for most practical cases, and may be inserted directly in the vector diagram, hence simplifying the analysis.


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1. AMERICAN STANDARDS FOR ROTATING ELECTRICAL MACHINERY. Approved by American Standards Association, January 6, 1936.

2. TESTS ON ARMATURE RESISTANCE OF SYNCHRONOUS MACHINES, B. L. Robertson. ELECTRICAL ENGINEERING (AIEE TRANSACTIONS), volume 54, July 1935, pages 705–09.


Very truly yours,
CHARLES F. DALZIEL (A'33)
Instructor in Electrical Engineering,
University of California, Berkeley

## ASA Formula for 2-Winding Transformer Regulation

*To the Editor:*

I should like to submit the following as a derivation for the ASA equation for regulation of a 2-winding transformer. The notation used is the same as that used by J. E. Clem, page 466 of the May 1936 issue of ELECTRICAL ENGINEERING, in the paper "An Exact Formula for Transformer Regulation."

From figure 1 of this letter,

$$E_p = \sqrt{(E_s \cos\theta + IR)^2 + (E_s \sin\theta + IX)^2}$$

Dividing each side of the equation by $E_s$ gives

$$\frac{E_p}{E_s} = \sqrt{(m + r)^2 + (n + x)^2}$$

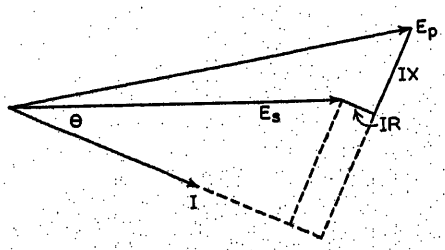



Fig. 1. Vector diagram

where $r = IR/E_s$ and $x = IX/E_s$

Per cent regulation =

$$\left[\frac{E_p - E_s}{E_s}\right] \times 100 = \left[\frac{E_p}{E_s} - 1\right] \times 100$$

$$= \left[\sqrt{(m + r)^2 + (n + x)^2} - 1\right] \times 100$$

Very truly yours,
JOHN D. SCARBOROUGH (Enrolled Student)
Michigan College of Mining and Technology, Houghton

# Personal Items

## W. H. Harrison Nominated for Presidency

WILLIAM HENRY HARRISON (A'20, M'30, F'31, vice-president) assistant vice-president, department of operation and engineering, American Telephone and Telegraph Company, New York, N. Y., has been nominated for the presidency of the AIEE for the 1937–38 term. Mr. Harrison was born June 11, 1892, at Brooklyn, N. Y., and was graduated in industrial electrical engineering at Pratt Institute in 1915. He entered the employ of the New York Telephone Company in 1909, where his work until 1915 included apparatus inspection, assembling, and wiring. From 1915 to 1919 he was engaged in telephone circuit design in the engineering department of the Western Electric Company, and in 1919 he became a member of the engineering staff of the American Telephone and Telegraph Company. In 1924 Mr. Harrison was made equipment and building engineer with general supervision of the engineering of the subscribers station and central office plant of the Bell Telephone System, and in 1929 he became plant engineer, with broadened responsibilities including general direction of the engineering, design, and layout of all departments of the Bell System plant, including system relations with other wire-using utilities. In 1933 Mr. Harrison was elected vice-president in charge of operations of The Bell Telephone Company of Pennsylvania and The Diamond State Telephone Company of Delaware, with headquarters in Philadelphia, Pa. He was appointed assistant vice-president in the department of operation and engineering in 1937. Mr. Harrison has a long record of active service in the Institute; he is at present vice-president representing the AIEE Middle Eastern District (number 2) and a member of the executive committee (1936–37) and committees on legislation affecting the engineering profession, 1932–37; Edison Medal, 1935–37; and Lamme Medal, 1935–38. In addition, he is a member of the special committee to consider Associate dues and related matters and the committee on revision of Section territories, and has been a member of the following technical committees: communication, 1935–36; technical program, 1929–36 (chairman 1931–33); co-ordination of Institute activities, 1931–33; publication, 1931–33; award of Institute prizes, 1931–34 (chairman 1931–33); and popular science award, 1931–34. Mr. Harrison also was a member of the AIEE national nominating committee in 1935, and was an AIEE representative on the Alfred Noble Prize committee of the American Society of Civil Engineers (1932–34) and on the American committee on marking of obstructions to air navigation during 1932–33.

## Vice-Presidential Nominees are Jollyman, McClellan, Mc Henry, Stein, Wood

JOSIAH PICKARD JOLLYMAN (A'05, M'25, F'30) chief of the division of hydroelectric and transmission engineering, Pacific Gas and Electric Company, San Francisco, Calif., has been nominated to serve the Institute as vice-president representing the Pacific District (number 8). Mr. Jollyman was born at Santa Barbara, Calif., October 29, 1879, and received the degree of bachelor of arts in electrical engineering at Stanford University in 1903. From 1903 to 1909 he was employed by the California Gas and Electric Corporation as an electrician and as superintendent of electrical construction. In 1909 he became electrical engineer for the Great Western Power Company of California, where he remained until he joined the engineering staff of the Pacific Gas and Electric Company in 1911. Since 1920 Mr. Jollyman has been chief of the division of hydroelectric and transmission engineering, in which position he has had charge of the electrical and mechanical design of 11 hydroelectric plants and the electrical design of several transmission lines and substations of large capacity. Mr. Jollyman has presented before the Institute several papers on transmission engineering subjects and has been a member of the committees on power stations (now power generation), 1923–24; and power transmission and distribution, 1915–17, 1923–29, 1930–37. He has been active in the affairs of the San Francisco Section, and was chairman of that Section during 1920–21.

LESLIE NEWMAN MCCLELLAN (A'14, M'26) chief electrical engineer, United States Bureau of Reclamation, Denver, Colo., has been nominated to serve the Institute as vice-president representing the North Central District (number 6). He was born at Middletown, Ohio, March 27, 1888, and received the degree of bachelor of science in electrical engineering in 1911 from the University of Southern California. He was then employed by the United States Reclamation Service at Phoenix, Ariz., on the Salt River project as electrical assistant, 1911–13; junior engineer, 1913–14; assistant engineer, 1914–15; and engineer in responsible charge of construction and operation of the power system, 1915–17. During 1917–18 he served overseas as a lieutenant in the United States Army Engineer Corps, upon his return becoming electrical engineer in the office of the chief engineer of the Reclamation Service at Denver, where he was engaged in the design of power plants, substations, and transmission lines. Mr. McClellan was employed by the Southern California Edison Company as engineer in the transmission department during 1923–24. Since 1924 he has held his present position as chief electrical engineer for the Bureau of Reclamation at Denver, where he has responsible charge of design, construction, and operation of power and pumping plants, substations, and transmission lines on the various reclamation projects of the Federal Government. Mr. McClellan is the author of papers on the Boulder Dam project published by the Institute, and was a member of the power transmission and distribution committee 1933–36.

MORRIS JAMES MC HENRY (A'11, M'20) district manager of the Canadian General Electric Company, Toronto, Ont., Canada, has been nominated to serve the Institute as vice-president representing the Canada District (number 10). Mr. Mc Henry was born at Catasauqua, Pa., August 7, 1888, and received the degree of bachelor of science in electrical engineering at McGill University in 1910. Following his graduation, and until 1912, he was employed by Smith, Kerry, and Chase, consulting engineers, Toronto, in power station design and field engineering. In 1912 he was employed by the Canadian General Electric Company as sales engineer in Toronto, and in 1916 became assistant manager of apparatus sales in the Toronto district. In 1918 Mr. Mc Henry accepted a position as manager and secretary-treasurer of the Walkerville Hydro-Electric System, and remained as chief executive of that system until 1924. In that year he became sales manager of the Ferranti Electric Company, Ltd., which position he relinquished in 1926 to become manager of the United States sales department of the Canadian General Electric Company. In 1930 he was appointed district manager for Ontario. Mr. Mc Henry has served the Institute as a member of the committee on industrial and domestic power during 1921–22, and has been active in local Institute affairs. In the Toronto Section he has served as director (1924) and chairman (1935–36), and as chairman of the Section committees on membership (1925) and papers (1926). Mr. Mc Henry is a past-president of the Association of Municipal Electric Utilities of Ontario and a member of the Association of Professional Engineers of Ontario, having served as a member of the board of governors of that organization during 1924 and 1925. He is president of the Electric Club of Toronto and president of the Electric Service League of Toronto.

IRVING MELVILLE STEIN (A'18, M'27) director of research for Leeds and Northrup Company, Philadelphia, Pa., has been nominated to serve the Institute as vice-president representing the Middle Eastern District (number 2). Mr. Stein was born at Long Branch, N. J., March 20, 1894, and obtained his technical education from the New York Edison evening technical school, Columbia University extension course, and Fort Wayne Correspondence School. He was employed in the meter department of the New York (N. Y.) Edison Company in 1911, and the following year was transferred to the standardizing laboratory. During 1913 he was in charge of the rehabilitation work on instruments damaged in the flood at Dayton, Ohio, then returned to the test department of the Edison company. In 1916 he was made assistant foreman of the standardizing laboratory, and the following year was made foreman. During this time he was also engaged in work on protective relays. During 1918 he was senior inspector in the eastern department of the U.S. Signal Corps, and also worked as personal assistant to Thomas A. Edison in the development of submarine and airplane locating devices. He was engaged by the Leeds and Northrup Company as sales engineer in 1919, and 2 years later was given charge of general division sales. In 1924 he was made assistant sales manager and in 1927 was given charge of development, engineering, production, publicity, and sales of combustion control apparatus. He is now director of research and a member of the executive committee of the company. Mr. Stein is the author of numerous technical articles. He has been a member of the Institute's publication committee since 1934 (chairman 1936–37), of the committee on coordination of Institute activities since 1933, and of the Sections committee since 1929, serving as chairman 1933–36. He served on the membership committee 1926–27 and 1931–33, and for 1936–37 has been appointed a member of the committees on technical program and award of Institute prizes. Among other organizations of which Mr. Stein is a member may be included the American Physical Society, American Chemical Society, American Electrochemical Society, Illuminating Engineering Society, Franklin Institute, and American Society for Testing Materials.

EDWIN DOW WOOD (A'21, M'26) general superintendent of the Louisville Gas & Electric Company, Louisville, Ky., has been nominated to serve the Institute as vice-president representing the Southern District (number 4). Mr. Wood was born at Montevideo, Uruguay, April 17, 1878, and attended high school at Callao, Peru. In 1903 he received the degree of bachelor of science at De Pauw University, Greencastle, Ind., and entered the employ of the Union Traction Company of Indiana. During the next year he was employed by the Pope-Waverly Electric Company of Indianapolis, Ind., and the General Electric Company at Schenectady, N. Y., for short periods before he joined the Empresa Electrica Santa Rosa at Lima, Peru, later the Empresas Electricas Asociadas. He became assistant chief engineer in charge of power plants for this company, and was acting chief engineer when he resigned in 1909 to become construction department foreman for the General Electric Company at Schenectady, N. Y. In the following year he was transferred to the engineering department in the Cincinnati, Ohio, district, where he was engaged in general power house and substation engineering work. Mr. Wood accepted the position of electrical operating engineer with the Louisville Gas & Electric Company in 1915, and was electrical engineer from 1926 to 1932, being appointed general superintendent in the latter year. In 1936 he was made a director of the company. Mr. Wood is a past-president of the Engineers and Architects Club of Louisville and a past-chairman of the Louisville Section, and until its dissolution was a member of the electrical apparatus committee of the former National Electric Light Association. He is co-author of an Institute paper published in 1931.

## Bush, Beardsley, Lane
### Nominated for Institute Directorships

VANNEVAR BUSH (A'15, M'19, F'24, Lamme Medalist '35) vice-president of Massachusetts Institute of Technology and dean of the school of engineering, Cambridge, Mass., has been nominated to serve the AIEE as a member of its board of directors. Doctor Bush was born at Everett, Mass., March 11, 1890. In 1913 he was graduated from Tufts College, and in 1916 was awarded the degree of doctor of engineering from Massachusetts Institute of Technology and Harvard University. In 1932 he received the honorary degree of doctor of science from Tufts College, and he is now a member of the board of trustees of that college. Following graduation from Tufts College he entered the testing department of the General Electric Company, and the next year was an instructor in mathematics at Tufts College. In 1915 he engaged in graduate study at M.I.T., and the following year returned to Tufts as assistant professor of electrical engineering. During 1917–18 Doctor Bush carried on research work in submarine detection for the United States Navy; then until 1923 was associate professor of electric power transmission at M.I.T. From 1917 to 1922 he was also consulting engineer for the American Radio and Research Corporation. In 1923 he was appointed professor of electric power transmission, holding this title until appointed to his present position in 1932. Doctor Bush long has been interested in the design of analyzing instruments and is internationally known for his achievements in this field. For one development he was awarded the Levy Medal of the Franklin Institute in 1928, and he received the AIEE Lamme Medal for 1935. Doctor Bush is a director

of the Spencer Thermostat Company and of Raytheon, Inc., and is a member of the corporation of Massachusetts Institute of Technology. He is the author of many technical articles and of "Operational Circuit Analysis," and, jointly with W. H. Timbie (A'10, F'24), of "Principles of Electrical Engineering." The Institute committees on which he has served include research (1924–30); electrophysics (1924–33, chairman 1931–33); power transmission and distribution (1925–27, 1928–29); education (1928–29); and technical program (1929–33). He is now a member of the Edison Medal and Lamme Medal committees, and representative on the division of engineering and industrial research of National Research Council. Doctor Bush is a fellow of the American Academy of Arts and Sciences and American Physical Society, and a member of the Society for the Promotion of Engineering Education, National Academy of Sciences, Phi Beta Kappa, Alpha Tau Omega, Sigma Xi, and Tau Beta Pi.

CLIFFORD RAY BEARDSLEY (A'08, M'20, F'30) superintendent of distribution, Brooklyn Edison Company, Brooklyn, N. Y., has been nominated to serve the Institute as a member of its board of directors. He was born at Bridgeport, Conn., December 19, 1885, and attended the Sheffield Scientific School of Yale University, from which he received the degree of bachelor of philosophy in electrical engineering in 1905. He then entered the testing department of the General Electric Company at Schenectady, N. Y., and subsequently was assigned to the offices at New York, N. Y., and New Haven, Conn. In 1911 he became sales agent for the United Illuminating Company at Bridgeport, where he had charge of sales, construction, and installation of factory electrifications. Seven years later he accepted the position of electrical engineer with Fred T. Ley & Company, Springfield, Mass., in which position he had charge of design and installation of power station and industrial electrical work, being concerned mostly with hydroelectric and steam plants and transmission lines. Mr. Beardsley accepted in 1923 the position with the Brooklyn Edison Company of electrical construction engineer in charge of inside-plant electrical construction in power stations, substations, and consumer vaults. In 1932 he was appointed assistant to the superintendent of distribution, and recently was advanced to the position of superintendent of distribution. During 1928–30 Mr. Beardsley was chairman of the accident prevention committee of the former National Electric Light Association, and he has served as chairman of the committees for the 1936 and 1937 winter conventions of the Institute. He has written numerous articles on the relation of engineering to safety.

FRANCIS HOWARD LANE (M'23) manager of the engineering division of the Public Utility Engineering and Service Corporation, Chicago, Ill., has been nominated to serve the Institute as a member of its board of directors. He was born at St. Louis, Mo., June 7, 1882, and studied electrical engineering at Lewis Institute, Chicago, Ill., from which he received the degree of mechanical engineer in 1904. He then entered the employ of H. M. Byllesby and Company as draftsman, and subsequently was engaged in preliminary investigations of projects, and construction. From 1910 to 1915 he was engaged in general investigations and appraisals of public-utility properties, and during 1915–17 was manager of the department of examinations and reports. Mr. Lane was made manager of engineering and construction of Byllesby Engineering and Management Corporation in 1917, and held this position continuously until the formation of the successor company, Public Utility Engineering and Management Corporation, in 1936, with which he assumed a similar position. He is a member of The American Society of Mechanical Engineers and the Western Society of Engineers.

### W. I. Slichter
### Renominated as Institute Treasurer

WALTER IRVINE SLICHTER (A'00, M'03, F'12, national treasurer, member for life) professor and head of the department of electrical engineering at Columbia University, New York, N. Y., has been nominated to succeed himself as treasurer of the Institute. Professor Slichter was born at St. Paul, Minnesota, May 7, 1873, and was graduated at Columbia University in 1896 with the degree of electrical engineer. He entered the employ of the General Electric Company as a student in July 1896, and the following year was transferred to the office of Doctor C. P. Steinmetz, where he was engaged for a year in carrying on experimental work, tests, and calculations on various subjects. During the following 2 years, he was engaged in designing induction motors, alternators, rotary converters, transformers, and special experimental apparatus. For a number of years thereafter he devoted most of his time to the design of electrical machinery and, more particularly, the equipment of electric railways. In 1910 he was appointed professor of electrical engineering and head of that department at Columbia University, which position he still fills. During the war he was civilian director of the Air Service school for radio officers at Columbia University. Since 1914, Professor Slichter has devoted considerable time to instruction in electrical engineering to naval officers of the postgraduate school of the United States Navy. National treasurer since 1930, he was a member of the board of directors of the Institute from 1918 to 1922 and vice-president from 1922 and 1924, and served on the following committees: board's committee on technical activities, 1918–20; board of examiners, 1915–18 and 1924–28; co-ordination of Institute activities, 1920–24 and 1925–27; editing (later publication) 1914–21; education, 1916–20; executive, 1919–24; meetings and papers (now technical program) 1917–24; industrial and domestic power (now general power applications) 1922–23; finance, 1923–24; standards, 1923–26; legislation affecting the engineering profession, 1931–36 (chairman 1933–35); Iwadare foundation, 1931–33; and special committee on model registration law, 1933–34. He was also Institute representative on the United States National Committee of the International Electrotechnical Commission, 1928–32. Professor Slichter is now serving as chairman of the committee on Columbia University scholarships, of which he has been a member since 1922 and chairman since 1925, and as a member of the committees on constitution and by-laws (1925–28 and 1930 to the present; chairman 1925–27), Edison Medal (1918–22 and 1930 to the present), and electrical machinery (1934 to the present). In addition, he has been a representative on the library board of United Engineering Trustees, Inc., since 1915, Engineering Foundation board since 1930, engineering societies monographs committee since 1930, and advisory board of the National Bureau of Engineering Registration since 1933. Professor Slichter is the author of many articles on technical subjects, and has presented several papers and discussions before the Institute. He is a member of The American Society of Mechanical Engineers, Society for the Promotion of Engineering Education, and other organizations.

## Frank Conrad to Receive Lamme Medal

FRANK CONRAD (A'02, Edison Medalist '30) assistant chief engineer of the Westinghouse Electric & Manufacturing Company, East Pittsburgh, Pa., has been awarded the Lamme Medal of the AIEE for 1936 " for his pioneering and basic developments in the fields of electric metering and protective systems." Doctor Conrad was



FRANK CONRAD

born at Pittsburgh, Pa., May 4, 1874, and joined the Westinghouse organization in 1890. In a short time he was transferred to the experimental and testing department, and in 1897 designed the so-called round type of watt-hour meter, which was smaller and more efficient than the previous square types. He then started the systematic redesign of all meters and instruments, which led to improvements in efficiency and the development of new types, among which were the relay-operated recording meter, power factor meter, electrostatic voltmeter, and ground detector. In 1904 Doctor Conrad was appointed general engineer, and for many years served as assistant to the vice-president in charge of engineering. He was appointed assistant chief engineer in 1921. About 1910 Doctor Conrad started the development of a complete elec-

trical system for automobiles, including in his designs voltage-regulated generators such as have come into universal use in the automobile industry in 1937. In 1912 he began investigations into radio telegraphy and telephony, designing and building radio transmitting and receiving equipment. Problems of power distribution for a-c railway systems also engaged his attention at this time. During the World War he aided in the production of telephone and telegraph equipment for the United States Army and Navy, and also designed grenades and grenade-throwing devices. Following the war he sent programs over the air from radio transmitters, and the equipment used by KDKA when that station began broadcasting in 1920 was designed by him. His investigations led to improved apparatus, and to a study of the short-wave field in which he sensed new possibilities. Other work in which he has been engaged includes units for household refrigerating purposes and electric clocks. Doctor Conrad is well-informed in biology, astronomy, and botany. In 1928 he was given the honorary degree of doctor of science by the University of Pittsburgh. Other awards he has received are the Morris Liebmann prize of the Institute of Radio Engineers in 1925, the Edison Medal of the AIEE in 1930, and the John Scott Medal of the City of Philadelphia in 1933. He is a fellow of the Institute of Radio Engineers and a member of the Society of Automotive Engineers and the American Association for the Advancement of Science, and holds the rank of lieutenant commander in the United States Naval Reserve.

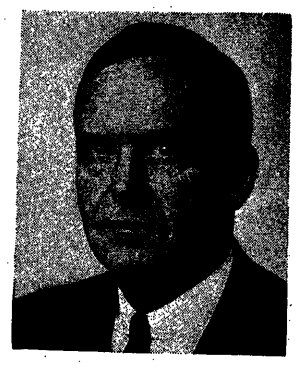
H. H. BEVERAGE (A'23, M'34) chief research engineer, R.C.A. Communications, Inc., New York, N. Y., recently was elected president of the Institute of Radio Engineers for the year 1937. Mr. Beverage was born October 14, 1893, at North Haven, Me., and was graduated from the University of Maine in 1915 with the degree of bachelor



H. H. BEVERAGE

of science in electrical engineering. Upon graduation he was engaged by the General Electric Company, Schenectady, N. Y., as a test engineer, but in 1916 was transferred to the radio laboratories of that company as assistant to Doctor E. F. W. Alexanderson (A'04, F'20). In 1920 Mr. Beverage accepted a position with the Radio Corporation of America, where he was placed in charge of radio research on communication equipment, and continued there until 1929, when he was transferred to R.C.A. Communications, Inc., as chief communications engineer. He has been chief research engineer since 1932. Mr. Beverage has distinguished himself in his research on aperiodic directive receiving antenna systems and receiving systems for reducing the effects of fading at high frequencies. He is the holder of several patents on communication devices and systems, and in 1923 was awarded the Morris Liebmann Memorial Prize of the Institute of Radio Engineers for his research work on directive antenna systems. He is author or co-author of many papers on communication subjects, including 2 papers presented before the Institute, and is at present a member of the Institute's committee on communication. Mr. Beverage is a fellow of the Radio Club of America.

J. H. PAYNE (A'12, M'32) formerly with the Westinghouse International Company, recently was appointed chief of the electrical division of the Bureau of Foreign and Domestic Commerce, United States Department of Commerce, Washington, D. C. Mr. Payne was born June 24, 1883, at Titusville, Pa., and was graduated from Armour Institute of Technology with the degree of bachelor of science in electrical engineering in 1905. Immediately following his graduation, he entered the employ of the Westing-



J. H. PAYNE

house Electric & Manufacturing Company, East Pittsburgh, Pa., being engaged first in engineering and construction work and later in the sales department at New York, N. Y. From 1915 to 1919 Mr. Payne had charge of a division making sales to mining companies. In 1920 he was transferred to the Westinghouse International Company and placed in charge of the selection and appointment of all of that company's distributors; later, he was made manager of the company's department of Europe, in which capacity he was in charge of the company's business in Europe and the dependencies of European countries. In 1929 he was appointed manager of the power department, in charge of the company's sales of central station and distribution equipment in all countries except the United States and Canada. Mr. Payne's duties with the Westinghouse International Company required extensive traveling in the United States and in 31 foreign countries.

W. H. LAWRENCE (A'99, M'12, member for life) chief operating engineer, The New York, (N. Y.) Edison Company, Inc., has retired. Mr. Lawrence was born February 28, 1870, at Middletown, Ohio. He entered the electrical industry in 1886, being employed as an apprentice for the General Electric Company, Schenectady, N. Y. After one year with that company, he became associated with the Edison Manufacturing Company at New York and soon thereafter filled the position of assistant superintendent of construction in the western offices of that company at Cincinnati, Ohio. He continued to serve in that capacity after the consolidation of the Edison and Thomson-Houston companies with the Central Thomson-Houston Company, but in 1889 was transferred to the Edison Electric Illuminating Company of New York. That company has since become The New York Edison Company, Inc., and Mr. Lawrence had completed 47 years of continuous service with the company at the time of his retirement. He is the author of several articles on station operation, including one paper presented before the Institute. He served the Institute as a member of the committee on power generation during the period 1920–29. Mr. Lawrence is a member of The American Society of Mechanical Engineers.

L. E. EMERICH (A'24) who has been district manager of technical division sales in the Chicago, Ill., offices of the Leeds & Northrup Company, has been transferred to the Philadelphia, Pa., offices of that company as assistant sales manager in the technical sales division. Mr. Emerich was born at Schuylkill Haven, Pa., in 1898, and received the degree of bachelor of science at Carnegie Institute. After serving briefly with the Westinghouse Electric & Manufacturing Company, East Pittsburgh, Pa., and the Public Service Electric and Gas Company, Newark, N. J., he entered the sales department of the Leeds & Northrup Company at Philadelphia in 1923 and since then has been associated with that company continuously.

D. G. EVANS (A'20) assistant general manager of the Wisconsin Gas and Electric Company, Racine, has been appointed general manager. Mr. Evans was born at Larned, Kans., in 1887, and received the degree of bachelor of science in electrical engineering at the University of Illinois in 1917. Following a brief service as transformer test engineer for the Wagner Electrical Manufacturing Company, he entered the employ of the Wisconsin Gas and Electric Company as an engineer in 1919. His service with that company has been without interruption.

J. R. READ (A'04) who has been district manager for the Canadian Westinghouse Company, Ltd., at Vancouver, B. C., Can., has been appointed vice-president of the company with headquarters at Hamilton, Ont. Mr. Read was born October 24, 1879, in Virginia. His early electrical experience was gained with the Westinghouse Electric & Manufacturing Company at East Pittsburgh, Pa. In 1901 he was engaged as con-

sulting electrician for various gold-dredging companies in California, and later he became electrical engineer for the Northern California Power Company at Redding. His Canadian experience began in 1904 with his engagement as district-office sales engineer for the Vancouver district office of the Canadian Westinghouse Company. In 1908 he was appointed district manager, and since that time has been associated with many important projects.

G. G. POST (A'11, F'33, past vice-president) vice-president in charge of power, Milwaukee Electric Railway & Light Company, Milwaukee, Wis., has been appointed a representative of the Institute upon the Commission of Washington Award to fill an unexpired term ending August 1, 1938. Mr. Post, who was a vice-president of the Institute 1934–36, has been a member of the Institute's committee on power generation since 1932, and has served on the committees on power transmission and distribution (1922–26), protective devices (1934–36), and Edison Medal (1935–36). He has also been active on technical committees of the Association of Edison Illuminating Companies and the Edison Electric Institute.

B. L. GOODLET (A'25, M'30) research engineer for the Metropolitan-Vickers Electrical Company, Ltd., Manchester, England, recently accepted an appointment as professor in the department of electrical engineering at the University of Capetown, South Africa. Professor Goodlet, a graduate of the Imperial School (Petrograd, Russia) and the University of Sheffield (England), has been associated with the Metropolitan-Vickers company since 1922.

J. F. LINCOLN (A'08, M'20) president of the Lincoln Electric Company, Cleveland, Ohio, was honored recently by the board of directors of the company when a newly created fund and foundation for welding research was named "The James F. Lincoln Arc Welding Foundation" in recognition of his pioneer work in promoting arc welding and perfecting and developing arc-welding equipment and electrodes. Mr. Lincoln has served on several Institute committees, and was a manager 1920-24.

NATHAN COHN (A'29) for several years district manager of technical division sales for the Pacific coast, Leeds & Northrup Company, San Francisco, Calif., has been transferred to the Chicago, Ill., offices of that company in a similar capacity. Mr. Cohn is a native (1907) of Hartford, Conn., and an electrochemical engineering graduate of Massachusetts Institute of Technology. He has been associated with the Leeds & Northrup Company in its sales departments since his graduation.

C. V. ARMSTRONG (A'36) sales engineer for Ingersoll-Rand Company, New York, N. Y., has been transferred to the Chicago, Ill., offices of that company.

H. C. BROWN (A'20) formerly employed in the U.S. Engineers office, Huntington, W. Va., now is with the engineering division, World's Fair, Inc., New York, N. Y.

A. R. WELLWOOD (M'22, F'36) former director of the regional office of the Federal Power Commission, Atlanta, Ga., has been appointed supervising engineer and placed in charge of all Public Works Administration power projects in Nebraska. Mr. Wellwood has been identified with the Federal Power Commission since 1934, and formerly was director of the Commission's electric rate survey, with headquarters at Washington, D. C.

E. E. DREESE (M'25) chairman of the electrical engineering department, Ohio State University, Columbus, has been appointed a trustee of "The James F. Lincoln Arc Welding Foundation," created recently to aid welding research. Principal direction of the foundation's work will be given by him. He has been a member of the Institute's committees on education and electrophysics since 1935, and is a member of the committee on student Branches.

L. M. LA FEVER (A'26) formerly an electrical tester for the Westinghouse Electric & Manufacturing Company, East Pittsburgh, Pa., has been transferred to the New York, N. Y., offices of that company as a field service engineer.

S. B. GAYLORD (A'36) who has been employed by the Western Public Service Company, Broken Bow, Nebr., recently accepted a position in the test engineering department of the General Electric Company, Schenectady, N. Y.

P. B. WAHLQUIST (M'29) formerly manager of the concessions department, Telefonaktiebolaget, L. M. Ericksson, Stockholm, Sweden, has accepted an appointment as general manager, Empresa de Telefonos Ericsson, Mexico City, Mexico.

I. T. MONSETH (A'26) engineering representative, Westinghouse Electric & Manufacturing Company, Kansas City, Mo., has been transferred to the St. Louis, Mo., offices of that company.

H. A. STANLEY (A'07, M'19) plant engineer of the Berkshire Fine Spinning Associates, Inc., Fall River, Mass., has been transferred to the Providence, R. I., offices of that company.

## Obituary

EDWARD BARNARD MEYER (A'05, M'13, F'27, past vice-president, past-president) chief engineer of the Public Service Electric and Gas Company, Newark, N. J., died January 31, 1937. Doctor Meyer was born October 22, 1882, at Newark. He received his technical education at the Newark Technical School, from which he was graduated in 1901; and at Pratt Institute, Brooklyn, N. Y., where he was graduated in the electrical engineering course in 1903; in 1936 he received the honorary degree of doctor of engineering from the Newark College of Engineering. Following his graduation from Pratt Institute in 1903, Doctor Meyer entered the employ of the Public Service Corporation of New Jersey as an engineering assistant, and remained with that organization and its subsidiary companies continuously until 1922. During that period he became, in 1906, field engineer in charge of underground conduit and cable system; in 1909, assistant engineer on special engineering reports, estimates, and construction work; in 1912, assistant to the chief engineer; and in 1919 assistant chief engineer. When the Public Service Production Company was formed in 1922, he was made its chief engineer. In 1929 Doctor Meyer was made a vice-president of the Public Service Production Company, and in 1930, on the occasion of the merger of that company with United Engineers and Constructors, Inc., he was appointed a vice-president of the latter corporation in the capacity of executive and engineering head of the Newark office. He was appointed chief engineer of the Public Service Electric and Gas Company in 1935. Doctor Meyer was liberal in contributing his energy and ability to the causes of the Institute; he was a director from 1928 to 1931, a vice-president during 1932–34, and president for the term 1935–36. In addition, he served on the following committees: executive, 1928–30, 1932–34, and 1935–37 (chairman 1935–36); constitution and by-laws, 1929–35 (chairman 1934–35); co-ordination of Institute activities, 1925–35 (chairman 1934–35); Edison Medal, 1927–29 and 1930–36; finance, 1927–31 and 1932–34 (chairman 1928–30, 1933–34); headquarters, 1928–30 and 1933–34; Lamme Medal, 1928–30; membership, 1924–25; award of Institute prizes, 1925–28 and 1931–34 (chairman 1925–27); publication, 1923–35 (chairman 1927–28, 1931–34); Sections, 1926–27; technical program 1918–29, 1932–34 (chairman 1925–27); transfers, 1932–35 (chairman 1932–33); power generation, 1928–32; code of principles of professional conduct, 1936–37; and power transmission and distribution, 1918–24 (chairman 1918–23). Doctor Meyer served also on the special committees on Institute policies, 1931–33; Associate dues and related matters, 1932–37; on revision of Section territories (1935–37); and biographies and talking motion pictures, 1930–33. He served as an Institute representative on the U.S. National Committee of the International Electrotechnical Commission, 1927 to 1930; the American Engineering Council, 1935–36; the Charles A. Coffin fellowship and research fund committee, 1935–36; and on the Engineering Societies monographs committee, 1930–35. He was a member of the John Fritz Medal board of award for the term 1935–39. Doctor Meyer's other technical activities included participation in the affairs of the American Standards Association, the former National Electric Light Association, The American Society of Mechanical Engineers. His numerous contributions to the technical press include a book, "Underground Transmission and Distribution."

CRANDALL ZACHARIAH ROSENCRANS (M' 36) assistant director of research, Leeds & Northrup Company, Philadelphia, Pa., died January 7, 1937. Mr. Rosencrans was born January 4, 1897, at Chicago, Ill. He received the degrees of bachelor of science in mechanical engineering (1919), master

of science in mechanical engineering (1921), and mechanical engineer (1929) at the University of Illinois, and at the time of his death had nearly completed the requirements for the degree of doctor of philosophy. Following his graduation in 1921, he was appointed to the staff of the University of Illinois Engineering Experiment Station, where he became engaged in independent research on the thermodynamics of gas and oil engines, the mechanism of explosions, and gas-engine testing. In 1926 Mr. Rosencrans accepted a position as research engineer with the Leeds & Northrup Company, and during the following 2 years was responsible for research and development work on electrical methods of gas analysis. From 1928 to 1934 he served as chief of the mechanical division and acting chief of the metallurgical division, and for one year (1928–29) as chief of the chemical division of that company's research department. He was appointed assistant director of research in 1934. Mr. Rosencrans was the holder of several patents on electrical and mechanical measuring devices, and was the author of many scientific papers and articles. He was a member of The American Society of Mechanical Engineers, American Chemical Society, Franklin Institute, Institute of Metals (British), American Society of Refrigerating Engineers, American Association for the Advancement of Science, Verein Deutscher Ingenieure (German), Sigma Xi, and Tau Beta Pi.

WILLIAM DAVID GHERKY (A'95, M'96, F'13, member for life) president of the Railway Track-Work Company, Philadelphia, Pa., died January 17, 1937. Mr. Gherky was born January 7, 1868, at Portsmouth, Ohio. In 1886 and 1887 he was employed as a telegraph operator in railway and commercial service, and in 1888 was engaged by the Edison Electric Company and placed in charge of a 2,400-lamp plant and its associated underground system. At the end of that year he was transferred to the engineering department of the Edison United Manufacturing Company. He remained only briefly with the Edison companies, however, and after serving with the Field Engineering Company, New York, N. Y., accepted a position as engineer in charge of the underground system of the Philadelphia (Pa.) Traction Company in 1893. Later Mr. Gherky organized the Railway Track-Work Company and in 1917 formed the General Grinding Wheel Corporation, of which he was chairman of the board. He was a member of the American Association for the Advancement of Science.

JOHN WILBERT PURCELL (A'13) assistant engineer, Hydro-Electric Power Commission of Ontario, Toronto, died December 12, 1936. Mr. Purcell was born February 29, 1872, at Listowel, Ont., Canada. In 1890 he entered the electrical industry and worked in various manufacturing plants until 1893, when he became superintendent and chief inspector of the Detroit Electric Light and Power Company. He remained in that position until the company was sold in 1896. At that time he entered the employ of Hiram Walker and Sons, Walkerville, Ont., as superintendent of the light and power department. Mr. Purcell joined the staff of the Hydro-Electric Commission in 1912 as assistant engineer in the municipal engineering department, where his duties consisted of developing loads in urban municipalities and rural districts, and in the search for applications of electricity to agricultural uses. He was a member of the Association of Professional Engineers of Ontario, and formerly was an active member of the Canadian Electrical Association.

FREMONT WILSON (A'88, M'88, F'12, member for life) retired consulting engineer, Albany, N. Y., died October 27, 1936, according to word just received at Institute headquarters. Mr. Wilson was born July 15, 1861, at New York, N. Y., and attended the College of the City of New York. In 1882 he was employed by the Western Union Telegraph Company, but in the following year became associated with the Kuth Electric Company. From 1884 to 1887 he was engaged by the Edison Electric Company, New York, in the development of electric illuminating equipment, and from 1887 until 1892 he was with the Sprague Electric Company. Mr. Wilson established his own consulting engineering offices in New York in 1892, continuing as consultant to many electrical manufacturers until his retirement in 1934. He was particularly interested in the safety features of electrical devices, and was for many years consulting electrical engineer to the New York City Bureau of Fire Underwriters.

JOHN CLEMENT DOLPH (A'03, member for life) president and founder of the John C. Dolph Company, Newark, N. J., died February 5, 1937. Mr. Dolph was born September 28, 1864, at North East, Pa. He entered the electrical industry by accepting employment as an apprentice electrician with the Short Electric Railway Company, Cleveland, Ohio; later, he established his own business as a sales representative in electrical and street railway supplies, in New York, N. Y. In 1898 Mr. Dolph became manager of the insulating varnish department of the Sterling Varnish Company Pittsburgh, Pa., and in 1901 accepted a similar position with the Standard Varnish Company, New York. In 1910 he moved to Newark and established his own insulating varnish company under the name of the John C. Dolph Company. He was considered an authority on insulating varnish.

# Membership

## Recommended for Transfer

The board of examiners, at its meeting on February 17, 1937, recommended the following members for transfer to the grade of membership indicated. Any objection to these transfers should be filed at once with the national secretary.

**To Grade of Fellow**

Curry, Walter A., assistant professor of electrical engineering, Columbia University, New York, N. Y.
Mapes, Leland R., chief engineer, Illinois Bell Telephone Company, Chicago, Ill.

2 to Grade of Fellow

**To Grade of Member**

Judson, W. G., electrical engineer, Ward Leonard Electric Company, Mount Vernon, N. Y.
Rathbun, H. V., transmission engineer, Kansas City Power and Light Company, Kansas City, Mo.
Reznicek, Josef, professor of electrical engineering, Technical University, Prague, Czechoslovakia.
Starr, F. M., central station engineering department, General Electric Company, Schenectady, N. Y.
Summerfield, S. C., assistant engineer, New Jersey Bell Telephone Company, Newark.
Trost, F. J., assistant division distribution engineer, Public Service Electric and Gas Company, Jersey City, N. J.

6 to Grade of Member

## Applications for Election

Applications have been received at headquarters from the following candidates for election to membership in the Institute. If the applicant has applied for direct admission to a grade higher than Associate, the grade follows immediately after the name. Any member objecting to the election of any of these candidates should so inform the national secretary before March 31, 1937 or May 31, 1937, if the applicant resides outside of the United States or Canada.

Abbott, L. J., Texas Power and Light Co., Decatur, Texas.
Aicher, L. C., Jr., Allis-Chalmers Manufacturing Company, Milwaukee, Wis.
Ambrosio, B. F., 335 Linwood Street, Brooklyn, N. Y.
Anderson, R. E., Lonoke, Ark.
Angelopoulos, N. C., Engineers, United States Army, Fort DuPont, Del.
Askren, L.eR., Frigidaire Corporation, Dayton, Ohio.
Bailey, C. W., Schlumberger Well Surveying Corporation, Tyler, Texas.
Barken, J., Powell and Power Engineers, Dallas, Texas.
Barbaro, A., 17 Batavia Place, Harrison, N. Y.
Barnard, R. B. (Member), U.S. Engineer's, 523 Pittock Building, Portland, Ore.
Barnes, D. P., Southern Utah Power Company, Cedar City, Utah.
Barr, J. M., Jr., 1515 Blanding Street, Columbia, S. C.
Bastedo, E. H., Anaconda Wire and Cable Company, Hastings-on-Hudson, N. Y.
Beahm, E. M., Albuquerque Gas and Electric Company, Albuquerque, New Mexico.
Beamer, S., Fireman's Fund Idemnity Company, San Francisco, Calif.
Beasley, R. R., Denver and Rio Grande Western Railroad Company, Murray, Utah.
Belding, M. D., Westinghouse Electric & Manufacturing Company, Knoxville, Tenn.
Bellows, G., Jr., General Electric Company, Schenectady, N. Y.
Betzer, R. W., Westinghouse Electric & Manufacturing Company, East Pittsburgh, Pa.
Beveridge, A. B., General Electric Company, Schenectady, N. Y.
Bixler, C. H., Allis-Chalmers Manufacturing Company, Pittsburgh, Pa.
Black, K. H., United States Army, Fort Lawton, Seattle, Wash.
Blake, W. J., American Rolling Mills, Middletown, Ohio.
Blair, F. M., Y.M.C.A., Evansville, Ind.
Bobo, R. A., Phillips Petroleum Company, Oklahoma City, Okla.
Bodholt, I. F., Western Electric Company, Kearny, N. J.
Bodine, R. B., General Electric Company, Schenectady, N. Y.
Bowman, H. J., Consumers Power Company, Kalamazoo, Mich.
Brands, W. H., Buffalo General Electric Company, Buffalo, N. Y.
Brannin, R. S., Jr., West Texas Utilities Company, Abilene, Texas.
Bridges, J. M., New York Telephone Company, Brooklyn, N. Y.

Brill, E. C., Emerson Electric Manufacturing Company, St. Louis, Mo.
Brinkerhoff, J. K., Allis-Chalmers Manufacturing Company, West Allis, Wis.
Brock, H. A., Oklahoma Gas and Electric Company, Muskogee, Okla.
Brundage, T. W., General Electric Company, Pittsfield, Mass.
Brumfiel, R. W., Tennessee Power Company, Chattanooga, Tenn.
Bryan, H. V., Jr., Bethlehem Steel Company, Sparrows Point, Md.
Buchanan, C. H., 431 Avenue D, Forest Hills, Wilkinsburg, Pa.
Buck, L. L., New Jersey Bell Telephone Company, Newark, N. J.
Budington, W. I., Westinghouse Electric & Manufacturing Company, Chicopee Falls, Mass.
Buckeridge, R. M., Shallcross Controls, Inc., Milwaukee, Wis.
Burr, L. S., Fibreboard Products, Inc., Stockton, Calif.
Burkhardt, N. C., Cutler-Hammer, Inc., Milwaukee, Wis.
Caldwell, R. J., General Electric Company, Pittsfield, Mass.
Campbell, S. P., Coleman Lamp and Stove Company, Wichita, Kan.
Campani, L. M., United States Gauge Company, Sellersville, Pa.
Carolan, J. G., 58 Holland Avenue, Floral Park, N. Y.
Cataldo, V. M., Sears Roebuck and Company, New York, N. Y.
Chitwood, R. E., Kansas Power and Light Company, Hiawatha, Kan.
Chmielewicz, E. A., Acme Electric and Manufacturing Company, Cleveland, Ohio.
Cissell, R. F., General Electric Company, Erie, Pa.
Clark, O., Continental Can Company, Oakland, Calif.
Cline, R. F., Norton Company, Chippawa, Ont., Canada.
Cole, J. D., Schweitzer and Conrad, Chicago, Ill.
Coleman, O. K. (Member), American Gas and Electric Company, New York, N. Y.
Condren, J. M., Jr., Otis Elevator Company, New York, N. Y.
Converse, H. D., Fulton Sylphon Company, Knoxville, Tenn.
Cook, W. L., General Fire Company, Providence, R. I.
Cornelius, M. P., Officer's Reserve Corps, Fort Bliss, Texas.
Craib, J. F., Stromberg Carlson Telephone Manufacturing Company, Rochester, N. Y.
Cross, C. B., Narragansett Electric Company, Providence, R. I.
Costa, J., Star Fuel Oil Company, Inc., Ridgefield Park, N. J.
Culan, D. E., Fibreboard Products, Inc., Antioch, Calif.
Curtis, E. M., American Steel & Wire Company, Worcester, Mass.
Czehatowski, A. W., 7 Limerick Street, Gardner, Mass.
Danford, F. E., General Electric Company, Erie, Pa.
Daniel, C. A., General Electric Company, Schenectady, N. Y.
Danko, J. T., McKeesport Technical High, McKeesport, Pa.
Dasburg, A. van C., Baltimore and Ohio Railroad Company, Cincinnati, Ohio.
David, T. H., Jr., General Electric Company, Fort Wayne, Ind.
Davis, G. G., General Electric Company, Schenectady, N. Y.
Davis, L. B., Chesapeake and Potomac Telephone Company, Washington, D. C.
Dawson, J. H., Sumter Machinery Company, Sumter, S. C.
Del Gaizo, C. L., Indiana Bell Telephone Company, Indianapolis, Ind.
Dempsey, W. A., New England Power System, Lawrence, Mass.
Dickinson, W. H., 105 Haven Avenue, New York, N. Y.
Diehl, R. P., (Member) Park City Consolidated Mines Company, Park City, Utah.
Dodson, H. A., Southwestern Light and Power Company, Lawton, Okla.
Domby, H. R., General Electric Company, Fort Wayne, Ind.
Donahue, J., 266 Gifford Avenue, San Jose, Calif.
Dorsey, J. S., Monroe Calculating Machine Company, Manchester, N. H.
Dougherty, C. J., 2122 Cass Street, Fort Wayne, Ind.
Dover, R. S., Fansteel Metallurgical Corporation, North Chicago, Ill.
Draper, H. K., Pacific Lumber Company, Scotia, Calif.
Dueker, K. E., Southern California Edison Company Ltd., Big Creek, Calif.
Dunlap, C. W., Jr., 5406 Red Oak Drive, Hollywood, Calif.
Dwyer, J. J., Omega Gold Mines Ltd., Larder Lake, Ont., Canada.
Eager, G. S., Jr., Bell Telephone Laboratories, Inc., New York, N. Y.
Earls, H. G., General Electric Company, Schenectady, N. Y.
Ellis, E. P., 19 Curtis Place, Maplewood, N. J.
Eichler, W. G., Square D Company, Los Angeles, Calif.
Eisenhut, W. F., Consolidated Edison Company of New York Inc., New York, N. Y.
Ellis, E. R., Alabama Power Company, Birmingham, Ala.
Elmendorf, C. H., III, Bell Telephone Laboratories, Inc., New York, N. Y.
Ember, T., Electrical Products Inc., Baltimore, Md.
Eppes, J. B., Jr., Chesapeake and Potomac Telephone Company, Severna Park, Md.
Erwin, R. A., Department of Water & Power, Los Angeles, Calif.
Esayian, C. G., Philadelphia Storage Battery Company, Philadelphia, Pa.
Escher, H., Jr., General Electric Company, Bloomfield, N. J.
Evans, G. S., Westinghouse Electric & Manufacturing Company, Turtle Creek, Pa.
Evans, T. C., Jr., Federal Power Commission, Washington, D. C.
Eveland, E. H., New York Telephone Company, Brooklyn, N. Y.
Feeney, R. J., Kinnear Manufacturing Company, Columbus, Ohio.
Fenimore, R. A., Indiana Bell Telephone Company, Indianapolis, Ind.
Fenton, R. F., Jr., Box 296, Clarks, La.
Fingerle, W., Jr., Duro Test Corporation, New York, N. Y.
Fink, L. R., 1686 Scenic Avenue, Berkeley, Calif.
Fisher, C. A., E. I. du Pont de Nemours and Company, Buffalo, N. Y.
Fisher, W. C., 24 Benson Avenue, Westwood, N. J.
Flarsheim, E. S., Liebel Flarsheim Company, Cincinnati, Ohio.
Fleming, J. G., Cambridge Instrument Company Inc., Ossining, N. Y.
Forsberg, E., John Morrell and Company, Sioux Falls, S. D.
Fowler, R., Jr., New England Power Association, Providence, R. I.
Fox, J. P., Public Service Company of Northern Illinois, Evanston, Ill.
Frederick, W. R., International Business Machine Corporation, Endicott, N. Y.
Friede, H. A. (Member), Police Telegraph and Municipal Telephone System, Washington, D. C.
Friel, A. C., 500 Wolverine Building, Ann Arbor, Mich.
Fritschel, P. G., General Electric Company, Schenectady, N. Y.
Frolich, J. F., Port of New York Authority, New York, N. Y.
Fuge, H. B., Diehl Manufacturing Company, Elizabethport, N. J.
Gamble, G. L., Bell Telephone Laboratories, Inc., New York, N. Y.
Garlan, H., 233 East 12th Street, New York, N. Y.
Garlinghouse, L. E., Idaho Power Company, Twin Falls, Idaho.
Garner, H. J., Board of Fire Underwriters of the Pacific, San Francisco, Calif.
Garr, D. E., General Electric Company, Erie, Pa.
Gee, S. C., General Electric Company, Schenectady, N. Y.
Gibson, M. P., Gibson Dry Goods Company, Plattsburg, Mo.
Gil, F., Mex. Meridional de Fza., Miacatlan, Mor., Mexico.
Gilardi, A. J., 2552 Haste Street, Berkeley, Calif.
Gilbert, T. H., San Diego Consolidated Gas and Electric Company, San Diego, Calif.
Ginn, W. S., General Electric Company, Schenectady, N. Y.
Gitelson, S., Simplex Wire and Cable Company, Belmont, Mass.
Goudenkoff, A., Canadian Electrical Manufacturing Company Ltd., Vancouver, B. C., Canada.
Gould, J. P., Copperweld Steel Corporation, Chicago, Ill.
Grady, C. D., 215 No. 12 Boulevard, St. Louis, Mo.
Grange, L. N., Mountain States Telephone and Telegraph Company, Ogden, Utah.
Granvdal, N., American Chicle Company, Long Island City, N. Y.
Gray, J. B., Puget Sound Power and Light Co., Renton, Wash.
Gray, S. McK. (Member), Electrical Testing Laboratories, New York, N. Y.
Gregory, C. N., Jr., Philadelphia Storage Battery Company, Philadelphia, Pa.
Greulich, R. A., Pacific Telephone and Telegraph Company, Elko, Nev.
Grim, J. S., Jr. (Member), American Telephone and Telegraph Company, New York, N. Y.
Grimshaw, C. S., General Electric Company, Schenectady, N. Y.
Grossman, B., 475 Paulison Avenue, Passaic, N. J.
Groves, W. E., Radio Station KSL, Salt Lake City, Utah.
Guenzel, E. G., 326 Union State Bank Building, Omaha, Neb.
Haasch, D. E., Idaho Power Company, Weiser, Idaho.
Haeger, A. J., Guardian Electric Company, Chicago, Ill.
Halkins, W. B., Philco Radio and Television Company, Philadelphia, Pa.
Halpert, P., Aerovox Corporation, Brooklyn, N. Y.
Hammond, F. C., S. S. White Dental Manufacturing Company, Staten Island, N. Y.
Hammond, J. R., Indiana and Michigan Electric Company, South Bend, Ind.
Harley, P. C., Western Union Telegraph Company, New York, N. Y.
Harmon, A. G., 1043 Common Street, Lake Charles, La.
Harkness, J. A., Pacific Scientific Company, Los Angeles, Calif.
Happe, W. H., Jr., Consolidated Edison Company, New York, N. Y.
Harmer, W. R., Canadian General Electric Company Ltd., Toronto, Ont., Can.
Harris, P. R., Southwestern Gas and Electric Company, Texarkana, Ark.
Healey, D. S., Jr., General Electric Company, Schenectady, N. Y.
Heath, E. F., Brooklyn Edison Company, Inc., Brooklyn, New York.
Hecht, H. N., 529 Bainbridge Street, Philadelphia, Pa.
Helmuth, R. E., Sunbeam Electrical Manufacturing Company, Evansville, Ind.
Hill, R. A., Western Geophysical Company, Los Angeles, Calif.
Hill, V. F., General Electric Company, Providence, R. I.
Hill, J. J., Westinghouse Electric & Manufacturing Company, East Pittsburgh, Pa.
Hilton, O. B., Indiana Bell Telephone Company, Indianapolis, Ind.
Hoffman, F. O., Cutler-Hammer, Inc., Milwaukee, Wis.
Hollingsworth, L. M., 667 Ninth Avenue, San Francisco, Calif.
Hornbeck, A. J., General Electric Company, Schenectady, N. Y.
Horr, A. F., Electric Steam Sterilizing Company, New York, N. Y.
Hottenstein, J. M., Philco Radio and Television Company, Philadelphia, Pa.
Howe, L. McL., Saskatchewan Power Commission, Saskatoon, Sask., Canada.
Huck, A. J., Knapp-Monarch and Company, St. Louis, Mo.
Hullinger, O. M., Line Material Company, So. Milwaukee, Wis.
Hunkins, H. R., Western Electric Company, Kearny, N. J.
Hurd, C. T., Allis-Chalmers Manufacturing Company, Seattle, Wash.
Hyde, E. L., Carolina Power and Light Company, Raleigh, N. C.
Immel, R. B., Westinghouse Electric & Manufacturing Company, East Pittsburgh, Pa.
Jeffcock, H. W., 55 Chestnut Street, Cohoes, N. Y.
Jenkins, F. L., Jr., Duke Power Company, Spencer, N. C.
Johnson, C. R., United States Rubber Products Inc., New York, N. Y.
Johnson, E. F., 3427 Norton Street, Everett, Wash.
Johnson, H. C., Newton, Abbe and Company, Boston, Mass.
Johnson, W. J., Philadelphia Electric Company, Philadelphia, Pa.
Johnston, R. W., Commonwealth and Southern Corporation, Jackson, Mich.
Katz, R., Ohio University, Athens, Ohio.
Kaufmann, H. A., University of Cincinnati, Cincinnati, Ohio.
Kayle, A. W., Western Electric Company, Kearny, N. J.
Keim, D. Y., Hygrade Sylvania Corporation, Emporium, Pa.
Kennedy, R. V., 728 North 14th Street, Milwaukee, Wis.
Kernnen, E. W., 202½ Portage Street, Hibbing, Minn.
Kersey, L. R., 2046 W. 35th Avenue, Vancouver, B. C., Canada.
Killen, R. B., Dayton Power and Light Company, Dayton, Ohio.
King, K. F., Pure Oil Company, Cincinnati, Ohio.
Kleiman, M., Thompson-Gibb Electric Welding Company, Lynn, Mass.
Klotz, L. J., Jr., Orlando Utilities Commission, Orlando, Fla.
Knightley, W. J., Southwestern Bell Telephone Company, Wichita, Kan.
Kooker, E. M., General Electric Company, Schenectady, N. Y.
Koontz, H. F., Public Service Company of Oklahoma, Vinita, Okla.
Krach, K. J., U.S. Army, 34th Infantry, Ft. George G. Mead, Md.
Kropf, V. J., Westinghouse Electric & Manufacturing Company, East Pittsburgh, Pa.
Kuehl, E. F., Square D Company, Detroit, Mich.
Kuehner, M. H., Otis Elevator Company, New York, N. Y.
L'Allemand, C. C., General Electric Company, Schenectady, N. Y.
La Marsh, J. E., Stewart Warner Corporation, Chicago, Ill.
Lane, H. R., Westinghouse Electric & Manufacturing Company, East Pittsburgh, Pa.
Lee, R. R., Fairbanks, Morse and Company, Beloit, Wis.
Lehenbaum, P., Jr., General Electric Company, Schenectady, N. Y.
Lehland, A., Burgess Battery Company, Madison, Wis.
Lehr, W. O., University of Tennessee, Knoxville, Tenn.
Lehmire, J. A., Electrical Testing Laboratories, New York, N. Y.
Lewellen, W. K., New England Power Association Malden, Mass.
Lewis, J. B., Minneapolis Honeywell Regulator Company, Boston, Mass.
Lewis, J. W., Holtzer Cabot Electric Company, Boston, Mass.
Lloyd, R. L., Underwriters' Laboratories Inc., New York, N. Y.
Lounsberry, E. P., Postal Telegraph Cable Company, New York, N. Y.
Lowe, R. O., Texas Agricultural and Mechanical College, College Station, Texas.
Lueke, W. G., Allis-Chalmers Manufacturing Company, West Allis, Wis.
Lukomitsch, L. R., Recording Devices, Inc., New York, N. Y.

Lundberg, M. E. (Member), Uintah Power and Light Company, Roosevelt, Utah.
Malone, J. D., Jr., New Orleans Public Service Inc., New Orleans, La.
Maloney, F. V., Jr., California Edison Company, Los Angeles, Calif.
Marco, G. P., 110 Florence Avenue, Highland Park, Mich.
Margrave, H. E., Kansas Gas and Electric Company, Wichita, Kan.
Marshall, L. E., Jr., Tennessee Valley Authority, Chattanooga, Tenn.
Mason, C. R., General Electric Company, Schenectady, N. Y.
Mason, J. W., 3rd, General Electric Company, Schenectady, N. Y.
Mather, N. W., Otis Elevator Company, San Francisco, Calif.
Matthews, R. B., Illinois Testing Laboratory Inc., Chicago, Ill.
McGuire, W. G., Magnolia Petroleum Company, New Orleans, La.
McBrearty, J. J., Pennsylvania Power and Light Company, Hazelton, Pa.
McConnell, V. O., Sinclair Refining Company, Houston, Texas.
McCrary, D. C., Southwestern Light and Power Company, Lawton, Okla.
McGowan, V. B., Commonwealth Edison Company, Chicago, Ill.
McLeod, L. W., Westinghouse Electric & Manufacturing Company, Wichita, Kan.
McRae, J. W., Bell Telephone Laboratories, Inc., Deal, N. J.
Mechler, E. A., Western Electric Company, Kearny, N. J.
Meister, M. W., Filer and Stowell Company, Milwaukee, Wis.
Mentzer, R. D., Indiana and Michigan Electric Company, South Bend, Ind.
Mezger, G. R., Allen B. DuMont Laboratories, Inc., Upper Montclair, N. J.
Michener, H. P., Jr., Underwriters Laboratories, Inc., New York, N. Y.
Middleton, H. J., Clinton, Ont., Canada.
Miles, H. A., Niagara Lockport and Ontario Power Company, Buffalo, N. Y.
Miller, J. M., Crown Willamette Paper Company, Camas, Wash.
Miller, K. K., Consolidated Edison Company of New York, Inc., New York, N. Y.
Miller, W. E., Bell Telephone Laboratories, Inc., New York, N. Y.
Millman, J., College of City of New York, New York, N. Y.
Mills, J. H., American Lava Corporation, Newark, N. J.
Milner, C. K., Ohio Bell Telephone Company, Cleveland, Ohio.
Mitchell, J. K., Jersey Bell Telephone Company, Newark, N. J.
Moa, H., c/o Mr. C. H. Cho, 71 Hammond Street, Cambridge, Mass.
Moehlenpah, W. G., 818 West Eula Court, Milwaukee, Wis.
Moersch, E. J., General Foods Corporation, Battle Creek, Mich.
Morgan, F. B., Wisconsin Telephone Company, Milwaukee, Wis.
Moreno, A., Jr., General Electric X-Ray Corporation, Chicago, Ill.
Morris, E. R., General Electric Company, Philadelphia, Pa.
Morrison, H. E., 2535 Channing Way, Berkeley, Calif.
Mudie, J. G., Detroit Edison Company, Detroit, Mich.
Mullin, J. T., 20 Blanken Avenue, San Francisco, Calif.
Murray, J. C., Jr., Crescent Instrument Wire and Cable Company, Trenton, N. J.
Nealy, V. L., Texas Pipe Line Company, Houston, Texas.
Neu, J., 16 West 71st Street, New York, N. Y.
Newton, J. P., General Electric Company, Schenectady, N. Y.
Norberg, C. G., United Dry Docks, Inc., Staten Island, N. Y.
Normann, J. A., New York Telephone Company, New York, N. Y.
Noweck, H. E., Western Electric Company, Baltimore, Md.
Oetting, R. L., General Electric Institute, Cleveland, Ohio.
Olson, E. W., Southern California Edison Company Ltd., Los Angeles, Calif.
Ora, S. M., Jr., General Electric Company, Schenectady, N. Y.
Ott, R. V., Carnegie Illinois Steel Company, Youngstown, Ohio.
Owings, S. B., Harnischfeger Corporation, Milwaukee, Wis.
Partridge, W. F., Hart Manufacturing Company, Poughkeepsie, N. Y.
Pearce, T. C. (Member), Potomac Electric Power Company, Washington, D. C.
Pekin, H. T., Tung-Sol Lamp Works, Newark, N. J.
Pendleton, W. W., General Electric Company, Schenectady, N. Y.
Pettersen, R. H., Brooklyn Edison Co., Inc., New York, N. Y.
Peterson, C. R., Washington Water Power Company, Spokane, Wash.
Phillips, A. H., E. M. Gilbert Engineering Corporation, Reading, Pa.
Phillips, T. A., Central Arizona Light and Power Company, Phoenix, Ariz.
Pickell, J., Jr., Southern Bell Telephone and Telegraph Company, Columbia, S. C.
Plumb, L. A., Bausch and Lomb Optical Company, Rochester, N. Y.
Pochkhanawalla, A. M., General Electric Company, Schenectady, N. Y.
Pollack, D., 311 Cooper Street, Camden, N. J.
Ponichtera, A. J., Western Electric Company, Kearny, N. J.
Porter, F. C., 859 South Genois Street, New Orleans, La.
Powell, E. E., Southwestern Bell Telephone Company, Wichita, Kan.
Profitt, A. F., Jr., Federal Power Commission, Washington, D. C.
Qurollo, J. J., Jr., Western United Gas and Electric Company, Aurora, Ill.
Radtke, S. R., 3426 North 1st Street, Milwaukee, Wis.
Radunsky, M. M., Knapp Monarck Electrical Company, St. Louis, Mo.
Ramo, S., General Electric Company, Schenectady, N. Y.
Randall, E. W., Jr., Stone and Webster Engineering Corporation, Erie, Pa.
Rarick, E. A., Albertson Company Inc., Sioux City, Iowa.
Rhyneer, S. M., P. O. Box 121, Absarokee, Mont.
Richman, S. I., Westinghouse Electric & Manufacturing Company, Newark, N. J.
Rigby, C. J., General Electric Company, Schenectady, N. Y.
Rieves, M. H., Commonwealth Edison Company, Chicago, Ill.
Rist, R. M., Gibbs and Hill Inc., New York, N. Y.
Robinson, W. L., Western Electric Company, Chicago, Ill.
Roeseler, W. L., Co. 4729 CCC, Belton, Mont.
Rogo, R. G., Consumers Power Company, Detroit, Mich.
Rohrbaugh, N. B., Paper Mill, Spring Grove, Pa.
Romain, B. P. (Member), Weston Electrical Instrument Corporation, Newark, N. J.
Rosta, J. G., 52 Robinson Street, New Brunswick, N. J.
Roth, E. C., Phillips Petroleum Company, Wichita, Kan.
Sandlin, D. S., Box 395, Ola, Ark.
Sarlin, F., Jr., Chesapeake and Potomac Telephone Company, of Baltimore City, Essex, Md.
Savage, P. R., Woodbury Telephone Company, Woodbury, Conn.
Savoie, C. C., Lula Plantation, Belle Rose, La.
Saxon, F. A., Georgia Power Company, Augusta, Ga.
Scanlan, J. M., Indiana Bell Telephone Company, Indianapolis, Ind.
Schenker, B., Diehl Manufacturing Company, Elizabethport, N. J.
Schjonberg, C. S., 60 East 5th Street, Houghton, Mich.
Schopp, O. J., General Electric Company, Schenectady, N. Y.
Schroeder, T. W., General Electric Company, Schenectady, N. Y.
Schuck, H. V., Trumbull Electric Manufacturing Company, Ludlow, Ky.
Schultis, J. J., Cleveland Railway Company, Cleveland, Ohio.
Schulz, E. H., University of Texas, Austin, Texas.
Schuster, E. F., American Transformer Company, Newark, N. J.
Schwalbert, W. H., Toledo Edison Company, Toledo, Ohio.
Scott, F. T., General Electric Company, Schenectady, N. Y.
Scott, J. M., Jr., Westinghouse Electric & Manufacturing Company, East Pittsburgh, Pa.
Seaward, C. R., General Electric Company, Schenectady, N. Y.
Seibert, A. P., Apex Steel Company, Los Angeles, Calif.
Shackton, W. H. (Member), Allen Bradley Company, Milwaukee, Wis.
Shanks, W. A., Harnischfeger Corporation, Milwaukee, Wis.
Shapiro, E. J., Standard Air Conditioning Inc., New Rochelle, N. Y.
Sharp, W. O., Bell Telephone Laboratories, Inc., New York, N. Y.
Shipley, R. B., Tennessee Public Service Company, Knoxville, Tenn.
Shirtum, R. C., Emerson Electrical Manufacturing Company, St. Louis, Mo.
Silvey, W. R., New York Telephone Company, New York.
Simpson, H. J., Gearhart Radio Corporation, Fresno, Calif.
Slauson, H. L., Jr., 7 Brookside Park, Old Greenwich, Conn.
Smith, B. H., Jr., Westinghouse Electric & Manufacturing Company, East Pittsburgh, Pa.
Smith, C. G., Pacific Gas and Electric Company, Salinas, Calif.
Smith, H. A., Youngstown Sheet and Tube Company, Indiana Harbor, Ind.
Smith, H. W., Oklahoma Gas and Electric Company, Oklahoma City, Okla.
Smith, C. G., Pacific Gas and Electric Company, Salinas, Calif.
Smith, K. C., New England Power Service Company, Boston, Mass.
Smith, W. P., University of Minnesota, Minneapolis, Minn.
Smithgall, H. E., Jr., Hygrade Sylvania Corporation, Emporium, Pa.
Smrz, G. L., Line Material Company, South Milwaukee, Wis.
Smulin, L. D., Ohio Brass Company, Barberton, Ohio
Soule, J. W., Wisconsin Public Service Corporation, Green Bay, Wis.
Spencer, F. A. (Member), Norwich University, Northfield, Vt.
Sprinkle, R. E., Belmont Radio Corporation, Chicago, Ill.
Stapp, W. H., Jr., Colorado State Highway Department, Denver, Colo.
Stahl, W. H., Jr., Bristol Company, Waterbury, Conn.
Stewart, H. L., Tennessee Valley Authority, Lebanon, Tenn.
Stiles, R. G., P. O. Box 254, Middlebury, Vt.
Stodola, E. K., Radio Engineering Laboratory Inc., Long Island City, N. Y.
Stokely, M. M., J. E. Sirrine and Company, Greenville, S. C.
Stulginskis, B. A. (Member), United Engineers & Constructors, Inc., Philadelphia, Pa.
Stumpf, G. H., Automatic Switch Company, New York, N. Y.
Stutz, G. W., Fairbanks, Morse and Company, Chicago, Ill.
Sudlow, W. H., Georgia Power Company, Augusta, Ga.
Summers, C. M., New York Central Railroad, Chicago, Ill.
Taggart, R. D., Moore Steam Turbine Corporation, Wellsville, N. Y.
Tankersley, C. E., Georgia Power Company, Augusta, Ga.
Tanner, D. W., General Electric Company, Erie, Pa.
Taylor, C. M., 354 Euclid Avenue, Elmira, N. Y.
Taylor, J. K., Rural Electrification Administration, Washington, D. C.
Teitler, A., Jr., Cornell Dubilier Corporation, South Plainfield, N. J.
Terry, J. E., Ritter Dental Manufacturing Company, Rochester, N. Y.
Terwilliger, D. D., Atlantic City Electric Company, Salem, N. J.
Thomas, J. F., Texas Power and Light Company, Dallas, Texas.
Trevino, R. C., P. O. Box 1105, Edinburg, Texas.
Turnau, W. F., General Electric Vapor Lamp Company, Hoboken, N. J.
Ulans, R. I., Consolidated Edison Co. of New York, Inc., New York, N. Y.
Van Haste, W., Bell Telephone Laboratories, Inc., New York, N. Y.
Varhus, H. H., Minneapolis General Electric Company, Minneapolis, Minn.
Volkhardt, V. (Miss), 1101 Emerson Street, Palo Alto, Calif.
Wainola, A. J., 1219 Dwight Way, Berkeley, Calif.
Wainwright, R. M., Montana Power Company, Butte, Mont.
Walker, J. R. (Member), General Cable Corporation, New York, N. Y.
Wallace, F. R., General Electric Company, Tecumseh, Kan.
Walter, G. B., 20 Belmont Street, Englewood, N. J.
Ward, S., Lehigh Foundries Inc., Easton, Pa.
Wareing, J. F., New Bedford Vocational School, New Bedford, Mass.
Warshaw, J., Brush Development Company, Cleveland, Ohio.
Watson, P. R., General Electric Company, Schenectady, N. Y.
Watt, C. W., Jr., Zinsmeyer Company, Los Angeles, Calif.
Weiss, H. M., Brush Development Company, Cleveland Heights, Ohio.
Welch, R. C., General Electric Company, Schenectady, N. Y.
Well, A. C., General Electric Company, Schenectady, N. Y.
Welton, W. R., Connecticut Light and Power Company, Waterbury, Conn.
Weir, A. M., Square D Company, Canada Ltd., Toronto, Ont., Canada.
Wertz, C. W., General Electric Company, Schenectady, N. Y.
Wessells, W. T., Franklin Electric Company, Philadelphia, Pa.
West, S. B., General Electric Company, Pittsfield, Mass.
Westcott, H. H., Ritter Dental Company, Rochester, N. Y.
Westrate, M., Commonwealth and Southern Corporation, Jackson, Mich.
Whitaker, J. A., Douglas Aircraft Company, Ocean Park, Calif.
Whipp, D. M., Box 312, Avalon, Calif.
Whitney, T. G., Electrical Research Products Inc., New York, N. Y.
Wilkens, K. N., Mueller Brass Company, Port Huron, Mich.
Winters, H. R., Oklahoma Gas and Electric Company, Sapulpa, Okla.
Wyndrum, R. W., American Telephone and Telegraph Company, New York, N. Y.
York, J. W., Westinghouse Electric & Manufacturing Company, East Pittsburgh, Pa.
Zaccaria, J. N., 113 Shaler Avenue, Fairview, N. J.
Zazvorka, J., Jr., 256 Humble Building, Houston, Texas.
Zenoni, W. E., 2750 Paulding Avenue, Bronx, New York, N. Y.

402 Domestic

**Foreign**

Amado, J. J., Jr., Panama Electrica, S. A., Panama City, Panama.
Carr, T. H. (Member), National Boiler and General Insurance Company Ltd., Manchester, England.
DeMel, C. H. J., Ganges Canal Grid Hydro Electric Scheme, Colombo, Ceylon.

Dexter, L. H., Porto Rico Railway Light and Power Company, San Juan, Porto Rico.
Garcia, J. B., Compania Mexicana de Petroleo "El Aguila," Tampico, Tamps., Mexico.
Gruenberg, W. E., Lago Oil and Transport Company, Ltd., Aruba, Dutch West Indies.
Kapur, R. N., British Insulated Cables Ltd., Peshawar, India.
Kondo, H., Yasukawa Electric Works, Yawata, Fukuoka-ken, Japan.
Moody, H. T. (Member), Rangoon Elec. Tramway & Supply Company, Ltd., Rangoon, Burma.
Stromberg, T. V., ASEA, Vasteras, Sweden.
Tien, C., Lohochai, Yenchenghsien, Honan, China.
Tillekeratne, T. S. V., Ganges Canal Grid Hydro Electric Scheme, Colombo, Ceylon.
Uhl, A. H., Synthetic Carbon and Engineering Company Ltd., Middlesex, England.
Velez, R. J., Central Juneos, Porto Rico.

**14 Foreign**

## Addresses Wanted

A list of members whose mail has been returned by the postal authorities is given below, with the addresses as they now appear on the Institute record. Any member knowing of corrections to these addresses will kindly communicate them at once to the office of the secretary at 33 West 39th St., New York, N. Y.

Eiler, E. E., 101 Brookline Court, Upper Darby, Pa.
Godoy, Ernesto R., Cia. Tel. y Tel. Mex., 16 de Septiembri No. 13, Mexico, D. F., Mex.
Hale, Edward E., Public Service Commission of New York, 80 Centre St., New York, N. Y.
Jones, Harry Kenneth, 5511 Kenmore Ave., Chicago, Ill.
Little, Leroy C., 3414—17th St., N., Cherrydale, Va.
Miyota, Nath S., 916½ Howell St., Seattle, Wash.
Moore, Everett, 821 Sunset Blvd., Los Angeles, Calif.
Peach, Paul S., Upperville, Va.
Pollastro, John B., Helper, Utah.
Sawyer, Fred E., 811 E. Wisconsin Ave., Milwaukee, Wis.
Wickel, F. A., Pier 42, Dollar S. S. Lines, San Francisco, Calif.
Wong, Harry Y. L., 771 Broadway, West New York, N. J.

**12 Addressed Wanted**

# Engineering Literature

## New Books in the Societies Library

Among the new books received at the Engineering Societies Library, New York, recently, are the following which have been selected because of their possible interest to the electrical engineer. Unless otherwise specified, books listed have been presented gratis by the publishers. The Institute assumes no responsibility for statements made in the following outlines, information for which is taken from the preface of the book in question.

CONGRÈS INTERNATIONAL des APPLICATIONS ELECTROCALORIFIQUES et ELECTROCHIMIQUES, Schéveningue, June 1936. Recueil des Travaux et Compte-Rendu des Séances. Publié sous la direction de l'institution Néerlandaise des Applications Electrocalorifiques et Electrochimiques, Secrétariat: Arnhem, Nachtegaalspad 1, Pays-Bas. Moorman's Periodieke Pers N.V., La Haye, September, 1936. 336 p., illus., diagrs., charts, tables, 10x6 in., cloth, 6 guilders. Includes papers on industrial electric heating, electric furnaces, and the heat treatment of metals. Some papers are in English, the remainder in French or German.

CONNECTING INDUCTION MOTORS. By A. M. Dudley. 3 ed. N. Y. and Lond., McGraw-Hill Book Company, 1936. 464 p., illustrated, 9x6 in., cloth $3.50. A practical guide to connection and repair of induction motors and in solving questions of making changes to meet varying conditions of voltage, current, and phase.

ELEKTRISCHE MASCHINEN. Volume 4. Die Induktionsmaschinen. By R. Richter. Berlin, Julius Springer, 1936. 440 p., illustrated, 9x6 in., cloth, 30 rm. Discusses the theory and design of single-phase and polyphase generators, motors, and voltage regulators. A-C commutator machines are omitted for consideration in a later volume. Useful to the advanced student.

MACRAE'S BLUE BOOK with which has been incorporated Hendrick's Commercial Register 44 ed. 1936/1937. Chicago, MacRae's Blue Book Company, 3,372 p., 11x8 in., cloth, $15.00 An annual directory following established lines. Includes lists of manufacturers of all industrial products, trade names, and trade facilities. Provides information on the makers of any product.

MATERIALPRÜFUNG mit RÖNTGENSTRAHLEN unter besonderer Berücksichtigung der Röntgenmetallkunde. By R. Glocker. 2 ed. Berlin, Julius Springer, 1936. 386 p., illustrated, 9x6 in., cloth, 33 rm. A practical text on the application of X rays to the study of metals. Discusses the production of X-rays, their properties and application. Emphasis is placed on practical methods of procedure.

MERCURY ARCS. By. F. J. Teago and J. F. Gill. Lond., Methuen and Company, 1936. 104 p., illustrated, 7x4 in., cloth, 3s. A brief outline of the more important electrical, mechanical, and operational features of the mercury arc. Adapted to those who wish a compact statement of modern views.

EIN NEUES ELEKTRISCHES SPRECH GERÄT ZUR NACHBILDUNG der MENSCHLICHEN VOKALE. (Einzelausgabe aus den Abhandlungen der Preussischen Akademie der Wissenschaften Jahrgang 1936. Phys.-Math. Klasse. Nr. 2). By K. W. Wagner. Berlin, Verlag der Akademie der Wissenschaften in Kommission bei Walter de Gruyter & Co., 1936. 44 p., illustrated, 11x6 in., paper, 3 rm. Describes a new electrical instrument for studying and reproducing the vowel sounds of the human voice, and gives the results obtained by the author.

SOUND EQUIPMENT, MOTION PICTURE PROJECTION, PUBLIC ADDRESS SYSTEMS. By J. R. Cameron. Woodmont, Conn., Cameron Publishing Company, 1936. 326 p., illustrated, 8x5 in., cloth, $5.00. Affords a course of instruction in the projection of sound pictures; the construction and operation of equipment is described in detail.

VALUE THEORY and BUSINESS CYCLES. By H. L. McCracken. 2 ed. N. Y. and Lond., McGraw-Hill Book Company, 1936. 259 p., charts, 9x6 in., cloth, $4.00. Designed to bring out the vital and fundamental relationship between value theory and business cycles.

VIBRATION and SOUND. By P. M. Morse. N. Y. and Lond., McGraw-Hill Book Company, 1936. 351 p., 9x6 in., cloth, $4.00. Intended primarily for students of physics and communication engineering, and is based on courses given at the Massachusetts Institute of Technology. Aims to give a general introduction to the theory of vibration and sound.

WIRELESS ENGINEERING. By L. S. Palmer. N. Y. and Lond., Longmans, Green, and Co., 1936. 544 p., illustrated, 9x6 in., cloth, $7.50. A revised and enlarged edition of "Wireless Principles and Practice." Provides information on all branches of radiotelegraphy and radiotelephony, in which theory and practice are combined. Suited to graduate students and practicing engineers in need of a reference book. Contains material on ultrashort-wave radio, beam-antenna systems, propagation through the ionosphere, and quartz oscillators.

APPLIED RADIOCHEMISTRY. (George Fisher Baker Nonresident Lectureship in Chemistry at Cornell University.) By O. Hahn. Ithaca, N. Y., Cornell University Press, 1936. 278 p., illustrated, 9x6 in., cloth, $250. Discusses the utilization of radioactive atoms as representatives of chemical elements in various lines of chemical research. Based upon lectures given at Cornell University in 1933.

SURVEY of the PRESENT ORGANIZATION of STANDARDIZATION; NATIONAL and INTERNATIONAL, published by the Central Office of the World Power Conference, Lond., W.C.2, 36 Kingsway, 1936. 55 p., tables, 11x7 in., paper 3s. 6d. (Gift of American National Committee, Interior Bldg., Washington, D. C.) Presents the facts regarding the national organization of standardization in 33 countries, and of 2 international bodies.

ASTM STANDARDS on ELECTRICAL INSULATING MATERIALS, prepared by Committee *D-9*, Specifications, Methods of Testing. September 1936. Philadelphia, Pa., American Society for Testing Materials, 1936. 329 p., illustrated, 9x6 in., paper, $2.00 ($1.50 to members). Includes the 1936 report of the committee on electric insulating materials with the proposed revisions of standards.

ÉLECTRICITÉ (Agenda Dunod) by L.-D. Fourcault. 56 ed. 392 p. Paris, Dunod, 1937. illustrated, 6x4 in., cloth, 20 frs. Contains numerical and other data frequently wanted by electrical engineers. Small enough for the pocket.


## Engineering Societies Library

29 West 39th Street, New York, N. Y.

MAINTAINED as a public reference library of engineering and the allied sciences, this library is a co-operative activity of the national societies of civil, electrical, mechanical, and mining engineers.

Resources of the library are available also to those unable to visit it in person. Lists of references, copies or translation of articles, and similar assistance may be obtained upon written application, subject only to charges sufficient to cover the cost of the work required.

A collection of modern technical books is available to any member residing in North America at a rental rate of five cents per day per volume, plus transportation charges.

Many other services are obtainable and an inquiry to the director of the library will bring information concerning them.


Les COMMUNICATIONS RADIO-ÉLECTRIQUES, part 2. By H. de Bellescize. Paris, Gauthier-Villars, 1936. 218 p., illus., 10x7 in., paper, 30 frs. (parts 1 and 2, 50 frs.). Discusses fundamental problems of radio communication, such as the elimination of interference and the increasing of certainty of communication.

ACCOUNTING PRINCIPLES for ENGINEERS. By C. Reitell and C. Van Sickel. 2 ed. N. Y. and Lond., McGraw-Hill Book Company, 1936. 518 p., 9x6 in., cloth, $4.00. Sets forth the elementary principles of accounting upon which accurate cost findings are based, including accounting technique, basic principles of valuation, factory controls, revenue accounts, and the outline of advanced cost finding. Based upon a course given at the University of Pittsburgh.

Book of ASTM STANDARDS issued triennially. 1936. 2 volumes. Philadelphia, Pa., American Society for Testing Materials. Illustrated, 9x6 in., lea., part 1, 898 p., $7.50; part 2, 1477 p., $7.50 (2 parts, $14.) Contains standard specifications, test methods, recommended practices, and definitions formally adopted by the society. One part covers metallic materials; the other, nonmetallic materials.

ATM—Archiv für Technisches Messen. Lieferungen 63–66, September–December 1936. Munich and Berlin, R. Oldenbourg. Illustrated, 12x8 in., paper, 1.50 rm. Devoted to brief accounts of new developments in apparatus and methods for technical measurements.

AMERICAN ELECTRICIANS' HANDBOOK. By T. Croft. 4th edition revised by C. C. Carr. New York and London, McGraw-Hill Book Company, 1936. 1051 pages, illustrated, 7x4 in., leather, $4.00. A handbook for wiremen, contractors, linemen, and plant superintendents.

ANALYSES of BUSINESS CYCLES. By A. B. Adams. New York and London, McGraw-Hill Book Company, 1936. 292 pages, illustrated, 9x6 in., cloth, $3.00. Discusses the causes of business fluctuations and suggests reforms in business practices that would tend to eliminate extreme cycles.

CONNECTING and TESTING DIRECT-CURRENT MACHINES. By F. A. Annett and A. C. Roe. 2nd edition. New York and London, McGraw-Hill Book Company, 1937. 302 pages, illustrated, 9x6 in., cloth, $3.00. Gives practical instructions for the reconnection of d-c machines for a change in voltage or speed, or both, and also for locating and remedying faults.

ELECTRIC ARC WELDING PRACTICE. By H. L. Lewenz. London, Crosby Lockwood and Son, 1936. 126 pages, illustrated, 9x6 in., cloth, 8s. 6d. Describes the principles and practice of arc welding; intended to assist those who have actually to carry out the work.

ELECTRICITY. By W. L. Bragg. New York, Macmillan Company, 1936. 272 pages, illustrated, 9x6 in., cloth, $4.00. Presents the substance of the series of lectures delivered at the Royal Institution in 1934. Deals with the behavior of electrical charges, electrical circuits and magnets, and with such fundamental apparatus as cells and motors. Describes in detail the electrical apparatus in use in everyday life; written for the layman.

ELEKTROMOTOR und ARBEITSMASCHINE. (Schriftenreihe Ingenieurforthildung, Heft 1.) By F. Moeller and O. Repp. Berlin, J. Springer, 1936. 157 pages, illustrated, 9x6 in., paper, 4.80 rm. A practical textbook on electric motors and their use for driving machinery.

# Industrial Notes

**Large Motor Standardization.**—Electrical drives even for large power requirements have been developed to the extent that they are rapidly becoming standardized. For example, Westinghouse has built thirty-two identical steel mill motors rated at 1250 hp, 600 volts, 300–600 rpm. Installed in 4 different steel manufacturers' plants, each is used for driving cold strip or sheet mills.

**New Roebling Branch Manager.**—Arthur E. Gaynor has been appointed manager of the New York branch of John A. Roebling's Sons Co., succeeding William P. Bowman, who died on January 22.

**Cutler-Hammer Appointment.**—T. D. Montgomery was recently appointed by Cutler-Hammer, Inc., Milwaukee, as manager of the foreign sales division.

**Emerson Electric Appointment.**—The Emerson Electric Mfg. Co., St. Louis, has announced the appointment of Eugene P. Farris as manager of specialty sales, succeeding H. L. Parker, Jr., resigned.

**Lincoln Electric Appointments.**—The Lincoln Electric Co., Cleveland, Ohio, announces the appointment of B. J. Brugge, who spent 2 years superintending welding operations in the Near East, to the sales staff of its Los Angeles office. W. R. Smith has likewise been appointed to its sales staff. Robert A. Wilson, George Mandula, and A. T. Cox, Jr. have been appointed to the staff of the Chicago office.

**Pole Mounted Capacitors.**—A new type of weather-proof, steel clad, hermetically sealed 15 kva capacitor unit, suitable for pole mounting on distribution circuits, is announced by Westinghouse Electric & Mfg. Co., East Pittsburgh. These units contain an internal discharge device and are provided with means of mounting on brackets to crossarms or direct to poles, or in groups of four on single angle iron racks, making possible inexpensive installations up to 180 kilovoltamperes on one pair of crossarms.

**Marshall Electric Company Sold.**—The Ideal Commutator Dresser Co., Sycamore, Ill., announces the acquisition of the Marshall Electric Co. of Elkhart, Ind., manufacturers of automatic regulators for voltage, current and speed control of electrical equipment. The operations of the acquired company will be transferred as rapidly as possible to Sycamore and consolidated with the engineering, research and other departments of the purchaser.

**Westinghouse Office to Move.**—The Westinghouse Electric & Mfg. Co. will move its Pittsburgh office and some of its general offices now located at East Pittsburgh, to the Union National Bank Building in Pittsburgh about May 1. Occupying nine floors of the building, from the fifth to the thirteenth floors, the Pittsburgh district office, subsidiary district offices and headquarters offices including executive, legal, industrial relations, sales and accounting departments, will be centrally located in the Union Bank Building to facilitate their operations. Formerly the company's district office and subsidiary offices had been in this same building.

# Trade Literature

**Light-Sensitive Cell.**—Bulletin GEA-2467, 16 pp. Describes G-E light-sensitive cell, including complete technical and descriptive data. General Electric Co., Schenectady, N. Y.

**Beryllium Copper Alloys.**—Folder, 8 pp. Describes the properties of these heat-treatable copper alloys; lists electrical applications, among others, where it may be used to advantage. Beryllium Corp. of Pennsylvania, Reading, Pa.

**Transformers.**—Bulletin GEA-2442A, 8 pp. Describes unit-type distribution transformers; each unit completely self-contained, incorporating lightning and overload protection, overload indication, etc. General Electric Co., Schenectady, N. Y.

**Transformers.**—Catalog 105, 16 pp. Describes and illustrates the various phases of distribution transformer manufacture, showing cut-away models and including tables of voltage ratings, accessories, and price lists. R. E. Uptegraff Manufacturing Co., 316 No. Lexington Ave., Pittsburgh, Pa.

**Capacitors.**—Bulletin GEA-2494, 20 pp. Describes pole type distribution capacitors; a detailed presentation of power factor correction in distribution circuits and the applications and advantages of this type of equipment. General Electric Co., Schenectady, N. Y.

**Group Operated Switches.**—Bulletin 50, Cat. Sec. No. 1, 4 pp. Describes high-voltage, group operated switches, 88,000-S to 200,000 volts. This type is a rotating insulator, vertical break switch for outdoor substation and transmission line service. Pacific Electric Mfg. Corp., 5815 Third St., San Francisco, Calif.

**Outdoor Bus Supports.**—Descriptive Data 36-220, 16 pp. Includes specifications for apparatus insulators for standard and heavy duty service, bus supports for various types of mountings, and clamps for outdoor channel buses. Westinghouse Electric & Mfg. Co., E. Pittsburgh, Pa.

**Switchboards.** Bulletin GEA-2253A, 12 pp., "Modern Switchboard Styling." Largely a photographic treatment of the subject, illustrating the better appearance made possible by semiflush instrument mounting and available with control panels, metal-clad gear, cubicles, etc. General Electric Co., Schenectady, N. Y.

**Transformers.**—Bulletin 1186, 12 pp. Describes Type "SB" outage free distribution transformers. Discusses principles of operation, how transient surges are diverted, and the methods used to provide protection, as well as construction details of the transformers and protective equipment. Allis-Chalmers Mfg. Co., Milwaukee, Wis.

**Control Engineering Service.**—Booklet, 8 pp. Describes an engineering service for adapting leading manufacturers' apparatus to control problems of all kinds in every industry, and combining consultation, manufacturing, contracting, supervision and guaranteed results wherever a control problem arises to be solved. General Control Co., Cambridge, Mass.

**Motor Bearings.**—Bulletin EM-7, 40 pp. Describes and illustrates over 200 electric motor bearings. Alphabetical, progressive, and numerical size listings include bearings for any type motor. Sections are incorporated on bronze cored and solid bars, hexagon bars, lead-base and tin-base babbitt and general purpose phosphor bronze bearings. Johnson Bronze Co., New Castle, Pa.

**Tachometer.** Bulletin 705, 2 pp. Describes a new, normal rate hand tachometer, represented as about the most accurate device made for speed measurements The instrument has a scale graduated into 40 divisions. On the 1000 rpm range, this means that the instrument is arranged for 5 rpm per division and is quite easy to read to one fifth of a division or 1 rpm in 1000. Herman H. Sticht & Co., 27 Park Pl., New York City.

**Power-Factor Correction.**—Reference table for calculating necessary capacitor kva to correct load to desired power-factor. The chart among other functions computes the reactive kva required to raise the power-factor to any desired percentage. The reverse side of the chart shows the amount of current drawn by capacitors and also specifies the sizes of switches to be used with varying sizes of capacitors. Cornell-Dubilier Corp., South Plainfied, N. J.

**Micromax Recorder.**—Die-out ND(1), 8 pp. A novel advertising piece demonstrating the Silver-Anniversary Micromax Recorder. Cut to the actual shape of the recorder, the door of the case opens and swings out the chart carriage and whole mechanism into view, just as may be done with the actual instrument. Inside and out each unit is in true perspective, with chart and record in color. Though its range is that of a typical temperature recorder, the model demonstrates equally well the automatic indicating and recording of any of a wide variety of process conditions—not only temperature, but chemical concentration, pH, per cent $CO_2$, smoke density, liquid level, speed, frequency, load, voltage, etc. Leeds & Northrup Co., 4962 Stenton Ave., Philadelphia, Pa.

# Electrical Engineering

Registered U. S. Patent Office

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## The Cover

**Tapping an electric furnace in the Canton, Ohio, plant of the Republic Steel Corporation**




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(Founded 1884)



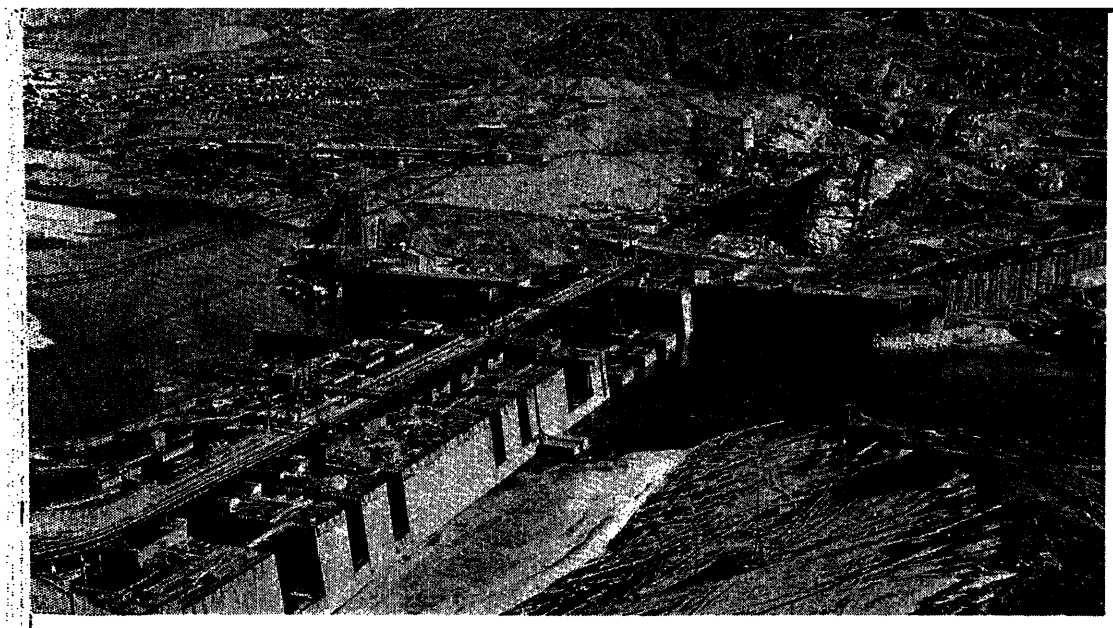
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**An inspection trip to the $375,000,000 Grand Coulee project on the Columbia River, about 92 miles from Spokane, Wash., is being included on the program of the Institute's 1937 Pacific Coast convention to be held in that city, August 30–September 3. It is planned also to include one or more papers dealing with the engineering features of the project. At the left is reproduced a photograph taken March 8 especially for ELECTRICAL ENGINEERING by the U.S. Bureau of Reclamation, showing the status of construction on that date. In the foreground is the completed foundation for one end of the dam which will rise to a maximum height of 550 feet and will contain 11,250,000 cubic yards of masonry. The entire project includes construction of a dam, a 2,700,000-horsepower power plant, and a pumping station on the Columbia River; a reservoir in Grand Coulee; main irrigation canals; and water distribution system on the project lands.**

# High Lights

**Engineering Education.** "American engineering colleges have a great responsibility in meeting the demands of the times so that their graduates will be capable as engineers and will also have . . . well-rounded ethical standards and broad interests. . ." So says a recognized authority in outlining current practices and trends in engineering education (*pages 414–17*). Careful consideration should be given to that phase of engineering education, and professional development, which follows the award of the bachelor's degree, according to another well-known educator (*pages 418–19*). Graduate courses for engineers are now being offered on a part-time basis by several educational institutions in Chicago, Ill. (*pages 417–18*). In order that the engineer may learn to write and speak with facility, it is suggested that the study of English should commence as soon as the student enters college and continue until he graduates (*pages 419–20*).

**Alternator Regulator.** A simple electronic voltage regulator for alternators, utilizing 2 mercury-vapor control tubes combined with a small inductance, capacitance, and resistance has been developed. Its sensitivity and operating speed are said to be comparable with those existing electronic regulators of more complicated design (*pages 462–4*).

**Economics and Business Courses.** To stimulate the interest of student engineers in economic problems, a brief but fairly comprehensive course in industrial economics and business methods is advocated in place of some of the highly specialized technical courses now included in engineering-college curricula (*pages 446–54*).

**End-Winding Inductance.** Formulas for calculating the end-winding self-inductance and leakage inductance of a salient-pole synchronous machine are given in a paper in this issue. An effort has been made to indicate the nature and consequences of the assumptions involved (*pages 355–61*).

**Magnetic Fluxmeter.** To provide means for continuous measurements of somewhat varying magnetic flux in air gaps, a fluxmeter employing 2 bismuth resistance elements (the resistance of which changes with changes in the flux) has been developed (*pages 441–5*).

**Ground Faults on Power Systems.** An extensive survey of faults to ground on representative power systems in different parts of the United States is recorded in this issue. (*pages 421–8*). Data on fault resistance obtained in this survey also are given (*pages 428–33*).

**Automatic Oscillograph.** Analysis of system disturbances alone may not justify the use of an automatic oscillograph, but this instrument may also be used to locate faults on transmission circuits, and for testing relays controlled by carrier current (*pages 438–40*).

**Oxidation in Insulating Oil.** A series of studies of accelerated oxidation in a highly refined paper-cable insulating oil is reported in this issue, with particular reference to the correlation between oxidation and electrical properties (*pages 465–74*).

**Electricity on Aircraft.** The use of electricity on aircraft has increased to such an extent that the wiring diagrams of modern planes are beginning to resemble those for electric power generating stations (*pages 406–10*).

**Voltage Drop.** Connection of load to only 2 phases in open star in a delta-star distribution network may sometimes be necessary; voltage regulation requires that the load be divided correctly, which may not mean equally, on the 2 phases (*pages 434–7*).

**Elihu Thomson Dead.** One of the last of the original group of great electrical pioneers, Elihu Thomson died March 13, 1937. He was a charter member of the AIEE and its fifth president (*pages 482–8*).

**District Meeting at Buffalo.** An interesting program of varied attractions has been planned for the North Eastern District meeting of the AIEE to be held in Buffalo, N. Y., May 5–7, 1937 (*pages 489–91*).

**Summer Convention.** Tentative plans for the Institute's 1937 summer convention to be held in Milwaukee, Wis., June 21–25, include 10 technical sessions and 1 general session (*page 491*).

**Auditory Perspective.** Reproduction of orchestral music in auditory perspective has been demonstrated out-of-doors with the orchestra present (*pages 412–13*).

**Prizes for Papers.** Rules for the award of Institute prizes for technical papers have been revised (*page 492*).

## DISCUSSIONS

Appearing in this issue are discussions of the following papers:


A-C Characteristics of Dielectrics—II—Banos . . 477

Dielectric Strength of Transformer Insulation—Bellaschi & Teague . . . . . 479



Statements and opinions given in articles and papers appearing in ELECTRICAL ENGINEERING are the expressions of contributors, for which the Institute assumes no responsibility. Correspondence is invited on all controversial matters. ¶ Subscriptions—$12 per year to United States, Mexico, Cuba, Porto Rico, Hawaii, Philippine Islands, Central and South America, Haiti, Spain, Spanish Colonies; $13 to Canada; $14 elsewhere. Single copy $1.50. ¶ Address changes must be received by the fifteenth of the month to be effective with the succeeding issue. Copies undelivered because of incorrect address cannot be replaced without charge. ¶ ELECTRICAL ENGINEERING is indexed annually by the Institute, weekly and monthly by *Engineering Index*, and monthly by *Industrial Arts Index*; abstracted monthly by *Science Abstracts* (London). ¶ Copyright 1937 by the American Institute of Electrical Engineers. Number of copies this issue—20,850.

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# The President on Membership

AT least once each year, the president should discuss with the members the subject of membership; for without members there could be no organization, and our fundamental purposes would be impossible of accomplishment. The major accomplishment of the Institute results from the voluntary service so willingly rendered by the national and District officers and committees, the Section's officers and committees, and the authors of the technical papers—a service much greater than, and in addition to, their financial support. However, a great work cannot be accomplished without expense, and funds are necessary to meet these expenses.

The booklet "Membership" by Everett S. Lee, chairman of the finance committee and past-chairman of the Section and membership committees, gives a clear picture as to the advantages of Institute membership, the funds provided by the members, and how they are wisely expended to "advance the theory and practice of electrical engineering and the allied arts and sciences, and to maintain a high professional standing among the members." It is quite unnecessary for me to endeavor to add to this picture.

A society is exactly what its members are, and I shall never be satisfied until every qualified and interested electrical engineer in America is a member of the Institute. The larger the number of qualified engineers who support the organization by their membership, the greater is the prestige of the society and the wider is the opportunity for service to the profession through an intelligent direction of the personnel and use of the funds which they provide.

I have carefully considered the motives which actuate an electrical engineer in applying for membership, and it seems to me that they can be classified in 2 groups.

A. SELFISH INTEREST

1. A desire to be one of a distinguished group.
2. An interest in our technical activities.
3. A desire to advance his professional standing.
4. A desire to broaden his ability through presentation of his ideas and discussion of the ideas of others.
5. The seeking of an opportunity for acquaintance and fellowship with others in their profession.

B. UNSELFISH INTEREST

1. A desire to advance the prestige and standing of his profession.
2. The wish to support an organization offering to the younger engineers, with whom he is associated, opportunities for development and advancement in technical knowledge.
3. The desire to be associated with and participate in the activities of a society devoted to service to the profession.

The membership may possibly be grouped in the following classes:

Class 1—*Sustaining.* Those, who in addition to their financial support, largely participate in organization activity, technical activity, student activity, and Section activity.

Class 2—*Participating.* Those who give financial support and attend the meetings and conventions.

Class 3—*Silent.* Those who render financial support and are interested, but do not participate.

Class 4—*Indifferent.* Those who give only financial support.

Class 5—*Dissatisfied.* Those, who through lack of information, lack of participation, or lack of consideration, feel that the organization is not effectively carrying out its purposes.

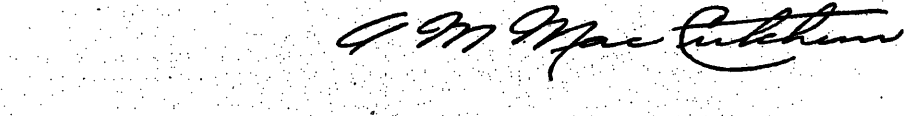
The first group is the most valuable, for in this group are the most interested members who consider membership in the AIEE a real privilege. It is the constant aim of the officers to transfer those in groups 3, 4, and 5 into groups 1 and 2; but the greatest factor in this desirable transfer is the member himself. Those who contribute most and participate most largely are invariably the most interested. From a very active member I have seldom heard any complaint as to the dues he pays, although he may logically suggest how his dues can better be expended.

Membership is one of our most important activities. It is not the purpose of the membership committee to argue or cajole an engineer into applying for membership; rather to inform him as to our purposes and aims, and draw to his attention the privilege and duty that is his if he is qualified.

I feel that the membership committee should give particular attention to the electrical engineers connected with companies using, but not manufacturing, electrical equipment, and in this they should be aided by the technical program committee. The fundamental purposes of the Institute would be greatly furthered by an increased membership in this group.

Would any engineer desire to see the activities of the professional societies discontinued? Does he wish others to carry on the work of which he should be a part, or does he wish to do his share? If, due to circumstances, he cannot be in class 1, how much greater is his obligation to be at least in class 3. If he feels that the society's activities should be modified, should he not join and within the organization lead the way to higher accomplishments?

The most powerful force toward increased prestige and increased opportunity for service through increased membership, is the attitude and co-operation of those who are now members. Each individual member should do his part. As expressed at the recent winter convention, our aim for 1937 should be to advise every qualified electrical engineer as to our aims and purposes, and invite his assistance in reaching our objective.





# Electricity Aloft

By S. PAUL JOHNSTON

**Apart from the more obvious uses of electrical devices for aircraft communication and navigation, electricity is playing an increasingly important rôle on board modern airliners.**

THE PROBLEM of electricity on aircraft has changed materially over the past 15 years. From a necessary evil whose sole function was to ignite explosive charges in engine cylinders, its use has become a question of first-rate importance in the design and operation of the modern airplane.

In 1918, embryo pilots in the Army Air Service used to sit up nights over the "complications" of the electrical circuits on the old Curtiss "Jennies" then in use. The "complications" consisted of a single magneto, 8 spark plugs, a simple "on" and "off" switch on the dash, and about 25 or 30 feet of wire.

By contrast, a modern military bomber, by no means a large airplane as ships go today, takes some 1,200 feet of wire to connect its various circuits. The large transport illustrated at the head of this article, which is known as the Douglas type *DC*-3 plane, and which is now in active production requires between 5,000 and 6,000 feet. Estimates for next year's 40-passenger machines show wiring requirements of over 18,000 feet per ship! The wiring diagrams are beginning to resemble the hookup for a central station or an automatic telephone exchange.

It would take many pages to examine in detail all the steps that lie between the old wartime planes and the modern passenger transport, electrically speaking. However, a few of the high spots might be touched upon to show that, although there are many special problems, basically the matter of the design and installation of the electrical equipment is not so different from the sort of thing with which, as a group, electrical engineers are already familiar.

Probably one of the earliest of the electrical problems on aircraft was the addition of the radio. But a detailed discussion of radio for communication and navigation is beyond the scope of this article. It may be pointed out in passing that beginning with the very simple wartime receiver and rudimentary transmitter, the equipment has been developed to the point where the new transports soon to be in operation will carry no less than 8 or 9 different radio sets of one kind or another, possibly including apparatus for facsimile reception and transmission and for "absolute" altitude determination. Each such installation costs many thousands of dollars, and adds several hundred pounds of weight to the airplane. Also, the power requirements of the radio are constantly increasing. Today the average transmitter has an input of 50 watts. Tomorrow it probably will be considerably greater.

## Lighting

Toward the end of the World War night flying began, and from early postwar mail days has been developed to the point where now flying is done at night as casually as in the daytime. This brought with it a number of lighting problems, apart from the question of lighting airports and airways—an important subject to electrical engineers, but also outside the bounds of the present discussion. Earliest solution to the emergency night landing problem was the carrying of a couple of open magnesium flares attached to the wing tips. This soon proved unsatisfactory, as well as dangerous, and the electric landing light came into being. Clearly, too, some form of navigation lights was necessary. Today, every commercial airplane must be

Essentially full text of an address presented before the transportation group of the AIEE New York Section on January 14, 1937.

equipped with powerful headlights for landing and also the familiar red, green, and white running lights.

Instrument-board lighting became of first-rate importance. The boards themselves have become immeasurably more complicated. Pilots must be able to see each instrument quickly and clearly. All sorts of direct and indirect lighting arrangements have been tried, including a development involving ultraviolet radiation. One airline has been studying the development of the argon light which projects an invisible ultraviolet ray. This ray is directed at radium-painted instrument dials and produces a brilliant glow. In total darkness the "black light" cannot be seen except for the effect it has on the radium dial faces. But even the best so far discovered still leaves something to be desired. A further complication arises from the fact that the intensity of the illumination must be varied at will by the pilot in order that the intensity of light in the cockpit will always match that outside so that his eyes do not have to adjust themselves when shifting from distant objects to the instruments and back again.

The lighting of passenger cabins is a special problem. Not only must general illumination be provided, but also individual reading lights, on separate circuits, must be installed at every seat, or in every berth. Toilets and washrooms, galleys, coat closets, mail pits, and baggage compartments must all have adequate lighting with separate controls. Warning lights in the pilot's cockpit indicate that all passenger and cargo compartment doors are properly closed and secured.

## Miscellaneous Devices

The dictates of passenger comfort have made necessary the provision of devices unthought of 15 years ago, as the accompanying pictures show. The galleys on the new ships will be provided with electric ranges for cooking—hot plates and grills. Coffee percolators and electric refrigerators also will appear. The latest washrooms are providing electric razors for the convenience of male passengers. Possibly air conditioning is in the offing.



United Air Lines

**Interior of "Skylounge" Mainliner**

Other electrical devices have already appeared and will continue to take on new forms as ships become larger. For years there has been complete call-buzzer service from passenger seats and from the cockpit to summon steward service. It was only one short step beyond that to a complete telephone system to all parts of the ship, a convenience that has already put in an appearance. The illuminated sign to warn of an approaching landing and to suggest the use of seat belts is commonplace. Then, since pilots are human and might sometimes forget to extend the retracted landing gear before settling down on a field, automatic warning devices that light red targets on instrument boards, or sound a warning horn behind the pilots' heads, or both, are now installed as regular equipment. All these are electrically operated and further complicate the maze of wiring on the modern airplane.

## Engine Equipment

The electrical problems connected with the engines themselves have become tremendously complicated. Ignition is still from magneto, but a much more powerful and dependable machine than those fitted on the old Curtiss *OX*-5 engines of 15 years ago. But where the wartime engines generally had only one, each modern aircraft engine has a complete dual system—2 magnetos, 2 complete sets of wiring, and 2 spark plugs per cylinder. There has been some discussion recently over the advisability of having 3 complete units per engine. Apart from duplication, the ignition has been further complicated electrically because of the presence of radio on aircraft. It is obvious that an ignition system but a few feet away from a highly sensitive radio receiver will cause trouble unless the former is electrically shielded. Complete metallic enclosure for every inch of ignition circuits is the only possible solution. This is not as simple as it may sound, and has been a source of no end of trouble that has not yet been completely overcome.

Even after many years of development, the spark plug is still a source of trouble and annoyance. The modern trend toward taking all possible power out of engine cylinders at high altitudes has opened new mechanical and electrical problems with plugs that were not thought of several years ago. New plugs are now coming into the market, however, that promise relief from present difficulties.

Starting engines 15 years ago was simply a matter of brawn. It was no problem (except to get clear without being hit on the head by the propeller) to "swing" a 90-horsepower engine. Starting a 1,000-horsepower motor is quite a different thing. Inertia starters energized by an electric motor, or direct-cranking electric starters are to be found on most ships today. The bigger the engines become, the larger the starters, and the greater the power required to operate them. All this is bad enough when

only one engine is involved. Most ships today have 2 engines. Tomorrow they will have 4—day after tomorrow, 6 or 8. Furthermore, the old single engine was in the nose of the ship. Multiple engines are commonly mounted along the wings where control for starters must be remote, connections complicated.

Because of the remote location of engines there are a number of other operations that can best be done electrically. Obvious is the measurement of temperatures at various parts of the engines by remote-reading thermocouples. Electrical gauges have been devised to show the level of fuel in tanks. Electric tachometers measure engine speeds in cockpits so far away from engines that mechanical drives would be too heavy and impractical. Engines may be accurately synchronized electrically, by matching up the phases of small alternators directly driven by each power plant. Lubricating oil in remote tanks may be warmed to operating temperatures before starting by immersion heaters permanently fitted. Certain instruments are kept free from accumulations of ice and snow by small electric heaters.

One of the latest electrical applications is the continuous indication of fuel-air mixtures in engine carburetors by analysis of the composition of exhaust gases in the exhaust manifold. The Cambridge Aero Mixture Indicator (now installed as regular equipment by most of the major airlines) operates on the thermal conductivity principle incorporating a Wheatstone bridge. The electrical characteristics of one leg of the bridge change with changes in the thermal conductivity of the surrounding exhaust gases, which, in turn, becomes a measure of the quantity of carbon dioxide in the gas. The latter, in turn, is a function of the fuel-air mixture supplied to the carburetor.

Every ship today where performance is an element is fitted with controllable-pitch propellers. The most common type is the hydraulic control developed by Hamilton-Standard of Hartford, Conn. Coming onto the market now, however, is a new electrically driven type introduced by Curtiss-Wright. Changes in blade pitch are made by a small electric motor mounted in the propeller hub and connected to the blades through gears with a very high reduction ratio. Power is supplied to the motor through a pair of slip rings and brushes. An automatic electrical governor has just been developed for this propeller so that it turns at constant speed regardless of power developed at the shaft.

## Retracting Units

There are a number of other electrical applications that have been developed through what may be called aerodynamic or operational considerations. For high speed and maximum efficiency an airplane must be "clean," that is, nothing must be permitted to project into the air stream that can possibly be withdrawn inside the smooth contours of the machine when in flight. This accounts for the present practice of retracting the landing wheels, wing tip floats (on flying boats), landing lights, certain radio antennas, and other projections while in the air. Today the field is divided between hydraulic and electrical mechanisms to accomplish these retractions, but, as the size of airplanes increases (and the trend is all in that direction) electric drives will probably predominate. Even if the actual operating elements are hydraulic, the pumps supplying the liquid under pressure will undoubtedly be electrically driven.

Ships that are "clean" require some sort of "air brake" to slow them down to a reasonable speed for safe landings. The brakes usually take the form of a flap under the trailing edge of the wing that may be pulled down at a sharp angle to the air stream. Such flaps, on large planes, are either hydraulically or electrically operated; but, as with the wheel retraction, as size increases, the electrical drive will probably predominate.

"De-icers" are a part of the winter equipment of modern commercial aircraft operating in northern countries. It is out of place here to describe their action, but sufficient to say that certain necessary control valves and air compressors are electrically driven.

The future holds other probabilities. As airplanes become very large—and indications are that the limit where these changes will have to be made is now approaching—it will be impossible for a pilot, unaided, to operate the flying controls. Some form of relay-operated servomechanism will have to be developed to move the control surfaces at the will of the pilot, just as a steering engine functions in a large steamship. Again, both hydraulic and electrical mechanisms are possibilities, but the probabilities favor the electrical. No ship has yet been built incorporating these ideas, but studies have already been made looking toward the future.

Also, as ships get larger, other power auxiliaries will be needed. Hoists will be needed for lifting cargo, for engine changing, for operating gang planks, for weighing anchors, and for a host of other things not yet thought of. For all such, the logical drive will be electrical.

## Power-Supply Problem

Doubtless the question has already occurred as to where the power is to come from to operate these many electrical devices. To date, the standard source of power on aircraft has been the ordinary storage battery—not exactly "ordinary," however, for the requirements of minimum weight, compactness, and high output have forced the development of special batteries. The average battery for transport planes today is $14^1/_2$ inches long, $7^1/_4$ inches wide, and $11^1/_4$ inches deep. It can supply about 88 ampere-hours at 12 volts and weighs about 70 pounds. One company has recently placed on the market a new battery having the same over-all dimensions and said to be capable of supplying 105 ampere-hours. Over-all dimensions are important because all modern transports have been built with a battery compartment of a standard size, and fundamental changes in design would be necessary to accommodate larger sizes.

Generators, driven directly by the airplane's engines, supply a certain amount of recharging to batteries in flight, but the demands are usually so high that the drain on the battery exceeds the replacement, and it is common

practice to remove batteries from every airplane at the end of every run and send them to the charging room. One of the last servicing operations before departure from a terminal station is to install a fresh battery in the plane.

It is good practice, also, in order to relieve the plane's battery of the heavy drains occasioned from starting engines to provide independent starting power on the ground. This may take the form of mechanical power applied from an outside mechanism (electrically driven, to be sure) or from providing starting batteries on small portable carts that may be connected into the plane's electrical circuits by means of cables and a plug in the body of the ship.

Electrical equipment, however, has been added faster than battery design could keep up. Even for present requirements, one battery is hard pressed to do the job. As soon as it becomes necessary to think in terms of 2 or 3 batteries on each plane, it becomes worth while to examine other possibilities to see if something else may not be found to yield the required power for the same weight carried. One answer is already in sight. It seems not unlikely that the large plane of the future will carry its own independently operated electrical power plant—a gasoline-driven motor-generator set delivering 110-volt alternating current.

Equipment already has been designed, and shortly will be commercially available in the form of small 4-cylinder air-cooled gasoline engines, to deliver at least 15 or 20 horsepower at altitudes up to 20,000 feet to drive a-c generators and other auxiliaries. These will be completely self-contained, will be installed in some convenient out-of-the-way place in the airplane (probably in one or more of the engine nacelles), and will be remotely controlled. Besides driving the generators they will also operate a number of auxiliaries now mounted on the main engines, thus improving over-all reliability by removing from the airplane's power plants a number of sources of potential failure. In addition, the exhaust heat from the small engines will furnish ample heat for maintaining proper temperatures in passenger cabins at high altitudes.



United Air Lines

**Pilots' cockpits are becoming increasingly complicated and present difficult lighting problems. This is on a Douglas DC-3 plane**

Another important feature is that such independent units may be kept in operation when the airplane is standing on the ground. Power is required in increasing quantities for use on board during stops, and it is obviously more economical—and safer—to keep the small plant running than to attempt to keep one of the main engines turning over to drive generators.

One of the first questions that came up in the consideration of independent a-c power plants was the matter of frequency. There would have been some advantages as far as operations on the ground were concerned in selecting 60 cycles. It would thus have been possible to plug into the circuits at the average field when standing in stations or in hangars. Weight considerations, however, ruled out 60 cycles. Familiar, of course, are the effects of higher frequencies in reducing the weight of iron in motors and transformers, so that the preference at the present time for equipment operating at 800 cycles is immediately clear. Some study has been given to intermediate frequencies, but the trend seems definitely toward the 800 level.

Once the break has been made away from the present 12-volt battery-operated system with its limitations, it is difficult

to predict how far electrically operated auxiliaries on aircraft may go. Once a really adequate source of electric power is assured in the form of an independent motor-generator set, designers may really begin to explore the possibilities of the field. They doubtless will find many new uses for electricity on airplanes that no one has yet dared to think about.

## Some Special Problems

So far, many points of similarity between the electrical problems on aircraft and the problems with which most electrical engineers are familiar have been considered. In closing, a few of the problems that are distinctly special because of the peculiar conditions under which aircraft operate may be mentioned.

First, and always foremost, is the question of weight. In other fields of transportation, weight control is a secondary consideration. In aircraft design it is all important. All additions to the tare weight of any airplane are immediately reflected in reduced range or in loss of pay load. The gross weight of an airplane for any desired level of safety or performance is fixed. Clearly, then, increases in the weight of the ship's structure or auxiliary equipment must come out of the fuel supply or out of the cargo. Each electrical unit, then, becomes a separate and distinct design problem, and must be treated as such. The separate load requirements must be calculated accurately and provided for without margins beyond those dictated by good sense for safe operation. For example, it will not do to install a $^3/_4$-horsepower motor simply because it happens to be on hand, when the job, with all allowances, requires $^5/_8$ horsepower. The difference in weight may seem negligible in each case, but the cumulative effect may run into many pounds. It is thus impossible to stock a few items to use over a wide range of requirements as is common industrial practice. Each item must be looked upon as distinctly special.

Likewise, mountings cannot be multiplied by 2 or by 3 just to be safe. Here, especially is weight control important. All fittings connecting electrical appliances to the main structure must be calculated down to the last ounce consistent with safe operation.

The selection of operating speeds for electrical equipment is dictated by weight considerations. In general industrial work, speeds are selected that will best fit certain desired operations. In aircraft, the highest practical operating speeds are selected to save weight. For example, an inertia-type engine starter turning at speeds up to 3,600 rpm may require a 20-pound flywheel to do a certain job. If the speed is increased to 12,000 rpm a wheel weighing between 2 and 3 pounds will produce the same energy. The same general considerations are true for the design of many items.

Because of the inherent characteristics of airplane structures, all the equipment mounted on them is constantly exposed to vibration over a wide range of frequencies. The ruggedness of design demanded by this type of treatment is not conducive to weight-saving, but again, the corners must be cut as closely as possible consistent with satisfactory operation. It is obvious, too, that such conveniences as delicately balanced relays and automatic switches cannot be used, although they often would be very helpful.

Another difficulty arises from the wide range of temperature to which aircraft is subject within a relatively short time. Thus an airplane may take off from sea level under moisture-saturated tropical conditions, and 25 or 30 minutes later be flying at some subzero condition at an altitude of 15,000 feet. Not only the temperature drop but the condensation may cause plenty of trouble in the electrical apparatus.

Then the wiring of all the electrical equipment is a problem in itself. Fifteen years ago, going back to wartime planes, a bit of open wiring on cleats did the job. Not so today. Everything must be run in metal conduit. All wiring and conduit must be mechanically strong to withstand the vibration. It must be electrically good to avoid possible fire hazard and to provide adequate radio shielding. In many places positive-action quick-detachable connecting plugs must be provided to permit quick replacement of certain units such as engines, whole radio sets, or individual instruments.

Space has not permitted more than a hasty review of the several problems of the electrical equipment on modern aircraft, but it is hoped that they have been demonstrated to be of vital importance to the development of our latest transportation industry, and that they are worthy of the attention of the best electrical talent in the country.



Westinghouse Photo

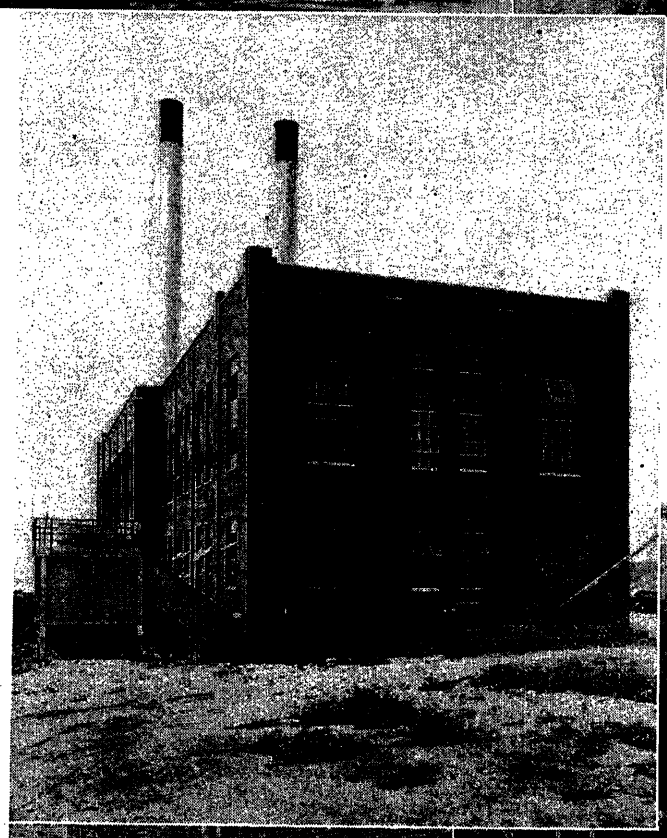
**Newark (N.J.) Airport at night**

# Power From Waste Heat of an Incinerator



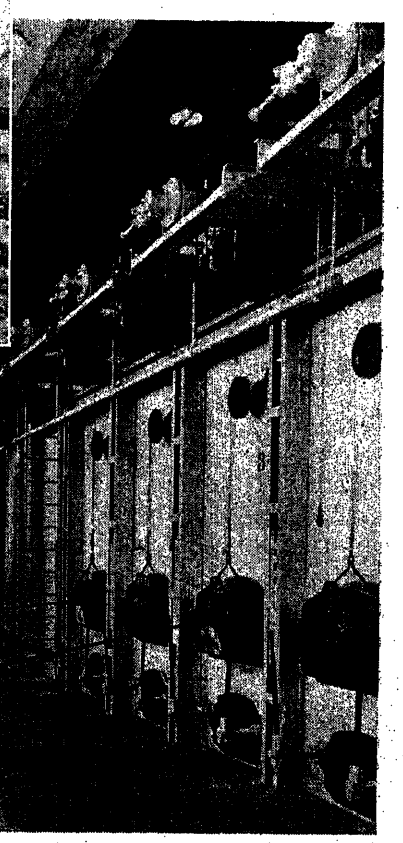


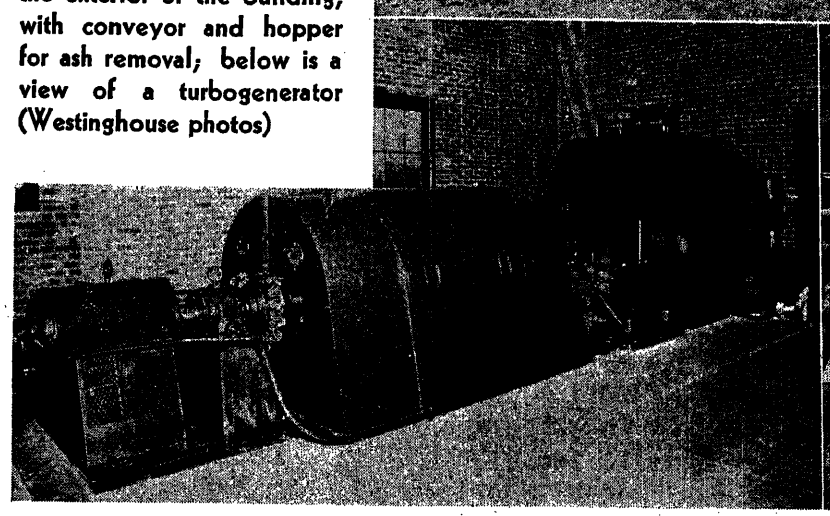
A new incinerator plant at Providence, R. I., uses the hot gases from a 5-cell incinerator with a normal capacity of 160 tons of refuse per 24 hours to generate steam in a 700-horsepower boiler at a pressure of 200 pounds per square inch. The steam is used in a 1,250-kw turbogenerator which furnishes power for operating the city's sewage disposal plant and will furnish power for a sewage pumping station now being motorized. A duplicate boiler and turbogenerator assure continuous service. The view above shows wrapped garbage and refuse being dumped into the 1,000-cubic-yard storage pit. At the right is shown the exterior of the building, with conveyor and hopper for ash removal; below is a view of a turbogenerator (Westinghouse photos)



(Above.) An electric crane with $1^1/_2$-cubic-yard bucket lifts refuse from storage pit to charging bin

(Below.) Stoking the furnace; gates operated pneumatically meter the refuse. Air is supplied by a turbine-driven forced-draft fan and is preheated





# Sound Reinforcing System for Hollywood Bowl

A NEW demonstration of the potentialities of the reproduction of orchestral music in auditory perspective was given at the Hollywood Bowl in California last August, when music reproduced in this manner was heard for the first time out-of-doors with the orchestra present. The occasion was a concert presented by Paramount Pictures with Leopold Stokowski acting as the conductor.

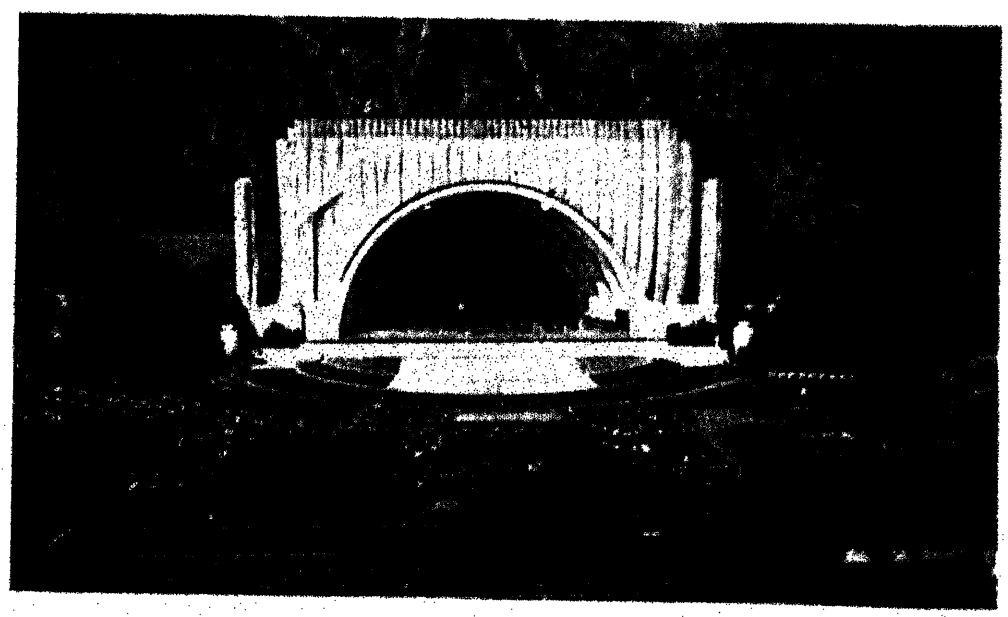
Reproduction in auditory perspective was first demonstrated in 1933. Music played in Philadelphia, Pa., was picked up by microphones, amplified, and transmitted over 3 special telephone circuits to Washington, D. C., where it was again amplified and reproduced by means of 3 huge loud-speakers. The equipment used in this original demonstration was described in a group of papers published in the January 1934 issue of ELECTRICAL ENGINEERING. The characteristics of this equipment were such that the entire frequency and volume range of the most exacting orchestral and vocal music could be reproduced without impairment of quality. The spatial arrangement of the microphones and the corresponding arrangement of loud-speakers was such as to provide substantially perfect auditory perspective. Both the original equipment, and that used in the Hollywood demonstration was developed by the Bell Telephone Laboratories, New York, N. Y.

The Hollywood Bowl is a natural amphitheater situated in a hollow surrounded by low hills. Oval in form with the stage at the lower end, its tiers of seats rise in curved rows up the sloping hillside at an inclination of about 12 degrees. It seats 22,500 persons. The orchestra plays in a large conical sound-reflecting shell on the stage. This shell raises the sound level effectively in the front and central portions of the seating area but not adequately in the side and back sections.

To correct these inequalities in sound distribution and to increase the general level of the music throughout the bowl a multichannel reproducing system was installed. This system also offered the additional advantages that (1) special effects could be obtained by changing the volume and sound quality with manual controls and (2) the loudness of the singers or solo instruments could be increased relative to that of the orchestra.

In providing such equipment for the bowl, conditions not previously encountered in indoor auditoriums had to be met. Since no walls or ceiling were present to reflect sound, arrangements had to be made to direct all the low as well as the high frequencies toward the audience. Moreover, since the loud speakers had to be placed near the orchestra to create the illusion that the sound all came from the orchestra, care had to be taken to prevent the sound from the loud speakers from feeding back into the microphones, which would cause singing. These and similar difficulties were overcome by using new equipment particularly designed for the demonstration.

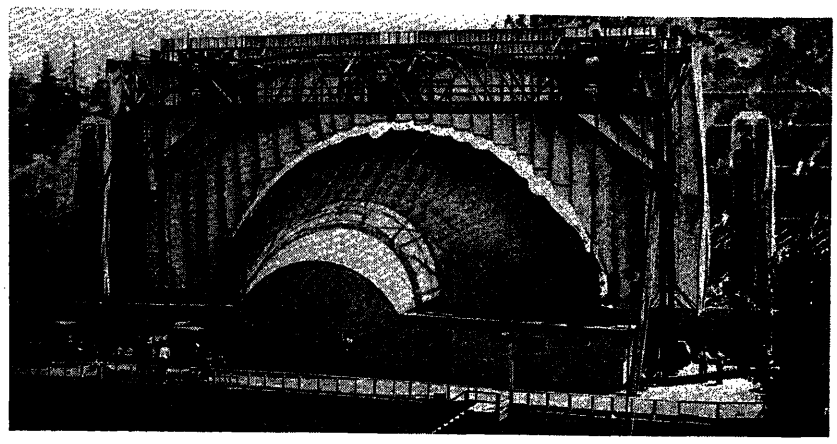
The general plan of the system as installed was to provide 3 microphone positions in front of the orchestra one at the left side, one in the center, and one at the right side. A separate amplifier channel of high power was provided for each of these positions and the output of each channel was connected to separate loud speakers mounted above the orchestra shell in positions corresponding to the microphones. Six microphones were used on the 3 channels. Two were connected in parallel on the left channel to give a satisfactory balance for the cellos, harps and bass viols, because the microphones had to be placed close to these instruments to avoid feedback. Two were located at the center so that one would be available to switch in instead of the regular microphone for vocal soloists. At the right, in addition to the regular microphone, there was an extra one out in front of the shell. This was used for harp and cello solo numbers instead of the regular microphone. The volume controls were located in the center of the seating area about 300 feet back from the shell, and at this position the gain of all 3 channels could be varied by one control. When the soloist's microphone



View of Hollywood Bowl after installation of loud-speakers

Includes essentially full text of an article by A. R. SOFFEL of the Bell Telephone Laboratories, Inc., New York, N. Y., published in the March 1937 issue of *Bell Laboratories Record*.

was switched to the center channel, however, a separate volume control was provided for it so that the level of the voice could be changed independently of that of the orchestra. Quality control made it possible to accentuate the low frequencies and temper the very high frequencies, and an equalizer compensated for the characteristics of the loud-speakers, microphones, and air-transmission path. The amplifiers were adjusted to keep the system below the "singing" point at all times. The acoustic power output of the side channels was 200 watts per channel and that of the center channel half that capacity.



**Rear of orchestra shell showing bridge structure erected to hold the $2^1/_2$ tons of loud-speakers**

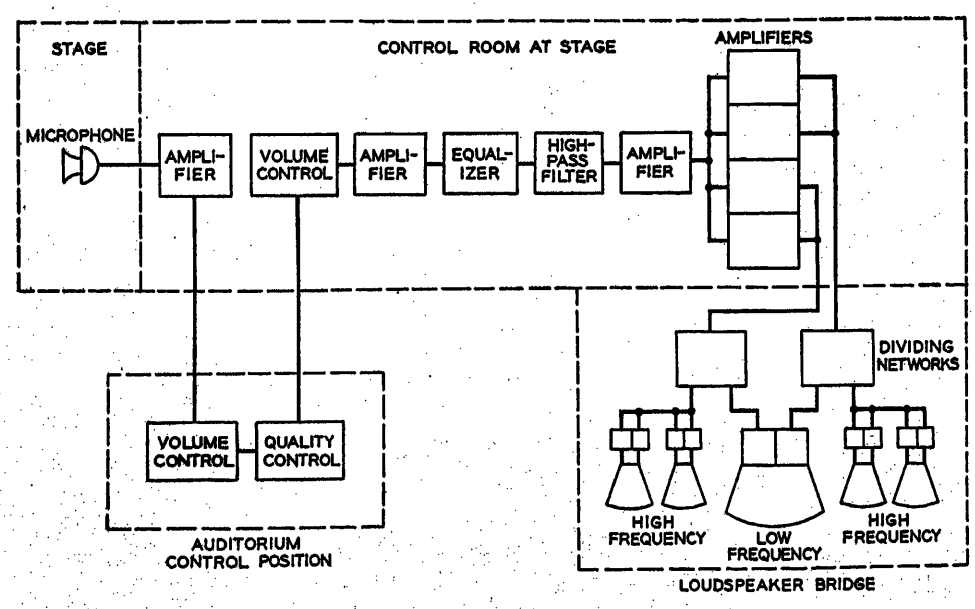
The loud-speaker groups on the sides consisted of 4 multiple-unit high-frequency horns each driven by 2 receivers. These were mounted above 2 low-frequency units, like those used in the Philadelphia-Washington demonstration, which were placed one on top of the other with a common extension. This extension presented an area of 10 by 12 feet at the mouth which made the low-frequency units directive down to 50 cycles. The sound beam of the horns, both low- and high-frequency, was about 85 degrees wide and 50 degrees high. The center loud-speaker group comprised 2 high-frequency horns and only one low-frequency unit, which was built out to 10 by 10 feet in mouth area. The field current supply to each side group consisted of 3 power units, while 2 units supplied the current for the center group.

To mount these $2^1/_2$ tons of loud-speakers above the orchestra shell it was necessary to construct a bridge structure 112 feet long and 12 feet wide, 45 feet above the ground. The center speakers were directly above the center of the shell and the side speakers were each 45 feet from the center of the bridge. The bridge was artistically draped and lighted, which added not a little to the appearance of the shell. All amplifier and circuit equipment was mounted in a room at the stage.

After the system had been installed, acoustical measurements were made with a high-speed level recorder at various places over the seating area and the horizontal angle of the high-frequency horns was adjusted to direct more of the sound to the back seats than to those in front. This resulted in a fairly even distribution of sound; 10 decibels was about the greatest difference in sound level between any 2 positions. The maximum gain settings were found with no audience in the bowl. With an audience, however, 4 or 5 decibels more gain could be used without trouble from "singing."

In actual tests with the orchestra present an increase in sound power of 40 times (16 decibels) was obtained when the gain of the system was set at maximum. Although ordinarily this much amplification was neither used nor desirable, it was available to accentuate crescendos. Even in the first row of seats where the sound of the orchestra itself arrived a fraction of a second before that from the loud-speakers, the illusion that all the sound was coming from the performers was still strong. At the rear of the bowl, $^1/_{10}$ mile from the stage, the music level was at full volume; and for the first time vocal soloists could be heard satisfactorily.

This demonstration was a good illustration of how telephonic research can help to expand the horizon of music. The multichannel reproducing system described here gives to an orchestra a covering power previously unattainable and makes possible fortissimo effects that could not be duplicated by the simultaneous efforts of hundreds of musicians.




**A typical "stereophonic" channel, 3 like this were used in the Hollywood demonstration**

# Engineering and Engineering Education

By A. A. POTTER
President, American Engineering Council

**Because it is considered to be timely, informative, and lucid, this article is republished* here so that the many members of the Institute who are interested in, but not intimately associated with, the field of engineering education may have the benefit of a reflection of current practices and trends in engineering education as seen by a recognized authority in that field.**

ENGINEERING strives to provide better and easier ways of satisfying human needs. The astounding improvements which the past 50 years have brought about in our standards of living have gone on simultaneously with a more general appreciation of engineering education. This type of education, started in this country about 110 years ago, received its first impetus by the passage of the Morril Land-Grant Act of 1862, which provided means for the rapid extension of engineering education. From 1862 to 1934 the number of engineering colleges in this country has increased from 6 to over 150, and the engineering enrollment from about 1,000 to over 50,000. The rapid growth in the number and in the enrollment of the engineering colleges of this country during the past 70 years is an indication that there has been public approval of the type of education offered by these institutions. To an increasing extent industries, utilities, and public works are dependent upon engineering college graduates for the solution of their technological problems as well as those of an administrative and executive character. It is significant, for example, that nearly all of the major executives of electrical manufacturing industries and of electrical utilities are graduates of engineering colleges.

Engineering of a century ago was mainly an art. Thus, engineering colleges during the earlier years of their existence stressed manual dexterity; they were concerned more with training for the acquirement of skill than with education in basic principles; they placed major emphasis upon studies which led to usefulness immediately after graduation and not upon general educational values. Developments in transportation, mechanical power, communication, illumination, chemical technology, mining, metallurgy, manufactured gas, central heating, mechanical refrigeration, and other new industries and public utilities have resulted in a demand for special educational preparation. Engineering colleges attempted to meet these new requirements by setting up numerous specialized engineering curricula. In fact, there developed a tendency to magnify the differences between civil, electrical, mining, mechanical, and other branches of engineering. This has resulted in training specialists who are fairly well versed in one narrow branch of engineering but lack preparation in basic theory and an appreciation of the work of other engineers. Actually the work of the engineer in practice has not followed these branches of specialization set up by engineering colleges and the engineering societies, but has been organized largely along the functional lines of research, design, production, operation, and sales.

Meanwhile the underlying sciences have been growing complex as rapidly as have their applications to industry. Also, organized society has become diversified even more rapidly than either. Thus the gap between what the incoming freshman student knew and what the engineer in practice was expected to know became too broad to bridge in 4 years. During the past 30 years there has been a definite trend away from the purely utilitarian and specialized in engineering education. The engineering colleges have given up the idea of trying to train, in a 4-year undergraduate curriculum, specialists for the various fields of application. The best of these institutions have been tightening their entrance requirements, and have been concentrating upon subjects which are basic and which the student has difficulty in acquiring by his own efforts. While the scope and range of the engineering field has been constantly broadening, increased emphasis is now being placed by engineering teachers upon fundamentals. Completeness of details is being subordinated to thoroughness. The providing of a background of engineering knowledge is not being considered as important as development of ability to reason logically and to arrive at truth by observation and analysis. The time given to informational courses is being greatly reduced and an effort is being made to awaken the creative instinct of the student, and to stimulate independence of thought and self-reliance. Specialization is being definitely discouraged for undergraduates, but is given a place in connection with research in the graduate programs of study which lead to the higher degrees.

Contrary to the general impression, undergraduate engineering instruction is not purely technical, but has been planned so that the undergraduate student devotes about one-half of his time to science, mathematics, and the humanities. Nearly all engineering undergraduate curricula include required courses in English, history, and economics. In a number of engineering colleges the undergraduate program of study permits electives in psychology, sociology, accounting, personnel administration, businesss law, banking, corporation finance, and other courses which are helpful to the student in acquiring an under-

* Full text of an article "Engineering and Engineering Education in the United States" republished with special permission from the January 1937 issue of "The Bent" of Tau Beta Pi.

Doctor A. A. POTTER is dean of engineering, Purdue University, Lafayette, Ind.; also, president of the American Engineering Council, past-president of The American Society of Mechanical Engineers, and past-president of the Society for the Promotion of Engineering Education.

standing of social and economic problems. To an increasing extent, engineering students are receiving instruction in industrial engineering and management. It is the general opinion, however, that extended business training should not take the place, in an engineering curriculum, of basic instruction in science and technology.

The growth of junior colleges and of lower and upper divisions in universities has brought to the front the relative advantages of the unified program in which the scientific, technological, and humanitarian studies form an orderly whole in an engineering curriculum, as contrasted with the divided process having two years of a general college or pre-engineering curriculum and a subsequent purely technical curriculum corresponding to the practice of law, medicine, and dentistry. The conclusions of the exhaustive survey made under the direction of the Society for the Promotion of Engineering Education during 1922–1929 favor the 4-year unified engineering college undergraduate curriculum with unity of supervision rather than the divided program under separate administration.

While the soundness of the unified 4-year engineering undergraduate curriculum cannot be questioned, concentration on collegiate forms of education seems to have resulted in the neglect of other forms of technical education. There are no doubt too many institutions in this country offering engineering instruction of collegiate grade. Adequate training facilities for trades and crafts are also available. However, there is a need for specialized technical training which can best be given in a post-secondary type of school, recently designated as a "technical institute." This type of institution is similar to the technical middle schools of Continental Europe and trains for callings and functions between the skilled crafts and the scientific professions. Industry apparently needs for every engineering college graduate 3 people trained in this type of post-secondary school, where the instruction is more intensive and more specialized, and the program of study is shorter than that of colleges.

Until very recently, the interest of engineering colleges has centered in undergraduate instruction, as industry and the engineering profession have given inadequate recognition to resident graduate study. However, during the past decade graduate study or some other form of advanced study has become a necessity for the higher technological posts of industry. In several cases industries have perfected special arrangements with the educational institutions of their localities so that the engineering college graduate may complete requirements for higher degrees by pursuing advanced study while he is gaining industrial experience. Growth in graduate study has been particularly noticeable since 1930, as many of the unemployed have been striving to improve their education. Graduate study is now receiving definite encouragement at a number of engineering colleges as the preparation of their staffs has improved and as better research facilities have become available for the solution of new and advanced problems.

Doctor William E. Wickenden, in his final report as director of the survey of engineering education by the SPEE, made the following pertinent statement about post-scholastic study:

> The most serious deficiency in engineering education is not so much in matter taught or omitted in college, as in allowing the orderly process of education to stop, where it often does, at graduation. To require all engineering students to remain 5 or 6 years in college would be an arbitrary solution, but an artificially simple one.—It seems that the most urgent educational task now before the engineering profession is to create and direct an effective program of continuation education for the first 5 years after graduation from college.

The engineering profession has, in the past, taken little active interest in shaping or in directing engineering education. What aid has been given to engineering education by engineers has been largely individual and unofficial and has not represented the concentrated thought or the united action of the engineering profession. It is, therefore, gratifying that the recently formed Engineers' Council for Professional Development, representing as it does the leading engineering societies, has its program focused upon the educational preparation of the engineer. This council has set as one of its main objectives definite encouragement for the further personal and professional development of the college graduate as a qualifying standard for certification into the engineering profession.

In planning for the future of engineering education it may be desirable to give consideration to the following matters:

The undergraduate engineering college curriculum, concentrated on the underlying fundamentals, should become an accepted form of modern collegiate education, as it acquaints the student with the processes, devices, and methods which make our civilization distinctive. Cultured people are those who understand their environment—the world in which they live—and no type of education so directly assists the individual to understand his present surroundings as engineering education. Some of the graduates of engineering college should be encouraged to continue their preparation for engineering as a career, but a much larger number should be assisted in qualifying to enter the other professions, business and public service.

Considerable pressure is being brought to bear upon engineering colleges to increase emphasis upon business procedure and industrial management. Doctor R. E. Doherty, president of the Carnegie Institute of Technology, is of the opinion that in our enthusiasm to train leaders for industry we must not forget to provide an educational preparation and a promising outlook for technical engineering leadership. President Doherty's warning is timely. Technical engineering leadership and scientific positions must be made worthy and promising on their own score and not merely as a stepping stone for executive and administrative positions. Furthermore, the requirements for a successful executive are a broad range of knowledge and a disciplined mind to attack new problems. All that the engineering college can hope to do is to lay a foundation upon which the graduate may build in preparation for technical or executive responsibilities. Patrick Henry has well stated: "I know of no way to judge the future but by the past." It is only by giving our

students a broad foundation that we can properly prepare them to cope with the changing conditions of our times.

Greater attention must be given to economic and historic studies so that the engineer will have a better appreciation of the co-ordination of technology and economics as well as of the science of government which controls his affairs. During the past year several engineering colleges have announced special curricula as preparation for public service. The functions of government are becoming more and more technological in character, and to an increasing extent the engineer's activities are concerned with public works. It is therefore becoming more desirable that all engineers have a better appreciation of the relation of engineering to the public and to its agent—the government. All intelligent people must take an active interest in public questions, as only under a stable government can one make the best use of his talents.

It may be well to give greater attention to studies which will prove helpful in acquainting the student with industrial working conditions, tendencies in industrial organization and legislation, and other matters which may enable him to appreciate the human problems he will encounter. The engineer must know the human element if he is to utilize most effectively the work he designs or builds.

The engineer of tomorrow must have a thorough scientific preparation if he is to make full use of the foundations laid by science. Science and technology are interdependent, and the future progress of one depends upon the other. There is a trend toward more thorough instruction in science and mathematics, and for the general broadening of basic theory in engineering instruction. Quality rather than quantity is the guide in revising programs of study, as the superficial familiarity with many subjects is less valuable than the complete mastery of a few.

College graduates are found to have difficulty in recognizing and in appreciating true values. A better coordination of the educational and social activities of the undergraduate may prove helpful. More of the engineering undergraduate studies should be administered by socially minded professors. A more accurate appraisal of college student activities may also prove desirable. In a number of industries, art and beauty have recently changed deficits into profits. American industry has become aware of the remarkable potency of beauty. Art as a living thing will have to be appreciated by the engineer of the future.

Engineering colleges will do well to devote more attention to the development of desirable personality traits in their students, such as a good address, an agreeable manner, a cheerful attitude, a co-operative ability, a pleasing disposition, and similar traits which are helpful to the professional man in taking his place in society.

A most important objective of all education is the development, on the part of youth, of worthy ideals of character and conduct. The stability of society and the basis for authority in a democratic government depend upon the character and ethical standards of people. It is the duty of all types of schools, colleges, and universities to inculcate high ethical standards, and particularly during the adolescent period of youth when one is highly susceptible to the call of high purpose and refined ideals.

There is always a demand for people of initiative who have the power to think independently and constructively. We are living in an age which places a premium on initiative, the power to take the lead, to plan, to originate. To develop such traits, students must be encouraged to take new paths, to try new experiments, to look into the unknown. To develop the creative leaders of the future, our college students must have opportunities to come in contact with teachers who are in search of nature's truths. Engineering progress is dependent upon research, and new knowledge is absolutely essential for the advancement of engineering education. Furthermore, effective graduate instruction must be accompanied by active research interest on the part of the staff. Engineering is a profession of progress, and the future advances in applied as well as in pure science will depend upon coordinated and organized research. During recent years research problems of great magnitude have been successfully solved by engineering colleges as a result of cooperative relations with industry. Engineering societies, trade associations, industries (both large and small), and public utilities have found that money invested in research at carefully selected engineering colleges paid big dividends, not only in practical results secured but also in increasing the supply of engineers who have the preparation to extend the frontiers of useful knowledge. The best engineering colleges are not satisfied with teaching and the conservation of knowledge as their only function. They realize that efficient technological instruction must find expression in the application of research. Such institutions are always ready to encourage their staffs and their students to extend the boundaries of engineering and other scientific knowledge. American industry has an opportunity to aid in improving the preparation of engineers and scientists by stimulating research in pure and applied science at technological institutions. Such support will result in advancing basic knowledge in science and engineering, will increase the supply of well trained personnel for the research laboratories of industry, and will insure a greater number of people who have intellectual curiosity and ability to extend the frontiers of knowledge.

Engineering touches the life of every person in an industrial nation, so that the general well-being is vitally dependent upon the education of the engineer. From its origin and nature, the engineering college has in the past fallen short of the prime glory of the so-called classical or liberal arts college, which has been fairly successful in inculcating in the minds of its students a strong sense of personal responsibility to their order, their country, and their civilization. This may be partly responsible for the fact that engineers have been in the past too much concerned with the problems of their specialty, and have given little attention to the wider significance of their work or to their social responsibilities. Engineers are expected to think more, to write more, and to talk more on social, political, and economic problems in order to be able to assist in their solution. The engineer must assume the

responsibility of social leadership along with representatives of other major professions, in order to aid in stabilizing our national economy and to insure a truly democratic government.

American engineering colleges have a great responsibility in meeting the demands of the times so that their graduates will be capable as engineers and will also have the well-rounded ethical standards and broad interests valid in any professional group. The engineer of today must have a thorough preparation in science and technology, as well as an appreciation of aesthetic values, economic forces, and social trends. At the same time, he must be interested in government and must be conscious of the fact that the stability of our type of government depends upon citizens—citizens with worthy ideals of character and conduct; citizens who are obedient to law; citizens interested in the common good; citizens tolerant of the lawful rights of others; and citizens who realize the interdependence of human rights and property rights.

# Part-Time Courses for Graduate Engineers in Chicago

By H. T. HEALD
Member, The Society for the Promotion of Engineering Education

ENGINEERING educators are familiar with the development of graduate work in engineering during the past 15 years, and know that graduate registrations have greatly increased during this period. The increasing importance of graduate training suggests that in large metropolitan communities opportunities should be provided to enable young engineers to carry on a program of advanced study through part-time classes while regularly employed.

Beginning in 1935 the Western Society of Engineers in Chicago has directed the attention of its education committee to this phase of education. . . the assignment of making a study of the facilities for part-time graduate education for engineers and for developing a plan whereby the Society might encourage this type of work.

The study carried out by this committee disclosed that approximately 8,000 engineers between the ages of 22 and 34 were employed in the Chicago area, and that, while adequate provision for undergraduate training was available in evening classes, very few advanced courses were being offered by Chicago colleges, aside from a limited program begun at Armour Institute of Technology in the spring of 1936. Various engineering societies had from time to time sponsored lecture courses, some of which proved quite successful, but the committee felt that any comprehensive program should be carried out by the regularly established educational institutions. Consequently, the co-operation of the University of Illinois and the Chicago colleges and universities was invited, and a plan developed for a program of courses to begin in the fall of 1936, to be sponsored jointly by the Western Society of Engineers and the educational institutions.

As a result, graduate courses for engineers are now being offered on a part-time basis by the University of Illinois, Armour Institute of Technology, Lewis Institute, and the University of Chicago. Courses for the first semester included one class in continuous frames offered by Professor Hardy Cross, through the extension division of the University of Illinois, at the rooms of the Western Society of Engineers; 9 courses, including Diesel engineering, heat and ventilation, alternating current networks, foundations and soil mechanics, water treatment, fuels and combustion, metallurgical materials of construction, advanced calculus and physics of electron tubes, by Armour Institute of Technology; courses in non-ferrous metallurgy, metallurgical calculations, and differential equations by Lewis Institute; and electrodynamics and X-ray crystal analysis, as well as other advanced work in science, at the University College of the University of Chicago. Approximately 300 students enrolled in the combined group of courses in the fall of 1936, showing that a real demand exists for advanced work of this type.

While it is undoubtedly true that only a portion of the students enrolled are interested in working toward an advanced degree, credits obtained are recognized by the respective institutions, and the program at Armour Institute of Technology permits a properly qualified graduate to earn the master's degree upon the completion of a minimum of 8 courses. Arrangements for transfer of credits between institutions are subject to the regulations of the respective schools.

The Western Society of Engineers, functioning as a correlating agency, has made its library available to all students enrolled in these classes, irrespective of membership, and has issued announcements, covering the entire program, which have been mailed to 9,000 engineering graduates.

During the current year the education committee of

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the Western Society of Engineers, including both educators and engineers, is studying the effectiveness of the program already being offered, and attempting to determine the needs for additional work of this type. To assist in this study the committee plans to collect opinions from employers of engineers, as well as to take a census among a large number of engineering graduates, to determine the general fields of engineering in which there may be a demand for advanced study. This information will enable the colleges to relate their programs closely to the needs of engineers in the Chicago area, and should be of material assistance in planning courses for 1937–38.

Although the general program of graduate work for engineers employed in Chicago is still in a development stage, the response to the first year's work has been particularly encouraging. With proper development in succeeding years this type of work seems destined to become an important service to engineers who desire to secure additional professional training during the early years of their employment.

# After Graduation—What Then?

By H. P. HAMMOND
President, The Society for the Promotion of Engineering Education

A PRINCIPLE on which there seems to be universal agreement is that it is notthe aim of the undergraduate curriculum to produce "finished" engineers—men capable of engaging in responsible professional practice. It follows, therefore, since the profession is concerned in the eventual development of men capable of such practice, that consideration—very careful consideration—should be given to that phase of engineering education, and of professional development, which follows the stage marked by the award of the bachelor's degree. This seems so obvious as scarcely to need statement, yet it is a matter to which very little constructive effort has been devoted and to which, until now, none has been directed by the profession as a whole.

Some 4-year graduates will and should remain in college for more extended training. At present about one-sixth of those holding the bachelor's degree continue their work for a fifth year and secure the master's degree, and a smaller, but increasing, proportion go on to the doctorate. This is as it should be; the engineering college, while not the only place, is doubtless the best place, generally speaking, in which programs of advanced study and research can be conducted. For the bulk of our graduates, however, the formal part of their engineering education stops at the end of the 4 collegiate years, whether or not this is best is not the question now under consideration; even, however, if the program of collegiate engineering education were extended to 5 years, or to 6, the fundamental question of the post-scholastic engineering education and the professional development of the young engineer would remain, demanding consideration of those interested in the welfare of the profession.

What are the elements of this problem and how may it be approached? It may be worth while to summarize some of them even though they are already well and widely known.

There is, of course, the problem of fitting the man to the job, or the job to the man (happily there are now jobs to which men can be fitted). This phase of the problem is of concern to every administrative and personnel officer. Real progress has been made in connection with it in recent years. A committee of the Society [for the Promotion of Engineering Education] under the chairmanship of Professor Bangs, of Cornell, has as its particular duty continued study of this matter.

There is also the problem of giving the graduate—or the about-to-be graduated student—some comprehensive knowledge of the profession he is about to enter—of its professional organizations, of the opportunities it offers and the responsibilities it involves, and of its ideals and ethical standards. Some progress has been made in connection with this phase of the general problem, but apparently less than its importance deserves. Both the schools and the profession have a direct responsibility in relation to it.

Every graduate who plans to follow engineering practice as a career should affiliate himself with the appropriate national societies and local groups of engineers and thereby identify himself as a member of the profession he is joining. While this may be considered as chiefly the concern of the engineering societies, it is one toward which the engineering schools should feel a sense of responsibility.

Then there is the matter of the continuation of the education of the young engineer, and this is the chief problem to which these remarks are addressed. Heretofore our profession has done, or perhaps it might be fairer to say has been able to do, very little in this connection. In some urban centers an increasing number of graduates are

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availing themselves of opportunities for post-graduate instruction offered in evening hours by colleges of the vicinity. In some industries, but almost exclusively in the largest, training programs are provided which range from regular study of a post-graduate nature to planned sequences of experience in various departments of the company. But on the whole there is little or nothing in our profession that serves the purpose of the period of systematic apprenticeship which the medical graduate experiences during his interneship. Up to the present time no means have been available of assisting or of guiding the graduate who feels the need systematically to continue his education through self-directed study. No greater need or opportunity exists for the engineering profession today than in this respect.

And finally there is the matter of informing the graduate of the requirements and procedures of the registration laws in the several states. The college and the profession jointly have an important responsibility in this connection.

Until the present time the various aspects of the induction of the graduate into his career and of his professional development and advancement have been dealt with only sporadically; the profession as a whole has not united in considering the matter or in providing means for dealing with it. The reason for this has been chiefly that no agency has existed through which a common program of effort could be undertaken. Now, happily, that lack no longer exists. The Engineers' Council for Professional Development, upon which the interest of the colleges has centered recently in connection with the accrediting program, has the broader purpose indicated by its title—*professional development.* Accrediting of schools, though a vital matter, is but one phase of the broader program which the council has undertaken. Matters relating to the personal and professional growth and development of the graduate as an engineer and a citizen are being dealt with by one of the council's committees, that on professional training. It was the inauguration of the program planned by this committee on which Past-President Rees [of SPEE] was actively engaged at the time of his death. O. W. Eshbach [chairman, AIEE committee on education] is now serving as the chairman of this committee, which is continuing the work along the same lines as those originally laid out. The work of this committee is of vital importance to the entire profession. It deserves to be supported and assisted . . . as need and opportunity arise.

# English in Engineering Education

By C. W. DUNHAM
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A MAN is able to convey his thoughts to another person only as perfectly as his own means of expression and the other's understanding of it will permit. Most people in our country are limited to the use of just one tool for this purpose—the English language. How great a part it plays in our lives! How great, then, should be its development! Yet engineers are notoriously weak in their mastery of it.

In the past we have given much study to the determination of the best curricula for the undergraduate work of our engineering colleges in order to give our young engineers the best possible preparation for their life work. My own contacts with graduates for the past 16 years indicate that the results have been good as far as technical education is concerned. However, young engineers are generally deficient in their ability to express themselves with effectiveness and facility, whether orally or in writing. Those who are really capable in this respect are the exceptions rather than the rule. Yet, unfortunately, many of the impressions which create the "boss's" idea of a man's ability are secured through the latter's use of English. Therefore, it is tremendously important for a young man to be competent in handling this great means of conveying his thoughts and knowledge if he is successfully to hold a position of leadership among other men who are well trained in this respect. The question naturally arises, "What can be done about it when the time and capacity of the students are already strained to the limit?"

Obviously, it is unwise to keep piling course upon course in undergraduate curricula. This should not be necessary in order to attain the desired result. Day after day the students are steeped in the study of mathematics, sciences, and similar subjects, but all these studies are carried on through the medium of the English language. Why then, cannot the development of the use of this medium itself become a well-planned though almost unconscious part of all studies?

Naturally, in this connection, the desired goal is the development of the ability to use the ordinary written and spoken words of everyday life with facility, to write concisely and well, to think straight, and to speak clearly and effectively while on one's feet before people as well

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as in the quiet of one's study. Not only the faculty members but the students themselves should realize the importance of these attainments.

To accomplish this goal the study of English should commence as soon as the student enters college and it should continue until he graduates. The faculty of the English department should teach the theory of writing and effective speaking, but the practice of its teachings should be carried out day after day in the other departments by having the closest kind of co-operation among them all. The English professors in a few hours each week should not be expected to counteract the effect of careless or bad habits formed elsewhere. These other departments should insist that all written examinations, reports, theses, and similar work of the students must be satisfactory in composition as well as in subject matter. Oral interrogations or recitations should be held in order to give valuable practice in quick thinking and extemporaneous speaking. These last will also give the students the incidental benefit of listening to the questions and answers of others.

Of course, such a program will require painstaking work on the part of the teachers. However, the possibilities for real service are too great to be neglected.

The classroom is not the only place where practice in the use of the English language should take place. Competition in public speaking, participation in the work of the college paper, preparation of essays and their presentation at meetings of the student branches of the engineering societies, discussion of such essays, prepared and extemporaneous debates, and similar activities should be a regular part of the college life.

I shall try to illustrate the need of this training and its benefits by giving a few examples from the experiences of engineers whom I know. All are true cases even though the names of the individuals are not disclosed.

A chief engineer wanted someone to study a certain bridge project and to make a report upon his findings. As it happened, the engineer who usually did such work for him was on his vacation, therefore, the problem was assigned to a younger man. The latter made the necessary investigation and estimate, then hastily compiled his report. He delivered it in person to the chief engineer. The latter read it in the presence of the assistant chief engineer and the author. He figuratively tore it to pieces because of its poor form and composition although he did not criticize the correctness of the figures. Obviously, that young engineer suffered much more than injury to his feelings.

In another instance a young designer was asked to help with some specification writing during an emergency. He soon demonstrated such clearness and exactness in writing that he was transferred to this part of the organization, receiving at the same time a substantial raise in salary and an advance in title. Some of his fellows failed to realize that the reason for his promotion was an accomplishment whose value they had overlooked.

The preparation of specifications is a good example of the need for exactness in writing. Repeatedly, trouble develops from their indefiniteness or misinterpretation of them. One case centered upon one short descriptive phrase of four words which the contractor claimed meant something entirely different from the intention of the author. The dispute was finally settled with a loss of about $75,000 to the owner.

In another instance a company wished to carry on a lecture program to advertise its engineering services. One of the concern's lawyers was assigned to the job. After the first attempt he was recalled because he did not have the technical background to answer the questions put to him. An engineer was then sent out to carry on the work. His knowledge was sufficient but his presentation of the subject was so uninteresting that he too was recalled immediately. The program finally had to be finished by a few of the men higher up in the company who took turns at the job. The effect of this affair upon the first 2 men needs no comment.

A different kind of case is that of a company which sent one of its engineers to confer with a customer about difficulties that had arisen between them. The engineer understood the matter well enough, but he could not discuss the details calmly and clearly. He soon became antagonistic in his attitude and failed miserably in his mission. The result was an oral order by the chief engineer stating that this man must never again be permitted to represent the company in such matters. His future progress was wrecked. One might say that this case represents poor character rather than weakness in the use of the English language. However, knowing the individual as I do, I believe that his failure was due largely to inexperience in debate and in controlling his speech under difficult circumstances.

Another case concerned 2 young engineers who were about equal in technical ability. The first seemed to be afraid to express himself and to present his views. When he attempted to do so he was inclined to be hesitant and unconvincing in his speech. The second was unafraid, forceful, yet tactful and clear in his discussions. The result was that the second young man steadily forged ahead of the other. Such things have happened too frequently to be commented upon further.

It seems to me that there are 2 sides to this matter of correct and effective use of English which one should master. The first is the attainment of a good vocabulary and knowledge of what is right and proper composition. The second is the development of courage and ability to get on one's feet, to say something worth while and to say it well. These can be mastered by the students only if they are given long-continued practice in writing and speaking in college until they become so accustomed to expressing themselves properly that eventually they are able to concentrate their minds upon their ideas rather than upon the search for words to express those ideas.

In conclusion, let me urge that proficiency in the use of the English language be given one of the chief places among the goals to be striven for by our engineering students. Let it be attained by the whole-hearted co-operation of the entire faculty of the colleges. Thus will our young engineers go forth to Life possessing one of the great qualifications for success.

# Power System Faults to Ground

## Part I: Characteristics

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## Synopsis

THE RESULTS of an extensive oscillographic study of power-system faults to ground are presented herewith. While this study was made primarily to obtain data useful in inductive co-ordination problems, the results are believed to be of general interest as well. They provide data on such items as frequency of occurrence of ground-current disturbances, their monthly distribution, duration, cause, method of clearance, and wave-trace characteristics. Data on fault resistance are given in part II, a companion paper.


## Introduction

In connection with a study of low-frequency residuals and methods for their control, conducted by the Joint Subcommittee on Development and Research of the Edison Electric Institute and the Bell Telephone System with the co-operation of several power companies, numerous oscillographic records of power-system currents and voltages at times of disturbances producing ground current, together with information as to the cause and nature of the disturbances, were obtained. Records were secured from 10 systems which were under observation for periods ranging from approximately 1 to approximately 5 years. These records have been analyzed from various standpoints to provide information as to characteristics of power-system faults and disturbances which involved ground current. Since some disturbances were self-clearing and some were due to reclosures on sustained faults, switching, etc., a somewhat special meaning has been attached herein to the terms "disturbance" and "fault" to facilitate the analysis of the data, namely:

*Disturbance.* Each individual oscillographic record of abnormal 60-cycle current, irrespective of its cause or duration, represents a disturbance.

*Faults.* The number of faults was arrived at by eliminating from the total recorded disturbances those having a duration of one cycle or less, and those which the power-system trouble records or the oscillogram characteristics indicated to be recurrences of, or reclosures on the same case of trouble. The word "fault" is therefore used to distinguish the disturbances which were probably associated with initial dielectric failure from the total number of disturbances recorded. The requirement of more than one cycle duration for faults was arbitrarily chosen to eliminate from this classification brief surges, many of which were attributed to switching, paralleling of 2 systems, etc.

The data presented herein apply, with minor exceptions, solely to disturbances producing earth-return current and are not concerned with disturbances resulting from phase-to-phase or 3-phase faults except to the extent that these may develop into ground faults as well.

The information given in this paper may be roughly divided into 3 main classes, relating, respectively, to (1) the monthly and yearly frequency distribution of disturbances and faults, (2) classification of disturbances to determine their cause and nature, this classification being based on power-system trouble reports, and (3) certain characteristics of troubles, such as duration, manner of fault clearance, and number and sequence of phase wires involved, this information being deduced principally from the appearance of the oscillographic records.

## Source and Nature of Data

The power companies who participated in the collection of the data and whose co-operation made this study possible were the Appalachian Electric Power Company, Central Illinois Light Company, Central Illinois Public Service Company, Superpower Company of Illinois, Dayton Power and Light Company, Pennsylvania Power and Light Company, Philadelphia Electric Company, Potomac Edison Company, Public Service Electric and Gas Company, Tennessee Electric Power Company, Union Gas and Electric Company, and Wisconsin Public Service Corporation.

The power systems utilized in the study are all located in territory where, according to data of the United States Weather Bureau,[1] the average expectancy of thunderstorm days per year is from 30 to 60. They cover an operating voltage range from 26 to 220 kv; some of them operate with directly grounded neutral and others with neutral grounded through impedance. Certain relevant characteristics, such as system voltage, circuit mileage, method of grounding neutral, and extent and kind of ground wires utilized are listed in table I.

For recording disturbances, automatic oscillographs were used. They were tripped, in most cases, by residual or neutral current and were provided with means for photographing the time of occurrence of each disturbance. Provision was made for recording neutral, residual, or line currents in all cases and for recording positive- and negative-sequence and line-to-ground voltages in some cases. All oscillographic records were correlated as far as was practicable with power-system trouble records.

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1. For all numbered references, see list at end of paper.

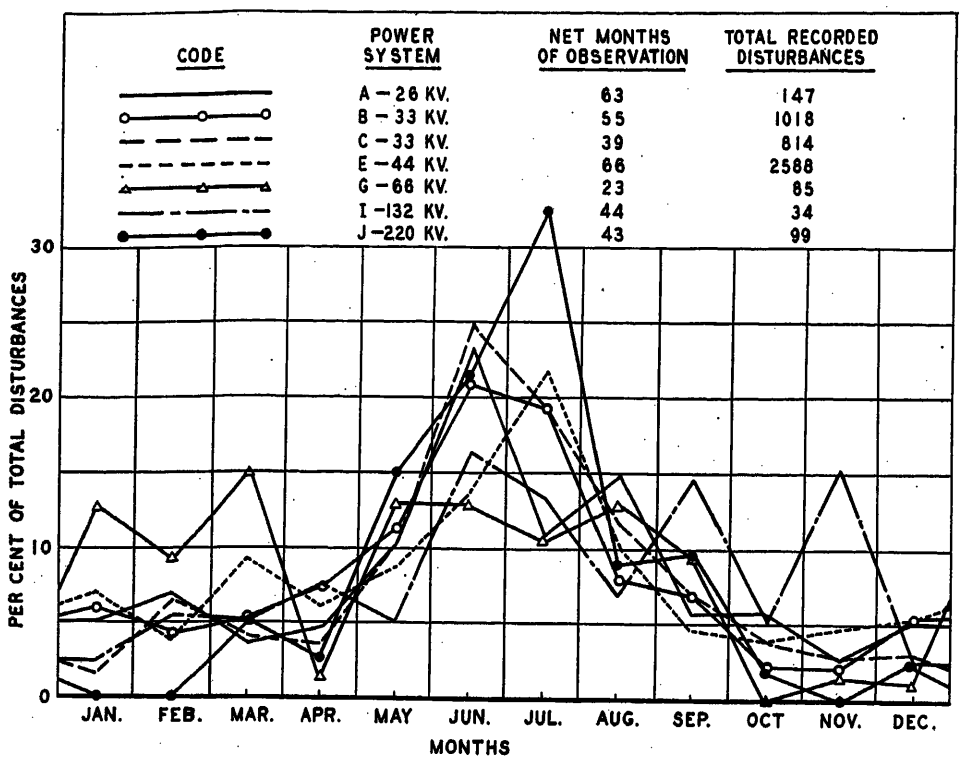



**Fig. 1. Monthly distribution of disturbances recorded during entire periods of observation; systems A to J, inclusive, 26 to 220 kv**

## Frequency Distribution of Disturbances and Faults

### Disturbances and Faults per Year per 100 Circuit Miles of Transmission Line

The yearly and, in most cases, the average yearly frequency of occurrence over several years, of disturbances and faults involving ground current are shown in table II for the various systems. This classification was made only for the 7 systems from which suitable data were obtained and only for the calendar years for which the data were practically complete.

The data indicate, in most instances, considerable variation from year to year. The most important cause of this variation is probably the varying severity of lightning storms in different years. This is well illustrated by the fact that weather reports for the city around which system *B* centers show that there were 51 days on which thunderstorms occurred in 1931, compared with 30 in 1930.

### Monthly Distribution

The monthly distribution of the disturbances recorded for the entire periods of observations on each of 7 systems are shown in figure 1. Systems *G* and *I* do not show as great a seasonal variation as the other systems, probably because these systems have more effective protection against lightning. System *J*, which operates at the highest voltage, shows a decided seasonal variation, due to the fact that a part of the line mileage is in hilly territory subject to severe electrical storms, and because, at the time of these observations, one section of line did not have effective ground-wire protection.

In figure 2 are shown 3 average curves of monthly distribution of disturbances. The 2 broken-line curves were prepared by averaging the percentages shown in figure 1 for the systems operating at voltages from 26 to 44 kv and 66 to 220 kv, respectively. The solid-line curve is a probability curve, based on the percentage data from all systems.

**Table I—Relevant Power-System Characteristics**

| Power System | Line Voltage Kv | Approximate Circuit Mileage: Wood Pole | Steel Tower | Cable | Total | Neutral Grounds: Number | Type | Ground Wires | Remarks |
|---|---|---|---|---|---|---|---|---|---|
| *A* | 26 | 140 | | 30 | 170 | 1 | 75-ohm resistor | None | Sequential observations on 2 similar networks |
| *B* | 33 | 275 | 125 | | 400 | 1 | 30-ohm resistor | Some low conductivity | *Equivalent zero-sequence impedance—540 ohms |
| *C* | 33 | 250 | | | 250 | 1<br>4 | Grounding bank*<br>Solid | Some low conductivity | |
| *D* | 37 | 64 | See remarks | | | | Solid | Some low conductivity | Only one 64-mile wood-pole line under observation |
| *E* | 44 | 193 | 342 | | 535 | 1 | 150-ohm resistor | See remarks | 72-mile high conductivity; remainder low conductivity or none |
| *F* | 44 | 215 | | | 215 | 2–4 | Solid | | Two grounds at first, others added later |
| *G* | 66 | 200 | 112 | 1 | 313 | 1 | 30- or 60-ohm resistor | Low conductivity | Switching arrangements permit resistance of 30 or 60 ohms |
| *H* | 120 | | | | 434 | | Solid | Low conductivity | Numerous neutral grounds on this system |
| *I* | 132 | | 167 | | 167 | 1 to 4 | Solid | High conductivity | Number of grounds gradually increased from 1 to 4 |
| *J* | 220 | | 354 | | 354 | 4 to 5 | Solid | High conductivity except one section for portion of period | System mileage changed from 234 to 354 |

## Correlation Results

Wherever practicable, the oscillograms obtained from each power system were correlated with power-system trouble records. In the case of system *E*, correlation was obtained for oscillograms of voltages induced in an inductively exposed telephone line as well as for the neutral-current records, thus increasing the amount of usable data from this system. The correlation provided information as to one or more of the following items: (1) whether or not a disturbance was noticed on the system at the time an oscillogram was obtained, (2) cause of disturbance, (3) number of phase wires involved, (4) how cleared, i.e., whether self- or circuit-breaker cleared, (5) location of disturbance (line involved and more definite location if known), (6) damage, if any, to the system, (7) any other pertinent information which was available.

In table III is given, where practicable, a classification of all correlated disturbances in accordance with the attributed primary cause of the disturbance and the nature of the trouble experienced on the power system. As mentioned earlier, only disturbances producing ground current, that is, one or 2 line-to-ground or unbalanced 3 phase-to-ground disturbances are included in these data. In order to show exactly what has been included in the various classifications, some of the items are explained in more detail at the end of the table.

In obtaining correlation between the oscillographic records and power-system troubles for system *E*, more attention was paid to the geographical location of the fault and the actual damage to the system than to the primary cause of the disturbance. For every other power system included in this report, the primary cause of the disturbance was given first consideration, but the correlation, especially with regard to lightning as the primary cause, is by no means considered perfect for any system. The correlation is probably the best for systems *A*, *I*, and *J*, but it is thought that the percentage of records directly attributed to lightning is, in all cases, especially system *E*, too small. It is probable that most of the disturbances in items *A*-2 and 3 of table III were also caused by lightning. Consequently the sums of the percentage values of items *A*-1, 2, and 3 of table III are probably more nearly representative of the percentages due to lightning than are values in item *A*-1 alone.

The values given in table III include all correlated disturbances, irrespective of their duration. While correlation of very short duration disturbances usually would not be expected, a number of those of one cycle or less duration were correlated as due to foreign objects in the line and failures at substations. It seems probable that these were mostly disturbances during the preliminary stages of dielectric failures, such as the spitting over of a transformer bushing just prior to breakdown. They were frequently closely followed by long-duration disturbances. For example, several consecutive oscillograms were sometimes obtained showing an occasional half-cycle or cycle of the type illustrated in the central portion of figure 5, followed by an oscillogram of uniform wave shape of the type shown at the bottom of figure 5. (This particular illustration is a reproduction of one

**Table II—Disturbances and Faults per Calendar Year per 100 Circuit Miles of Transmission Line**

(Only Those Producing Ground Current)

| Power System | 1930 | | | 1931 | | | 1932 | | | 1933 | | | 1934 | | | 1935 | | | Average | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Circuit Miles of Line | Disturbances | Faults | Circuit Miles of Line | Disturbances | Faults | Circuit Miles of Line | Disturbances | Faults | Circuit Miles of Line | Disturbances | Faults | Circuit Miles of Line | Disturbances | Faults | Circuit Miles of Line | Disturbances | Faults | Disturbances | Faults |
| *A*—26 kv | 169 | 15 | 12 | 169 | 21 | 16 | 169 | 29 | 21 | 169 | 13 | 10 | 172 | 10 | 8 | 18 | 13 | | | |
| *B*—33 kv | 860 | 36 | 28 | 400 | 64 | 41 | 400 | 55 | 35 | | | | | | | | | | 52 | 35 |
| *C*—33 kv | | | | | | | 250 | 80 | 54 | 250 | 108 | 69 | 250 | 90 | 56 | | | | 93 | 60 |
| *E*—44 kv | 585 | 108 | 45 | 535 | 94 | 48 | 535 | 85 | 36 | 535 | 88 | 46 | 535 | 65 | 30 | 88 | 41 | | | |
| *G*—66 kv | 313 | 13 | 8 | | | | | | | | | | | | | | | | 13 | 8 |
| *I*—132 kv | 167 | 6 | 5 | 167 | 5 | 4 | | | | | | | | | | | | | 6 | 5 |
| *J*—220 kv | 234 | 11 | 10 | 306 | 10 | 9 | 3 | 6 | 6 | 354 | 6 | 6 | | | | | | | 8 | 8 |

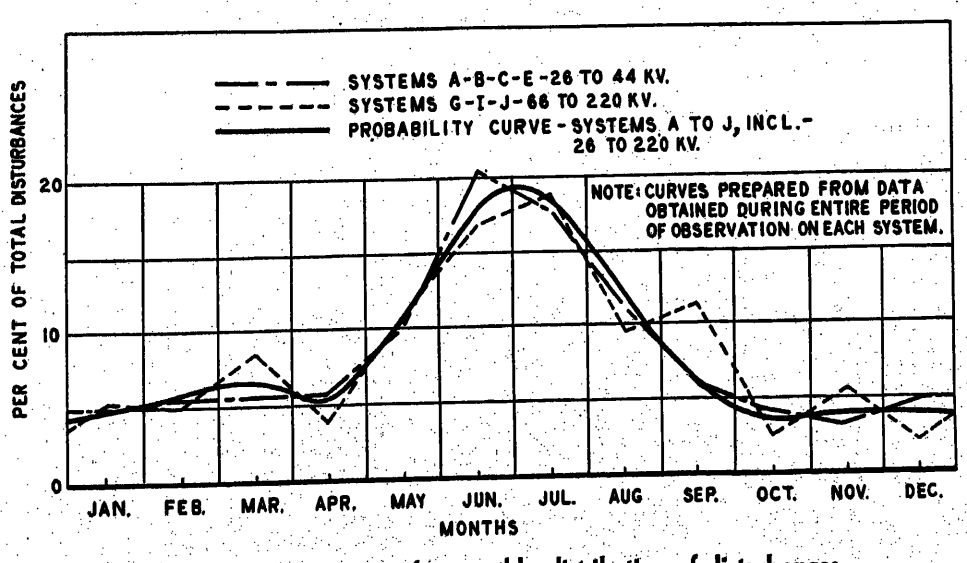



**Fig. 2. Average curves for monthly distribution of disturbances**

continuous oscillogram, and according to earlier definition, represents one disturbance.)

## Fault Characteristics Deduced From Oscillograms

### Durations of Disturbances and Faults

This portion of the analysis is intended to give, as nearly as possible, a representative picture of the distribution of disturbances and faults with respect to their durations while involving ground, as determined from oscillographic records of power-system neutral and residual currents. The results for each of 8 power systems are shown graphically by the cumulative percentage curves in figures 3 and 4. The differences between the curves in these 2 figures, for corresponding systems, are due largely to the elimination of disturbances of one cycle or less duration from the curves applying to faults.

Because of the multiple neutral grounding and system layouts, the durations for systems *F* and *H*, obtained by an oscillograph at only one location, were not necessarily the total durations of the troubles. For the other systems included in figures 3 and 4, total durations were shown by the oscillographic records.

### Wave-Trace Characteristics

The oscillograms of neutral or circuit-residual current from each of 9 power systems have been classified in accordance with the characteristics shown by their wave traces. Under this classification the oscillograms have been listed as those showing (1) uniform wave, (2) uniformly attenuated wave, and (3) irregular wave. Those having uniform wave traces presumably indicate constant resistance faults and the others variable resistance faults. The results of this study are shown in detail in table IV. Wherever oscillograms showed one cycle or less duration, or could not properly be included under any of the 3 classifications noted above, they have been placed under headings noting these facts.

Some typical oscillograms illustrating these characteristics are shown in figure 6. In many cases, the basis for this classification was not as clear-cut as might be inferred from these illustrations alone.

**Table IV—Wave-Trace Characteristics of Disturbances**

| Power System | Total Records Classified | Classification of Wave Trace, Per Cent: Uniform | Uniformly Attenuated | Irregular | One Cycle or Less Duration | Unable to Classify |
|---|---|---|---|---|---|---|
| *A* (26 kv) | 147 | 42.9 | 2.7 | 34.0 | 12.9 | 7.5 |
| *B* (33 kv) | 1,018 | 51.9 | 8.7 | 21.2 | 9.6 | 8.6 |
| *C* (33 kv) | 814 | 40.7 | 1.8 | 32.3 | 19.4 | 5.8 |
| *E* (44 kv) | 1,962 | 54.3 | 3.1 | 22.7 | 11.9 | 8.0 |
| *F* (44 kv) | 100 | 65.0 | 1.0 | 10.0 | 24.0 | 0 |
| *G* (66 kv) | 85 | 58.8 | 3.5 | 15.3 | 20.0 | 2.4 |
| *H* (120 kv) | 226 | 71.6 | 2.7 | 8.8 | 16.0 | 0.9 |
| *I* (132 kv) | 34 | 76.5 | 5.9 | 8.8 | 5.9 | 2.9 |
| *J* (220 kv) | 67 | 71.7 | 0 | 9.0 | 9.0 | 10.3 |

### Manner of Clearance

The determination of the manner in which a disturbance cleared, i.e., whether breaker-cleared, self-cleared, or involving some combination of these, was based on (1) correlation data and (2) appearance of the oscillogram wave trace. On this basis, the oscillographic records

**Table III—Correlated Disturbances Classified as to Primary Cause and Nature of Trouble**

| Description | Power System: A 26 Kv | B 33 Kv | C 33 Kv | E 44 Kv | F 44 Kv | G 66 Kv | H 120 Kv | I 132 Kv | J 220 Kv | A to F 26–44 Kv | H to J 120–220 Kv |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **Net disturbances used in the following classifications:** | 133 | 746 | 592 | 2171 | 84 | 84 | 65 | 29 | 110 | ... | .. |
| 1. Per cent on lines | 60.1 | 76.4 | 80.4 | 61.2 | 46.4 | 60.7 | 53.8 | 69.0 | 61.8 | 64.9 | 61.5 |
| 2. Per cent at substations | 33.1 | 9.5 | 11.3 | 28.9 | 25.0 | 15.5 | 33.9 | 27.6 | 15.5 | 21.6 | 25.7 |
| 3. Per cent—location unknown | 6.8 | 14.1 | 8.3 | 9.9 | 28.6 | 23.8 | 12.3 | 3.4 | 22.7 | 13.5 | 12.8 |
| **A. Classification as to primary cause** | Percentages of Net Disturbances—See Above | | | | | | | | | | |
| 1. Lightning | 39.7 | 47.6 | 57.7 | 41.7 | 27.4 | 33.3 | 52.2 | 31.1 | 60.9 | 42.9 | 48.1 |
| 2. Primary cause unknown | 38.4 | 18.6 | 19.8 | 21.0 | 1.2 | 0 | 4.6 | 24.1 | 8.2 | 19.8 | 12.3 |
| 3. Cause, location, and type of trouble unknown | 6.8 | 14.1 | 8.3 | 9.9 | 28.6 | 23.8 | 12.3 | 3.4 | 22.7 | 13.5 | 12.8 |
| Sum of above—probably due to lightning in most instances | 84.9 | 80.3 | 85.8 | 72.6 | 57.2 | 57.1 | 69.1 | 58.6 | 91.8 | 76.2 | 73.2 |
| 4. Wind, sleet, snow, rain, and flood—no lightning reported | 3.0 | 10.6 | 7.8 | 22.0 | 0 | 16.7 | 0 | 3.4 | 0.9 | 8.7 | 1.4 |
| 5. Foreign objects | 10.6 | 7.9 | 4.5 | 4.8 | 21.4 | 13.1 | 4.6 | 27.6 | 0.9 | 9.8 | 11.0 |
| 6. Switching | 1.5 | 1.2 | 1.9 | 0.6 | 21.4 | 13.1 | 26.3 | 10.4 | 6.4 | 5.3 | 14.4 |
| **B. Classification as to nature of trouble** | | | | | | | | | | | |
| 1. Flashovers | 51.0 | 58.4 | 66.8 | 42.2 | 52.4 | 54.7 | 61.5 | 48.2 | 83.6 | 54.2 | 64.5 |
| 2. Bushing failures | 3.7 | 1.7 | 3.5 | 15.4 | 0 | 0 | 1.5 | 0 | 1.8 | 4.9 | 1.1 |
| 3. Equipment failures | 0 | 2.0 | 4.1 | 7.8 | 3.6 | 0 | 0 | 6.9 | 6.4 | 3.5 | 4.4 |
| 4. Whipping conductors | 0 | 0.5 | 3.0 | 5.6 | 0 | 3.6 | 0 | 0 | 0 | 1.8 | 0 |
| 5. Conductors down—no structures reported down | 3.8 | 14.4 | 14.6 | 13.9 | 7.2 | 10.8 | 6.1 | 13.8 | 0.9 | 10.8 | 6.9 |
| 6. Failure of and damage to supporting structures | 0.8 | 11.3 | 2.8 | 9.1 | 0 | 8.3 | 0 | 0 | 0 | 4.8 | 0 |
| 7. Foreign objects—exclusive of those causing broken conductors or damaged structures, which are included in 5 and 6 above | 9.9 | 10.5 | 3.1 | 5.0 | 15.4 | 9.5 | 4.6 | 13.8 | 0.9 | 8.8 | 6.4 |
| 8. Switching | 1.5 | 1.2 | 1.9 | 0.6 | 21.4 | 13.1 | 26.3 | 10.4 | 6.4 | 5.3 | 14.4 |
| 9. Cable failure | 29.3 | 0 | 0.2 | 0.4 | 0 | 0 | 0 | 6.9 | 0 | 5.9 | 2.3 |

Explanation of items used in classification:

*Flashovers*—only cases where no damage was reported or only damage to insulators.

*Conductors down*—phase conductors, ground wires, etc.—no structures reported down.

*Equipment failure*—transformers, metering equipment, oil circuit breakers, lightning arresters, etc.

*Whipping conductors*—contacts with other conductors, line structures, or structures adjacent to line.

*Foreign objects*—wires, ropes, kites, airplane, crane boom, trees or limbs in line, blasting, etc. Accidents to persons and damage by fire.

*Switching*—includes disturbances due to switching and synchronizing under normal conditions.

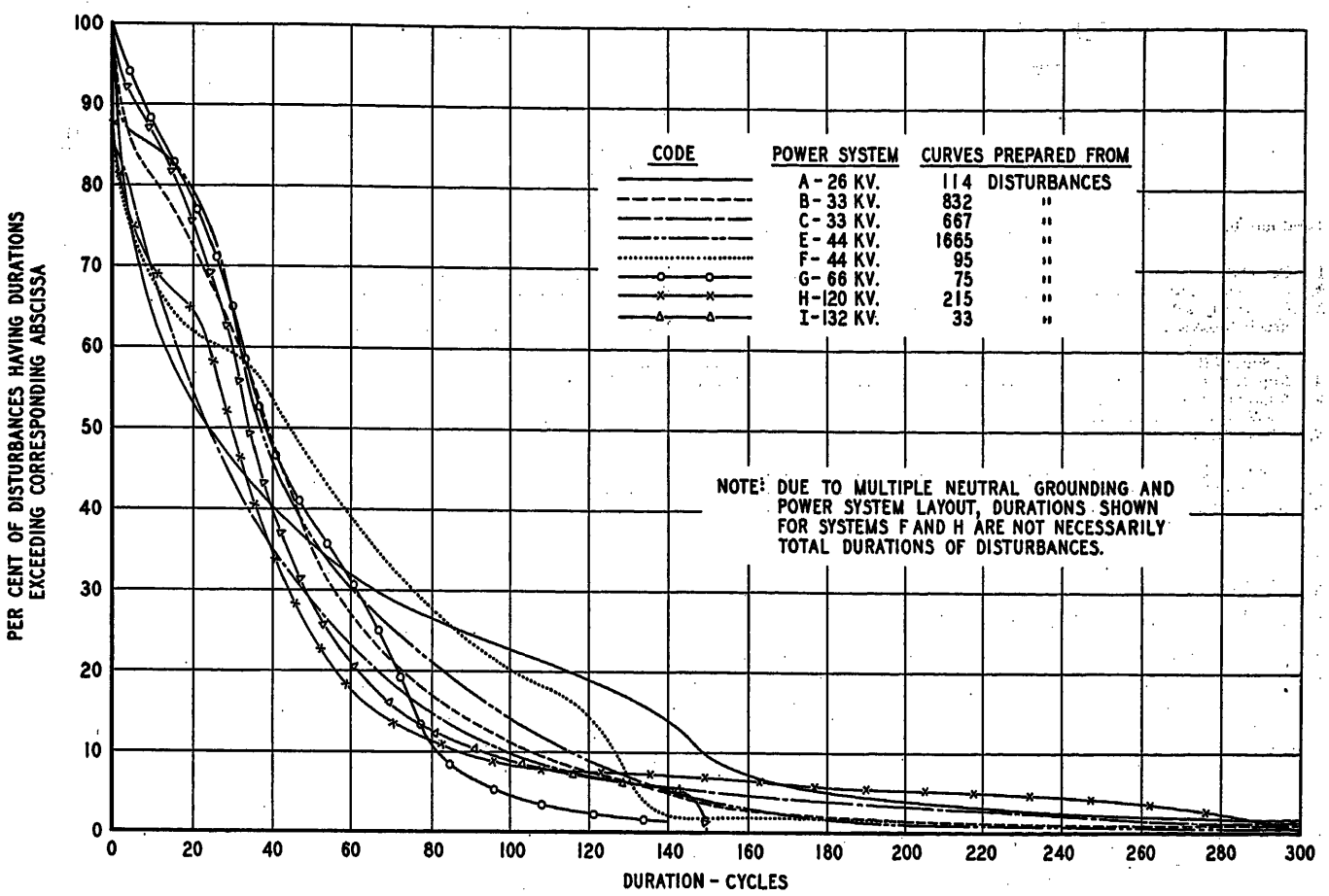



Fig. 3. Cumulative percentage curves of disturbance duration

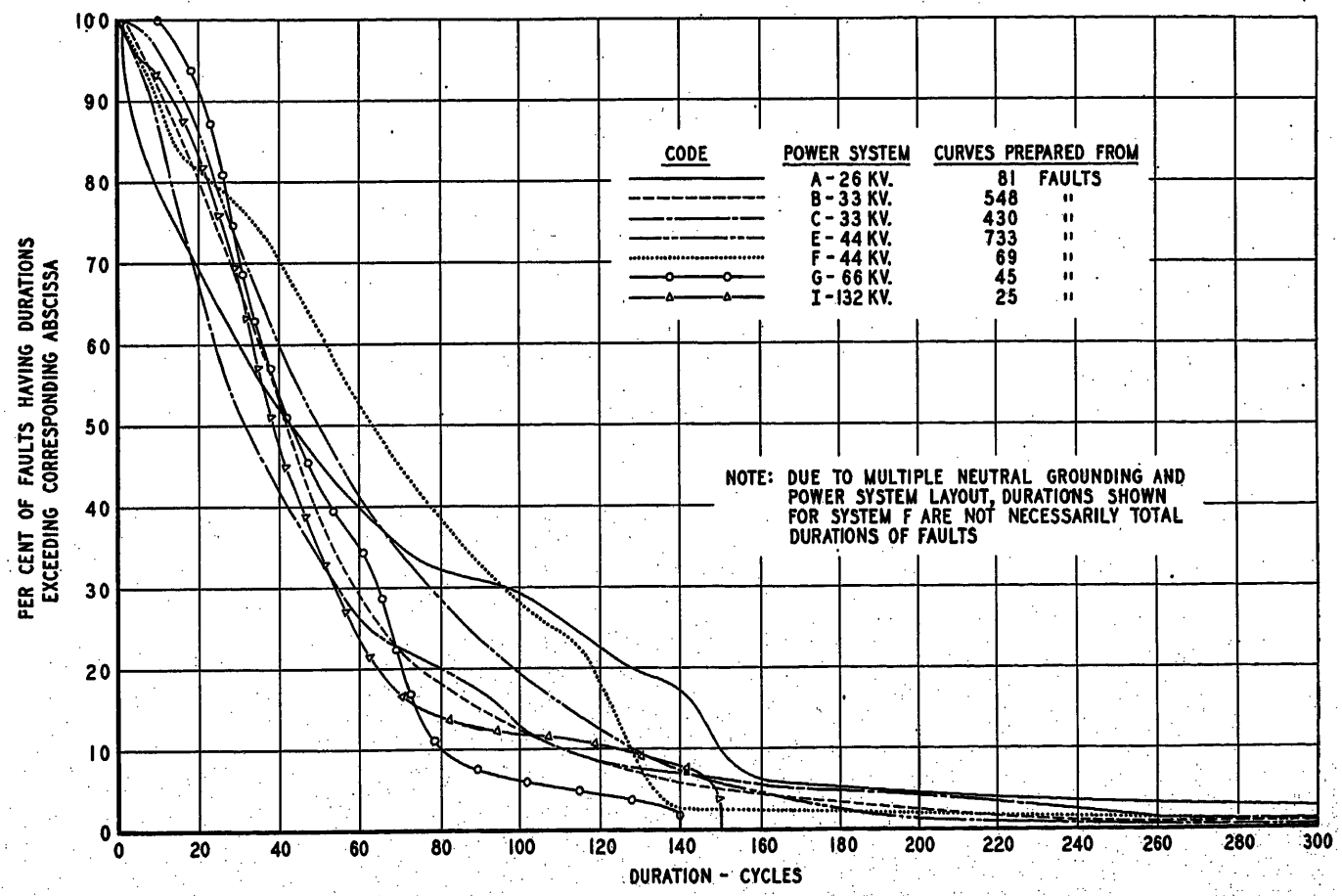



Fig. 4. Cumulative percentage curves of fault duration

## Table V—Classification of Recorded Disturbances as Regards Manner of Clearance

| | Power Systems | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | A 26 Kv | B 33 Kv | C 33 Kv | E 44 Kv | F 44 Kv | G 66 Kv | H 120 Kv | I 132 Kv | J 220 Kv | A to F 26–44 Kv | H to J 120–220 Kv |
| Total number of records considered | 147 | 1018 | 814 | 1962 | 100 | 85 | 226 | 34 | 67 | 4041 | 412 |
| | Values Below Percentages of Total Records Considered | | | | | | | | | | |
| 1. Correlated circuit-breaker-clearing | 59.8 | 48.6 | 46.8 | 58.8 | 50.0 | 74.1 | 29.2 | 85.3 | 61.2 | 52.4 | 58.6 |
| 2. Apparent circuit-breaker-clearing | 4.8 | 10.9 | 14.0 | 4.1 | 13.0 | 3.5 | 45.1 | 0 | 11.9 | 9.7 | 19.0 |
| 3. Apparently self-clearing one or more times followed by final circuit-breaker-clearing | 4.8 | 3.1 | 4.5 | 2.7 | 0 | 1.2 | 1.3 | 0 | 1.5 | 3.1 | 0.9 |
| Sum of items 1, 2, and 3 | 69.4 | 62.6 | 65.3 | 65.6 | 63.0 | 78.8 | 75.6 | 85.3 | 74.6 | 65.2 | 78.5 |
| 4. Apparent self-clearing | 4.1 | 5.0 | 3.7 | 4.3 | 13.0 | 0 | 4.9 | 5.9 | 3.0 | 6.1 | 4.6 |
| 5. Apparently self-clearing one or more times followed by final self-clearing | 2.7 | 5.5 | 3.5 | 2.5 | 0 | 0 | 1.8 | 0 | 0 | 2.8 | 0.6 |
| 6. Circuit-breaker operated but fault apparently self-clearing | 2.1 | 8.8 | 5.0 | 4.2 | 0 | 1.2 | 0.8 | 0 | 3.0 | 4.0 | 1.3 |
| Sum of items 4, 5, and 6 | 8.9 | 19.3 | 12.2 | 11.0 | 13.0 | 1.2 | 7.5 | 5.9 | 6.0 | 12.9 | 6.5 |
| 7. Records of one cycle or less duration | 12.9 | 9.6 | 19.4 | 11.9 | 24.0 | 20.0 | 16.0 | 5.9 | 9.0 | 15.6 | 10.3 |
| 8. Unable to classify | 8.8 | 8.5 | 3.1 | 11.5 | 0 | 0 | 0.9 | 2.9 | 10.4 | 6.3 | 4.7 |

have been classified as shown in table V. Wherever the word "apparent" precedes a method of clearing, this method was determined solely from the appearance of the oscillogram. In all other cases, the method of clearing was deduced from the appearance of the oscillogram in conjunction with the correlation data.

Records showing durations of one cycle or less have all been entered under item 7 of table V. Due to their short duration, it has been impossible to classify them. Some of them were due to synchronizing and switching, others were probably self-clearing short-duration disturbances. Probably in some instances the disturbance had an appreciable duration and for one reason or another the oscillograph obtained only a cycle or less of the record, thus accounting for correlation of some of them with circuit-breaker operations.

In figure 6 oscillograms *a* and *c* illustrate breaker-cleared faults; oscillogram *b* illustrates a self-cleared fault.

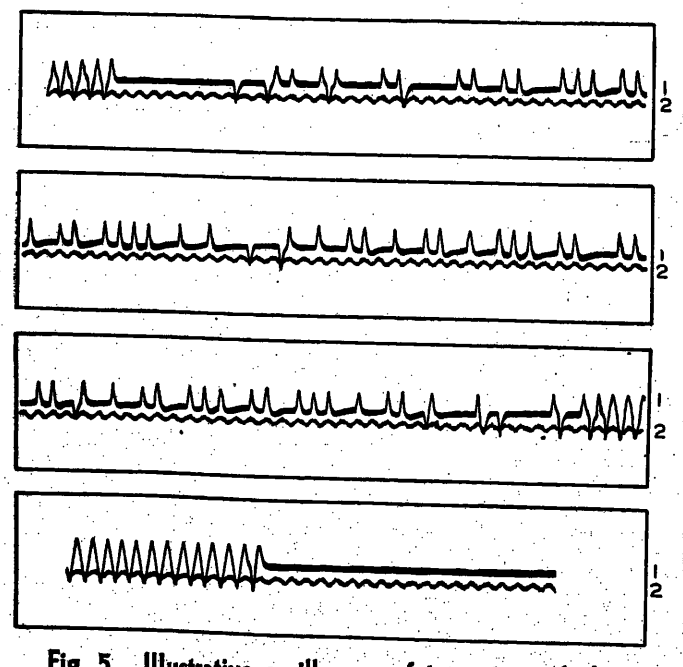



**Fig. 5. Illustrative oscillogram of intermittent fault to ground and complete final breakdown, system E**

1—Neutral current
2—Negative-sequence voltage

### Faults to Ground Involving More Than One Phase Wire

In table VI is given, for systems *A*, *B*, and *E*, a classification of faults with regard to the number of phase wires initially involved and certain subsequent changes therein.

In the case of system *A*, voltages to ground as well as neutral current and negative-sequence voltage[2] were recorded, providing an accurate basis for determining the number of phase wires involved in a fault.

In the case of systems *B* and *E*, the basis for determining the condition of one or multiple line-to-ground faults was largely the appearance of the negative-sequence voltage and neutral current wave traces. The negative-sequence voltage on these systems is low for one-line-to-

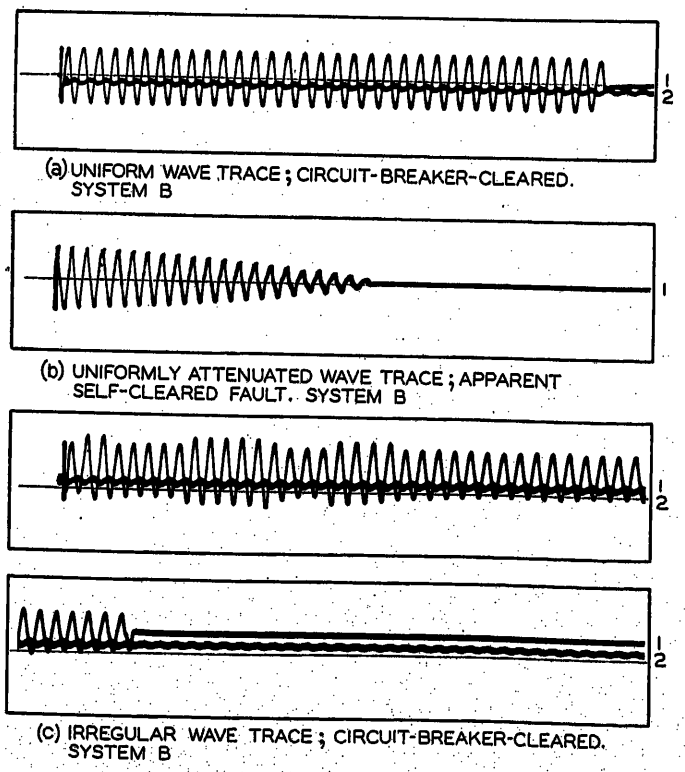



**Fig. 6. Illustrative oscillograms**

1—Neutral current
2—Negative-sequence current

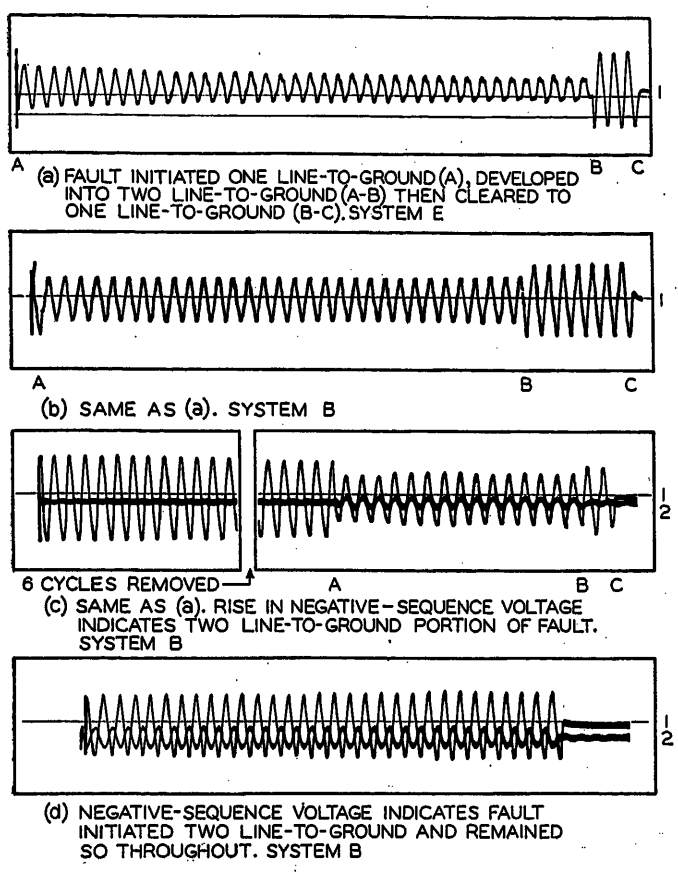



**Fig. 7. Illustrative oscillograms**

1—Neutral current
2—Negative-sequence current

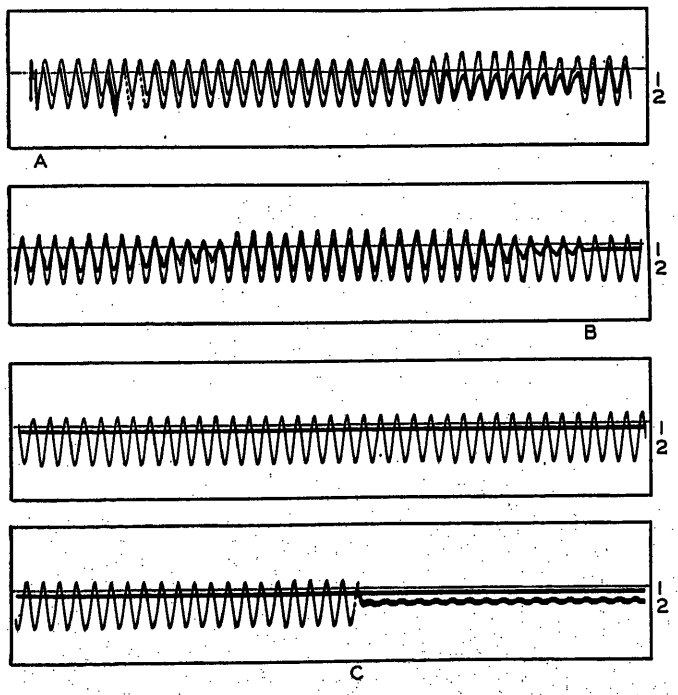



**Fig. 8. Illustrative oscillogram of development of fault from 2 line to ground (A to B) to 2 line without ground (B to C), fault self-cleared to ground and finally circuit-breaker-cleared, irregular wave trace, system B**

1—Neutral current
2—Negative-sequence voltage

ground faults and high for faults involving 2 phase wires. From inspection it is, in most instances, quite evident which ones were obtained during faults involving more than one phase wire and ground. Illustrations of this type of oscillogram are given in parts *c* and *d* of figure 7 and in figure 8. Figure 7, part *c*, indicates that the fault initiated as one line-to-ground and developed into 2 line-to-ground. The 2 line-to-ground portion of the fault is indicated by the decrease in neutral current accompanied by an increase in negative-sequence voltage. Figure 7, part *d*, and figure 8 show faults involving 2 phase wires throughout.

The neutral-current wave traces, especially in systems where neutral impedance is used, give additional information where ground faults developed from one to 2 line and then back to one line-to-ground. In such cases, an abrupt decrease occurs in the neutral-current magnitude when the second fault develops, followed perhaps by a return to the original value when one of the faults is cleared by breaker operation or otherwise. Oscillograms illustrating the changes in neutral current just referred to are shown in parts *a*, *b*, and *c* of figure 7. The validity of this method of determining the existence of faults to ground involving more than one phase wire has been verified by correlation with power-system operating records in a number of cases. Also the illustration in part *c* of figure 7, in which a negative-sequence voltage wave trace is shown, substantiates the classification of the records shown in parts *a* and *b*, thereof. In determining whether one or more than one point on the system was involved in a fault, the correlation and relay operation data were also utilized.

## Table VI—Classification of Faults Regarding Number and Sequence of Phase Wires Involved

| | Power System | | |
|---|---|---|---|
| | A–26 Kv | B–33 Kv | E–44 Kv |
| Total number of records considered | 105 | 373 | 418 |
| | Values Below Are Percentages of Total Records Considered | | |
| 1. Initiated 1 line-to-ground | 70.5 | 78.8 | 87.8 |
| 1.1 Remained 1 line-to-ground throughout | 52.4 | 67.5 | 77.5 |
| 1.2 Developed from 1 into 2 line-to-ground | 17.1 | 10.5 | 7.9 |
| 1.21 At one point | 11.3 | 4.0 | 3.8 |
| 1.22 At more than one point | 2.9 | | 1.0 |
| 1.23 Unable to classify | 2.9 | 6.5 | 3.1 |
| 1.3 Developed from 1 into 3 line-to-ground | 1.0 | 0.8 | 2.4 |
| 1.31 At one point | 1.0 | 0.3 | 1.0 |
| 1.32 At more than one point | | 0.3 | 0.2 |
| 1.33 Unable to classify | | 0.3 | 1.2 |
| 2. Initiated 2 line-to-ground | 23.8 | 17.4 | 6.3 |
| 2.1 Remained 2 line-to-ground throughout | 10.4 | 13.4 | 2.9 |
| 2.11 At one point | 5.6 | 6.1 | 1.2 |
| 2.12 At more than one point | 2.9 | 0.3 | 0.2 |
| 2.13 Unable to classify | 1.9 | 7.0 | 1.5 |
| 2.2 Developed from 2 into 3 line-to-ground | 12.4 | 1.9 | 1.7 |
| 2.21 At one point | 8.5 | 1.6 | 0.5 |
| 2.22 At more than one point | 2.9 | | |
| 2.23 Unable to classify | 1.0 | 0.3 | 1.2 |
| 2.3 Developed from 2 into 1 line-to-ground | 1.0 | 2.1 | 1.7 |
| 3. Initiated 3 line-to-ground | 5.7 | 3.8 | 5.9 |
| **Summary of Multiple Line-to-Ground Faults** | | | |
| 1. Total number of records indicating that more than one line and ground were involved | 47.6 | 32.4 | 22.5 |
| (a) At same point | 32.4 | 14.2 | 7.0 |
| (b) At different points | 9.5 | 1.1 | 2.6 |
| (c) Unable to classify | 5.7 | 17.1 | 12.9 |

No records which did not of themselves indicate multiple fault conditions were considered as such in this study, even though the correlation data indicated that more than one phase wire may have been in trouble. The reason for this was that the correlation data in many instances were not complete enough to base a classification entirely on them.

No classification of faults not involving ground could be made, since the oscillographs, in most instances, were not arranged to operate unless ground was involved. The classification was not extended beyond the first change in the number of phase wires involved. Thus, if an oscillogram indicated that a disturbance initiated as one line-to-ground and subsequently involved 2 and then 3 phase wires, the classification shows only the initiation of the disturbance and its development from a one line to a 2 line-to-ground fault.

An important reason for making this type of classification was to obtain some indication of the extent of double faults* due to overvoltage. It is felt that the development of a fault from one or 2 phase wires to a greater number of phase wires at more than one point on the power system is more indicative of the effect of overvoltage than is a fault which initiates as multiple line-to ground and remains so throughout, even though more than one point on the power system is involved. In the latter case the faults might well be caused by an electrical storm or storms extending over a large area. The percentage of total faults (and disturbances) which developed from one to multiple line-to-ground faults at different points is given below. This is a summation of the percentage figures given in table VI for items 1.22, 1.32, and 2.22. Also items 1.23, 1.33, and 2.23 of table VI, probably include some cases where the multiple fault developed at different locations.

| Power System | Neutral Resistance, Ohms | Percentage of Total Records Indicating the Development of a Fault From 1 or 2 Phase Wires to a Greater Number of Phase Wires and Involving More Than One Point on the Power System |
|---|---|---|
| *A*—26 kv | 75 | 5.8 |
| *B*—33 kv | 30 or 60 | 0.3 |
| *E*—44 kv | 150 | 1.2 |

The authors take this opportunity to thank, in behalf of the Joint Subcommittee on Development and Research of the Edison Electric Institute and Bell Telephone System, all of the companies and individuals therein who co-operated in securing the data on which this paper is based.

## References

1. Distribution of Thunderstorms in the United States, William H. Alexander. *Monthly Weather Review*, volume 52, July 1924, page 337.

2. New Sequence System of Polyphase Meters, R. D. Evans. *Electrical World*, volume 81, September 10, 1923, page 333.

* Two line-to-ground faults in which the fault on one phase wire is at a different point on the system from that on the other phase wire.

# Power System Faults to Ground

## Part II: Fault Resistance

By C. L. GILKESON, MEMBER AIEE  P. A. JEANNE, MEMBER AIEE  E. F. VAAGE, Member Am. Math. Soc.

## Synopsis

AN ALLOWANCE for fault resistance in fault current computations is desirable in certain types of problems. The present paper gives the results of a study made to determine reasonable values of fault resistance to use in computing line-to-ground fault currents, particularly in inductive co-ordination studies. The sources and nature of the data used in the study are described in a companion paper.[1]

## Introduction

For many purposes it is sufficient and even desirable. as in the case of certain relaying problems, for example, to assume zero fault impedance in computing fault currents. For certain other purposes, however, such as inductive co-ordination problems, it seems preferable to include in the calculations a representative value for fault impedance or to otherwise allow for its effect on fault currents.

For faults involving ground, fault impedance is generally understood to include the impedance in the path of the fault current between a phase wire at the point of fault and ground, including local ground resistance. Thus

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1. For all numbered references see list at end of paper.

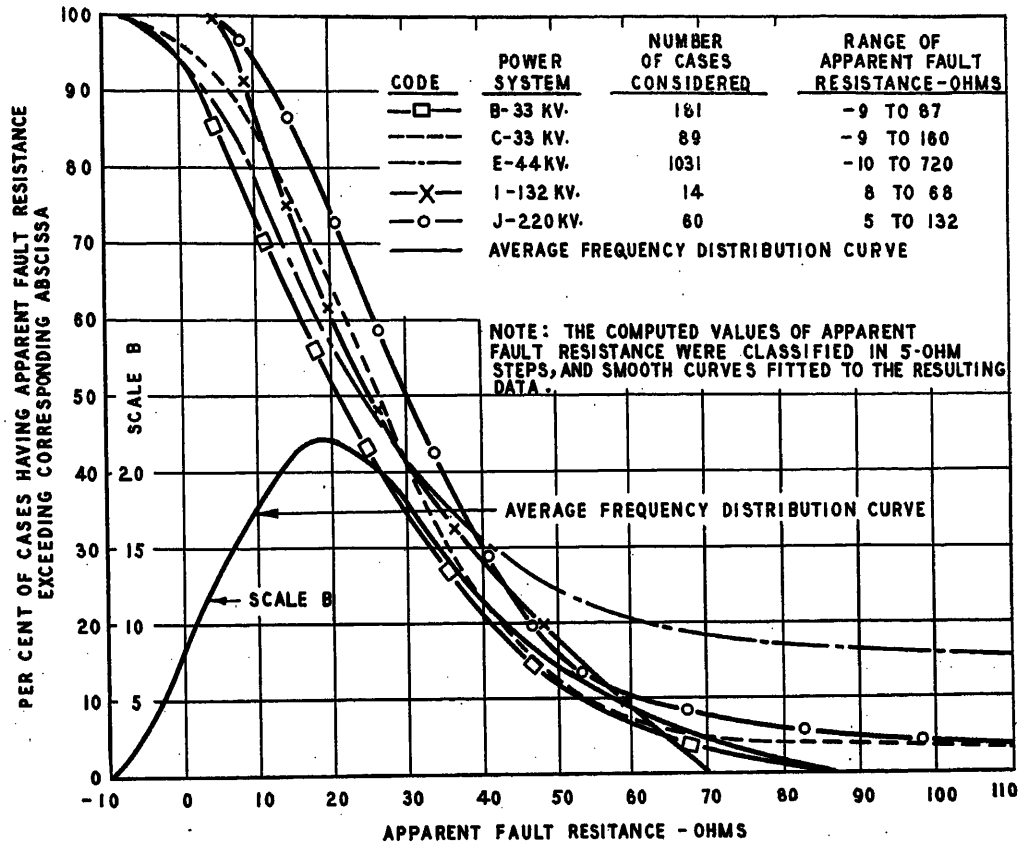



**Fig. 1. Cumulative percentage curves and average frequency distribution curve of apparent fault resistances**

fault impedance includes the resistance in the arc, in the contact between conductor and ground (in the case of wires falling on the earth), in tower footings, in a foreign object between conductor and tower (or ground) or in some combination of these factors. Fault impedance may be constant throughout the duration of a fault or it may vary continuously, as in the case of an arc which is blown out to gradual extinction by the wind. Fault impedance, in general, appears to be predominantly resistive and in this paper will be treated as though entirely so.

In this paper the approach to the problem of fault resistance is largely statistical and is based on an oscillographic study of power system fault currents, made by the Joint Subcommittee on Development and Research of the Edison Electric Institute and Bell System, in cooperation with a number of power companies. The power systems from which the data were obtained are, in most instances, referred to by a letter, i.e., system $A$, system $B$, etc. Information as to the characteristics of these systems and the nature and extent of the study on which this paper is based is given in a companion paper.[1]

The method of attack on the problem of fault resistance has, in general, been along 3 different lines:

1. Measurements of neutral current, supplemented by calculations, to determine the "apparent fault resistance" for one line-to-ground faults occurring under actual operating conditions.

2. Measurements of phase currents and voltages on a particular line to determine more directly the fault resistance under actual operating conditions.

3. Measurements (staged tests) and calculations of certain of the individual elements entering into or affecting fault resistance.

## Determination of Apparent Fault Resistance

### Theory and Limitations

For grounded systems, the formula for computing one line-to-ground fault currents by the method of symmetrical components is:

$$I_F = \frac{3E}{Z_1 + Z_2 + Z_0 + 3R_F} \qquad (1)$$

where

$I_F$ = fault current
$E$ = normal generated voltage to neutral
$Z_1$ = positive-sequence impedance of power system
$Z_2$ = negative-sequence impedance of power system
$Z_0$ = zero-sequence impedance of power system inclusive of neutral impedance but exclusive of fault resistance and capacitance to ground
$R_F$ = fault resistance (used here in preference to $Z_F$ to simplify explanation)

In case of accidental faults to ground during routine operation, $I_F$ cannot be measured directly, but in its place a measurement of neutral current at one or more points can be obtained. If there is but one neutral ground on the system $I_N = I_F$ (except for charging current); if there is more than one ground the division of the computed value of $I_F$ between the neutrals can be determined. Assuming that values of the sequence impedances of the power system are available or can be computed, that system conditions at the time of fault including fault location are known, and that measured values of one or more neutral currents under fault conditions are available, a value of $R_F$ can be determined which will make the computed value of $I_N$ equal to the measured value of neutral current.

The value of $R_F$ so obtained is of the nature of a "corrective resistance," since it includes in addition to fault resistance, the effects of differences between the actual and assumed constants of the system. Therefore, values of $R_F$ determined in this way are referred to herein as "apparent fault resistances." While this method may not give a true fault resistance, it provides a statistical

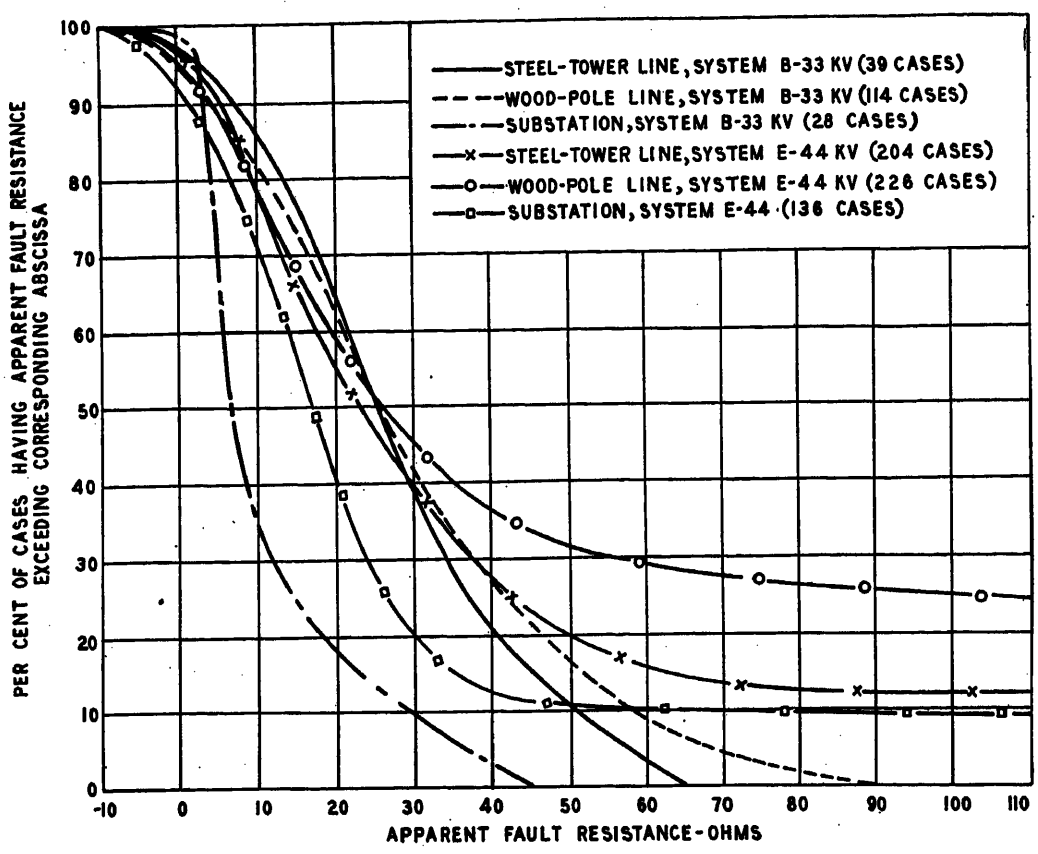



**Fig. 2. Cumulative percentage curves of apparent fault resistance for steel-tower line, wood-pole line, and substation faults**

method of arriving at a value for fault resistance for use in practical calculations of fault current. This method has been used in most of the fault resistance determinations made for this paper.

In a few of the cases a larger value of neutral current was measured than was computed under the assumption of a zero-ohm fault resistance, indicating that the conditions existing on the power system at the time of the fault, or some of the constants, were not accurately known. On directly grounded systems it will be seen, by reference to equation 1, that the largest fault current magnitude that can be calculated by varying $R_F$ (a real quantity), with other things fixed, is that which corresponds to a negative value of $R_F$ equal in absolute value to one third of the sum of the resistance components of the sequence impedances. Any assumed negative value of $R_F$ larger in absolute magnitude than this would decrease the computed fault current. In the cases used for this paper, one third of the sum of the resistance components of the sequence impedances seldom exceeded 5 ohms for the directly grounded systems. Of course, in cases where a neutral resistance is used, a negative value of $R_F$ much larger in absolute magnitude becomes mathematically possible. Negative values of apparent fault resistance, wherever indicated by the calculations, have been included and given equal weight in the analysis, although it is realized that physically they do not exist. The measured current for 2 cases from system *C*, one case from system *I* and 2 cases from system *J* so greatly exceeded the computed values that no figure for apparent fault resistance could be deduced and these cases were excluded in presenting the results.

## Results of Apparent Fault-Resistance Determinations

During some 6 years of oscillographic observations on several power systems, a total of 1,375 records were obtained for which the conditions existing on the power system at the time of fault were known with sufficient accuracy to permit computations of apparent fault resistance. The results of these computations for the 5 systems for which the data were sufficient to warrant curves are shown in figure 1.

Since these curves are similar in shape and lie fairly close together, an average cumulative percentage curve was determined from these curves and from it the average frequency distribution curve shown in figure 1 was derived. The abscissa corresponding to the peak of a frequency distribution curve is its mode, or most frequently occurring value. Similar distribution curves were also prepared for the individual systems. The modal, median, and average values of apparent fault resistance applying to the individual systems and the values from the average curve of figure 1 are shown in table I.

Systems *B* and *E* contain a considerable amount of both steel tower and wood pole line construction. The wood pole lines are not generally of the type recently advocated to take advantage of the wood insulation and some of them carry ground wires. The apparent fault resistance data for these systems were classified in accordance with the type of line to which the individual cases applied; also all apparent fault resistances deduced from substation faults were tabulated separately. Figure 2 shows the resultant cumulative percentage curves based on these classifications. For the respective systems, the curves applying to substations are much lower than those applying to lines of either type. While the curves for the steel tower lines on both systems indicate somewhat smaller apparent fault resistances than those for wood pole lines, particularly at the higher values, the modal values for these 2 types of lines are not very different for the respective systems.

Figure 3 shows average curves, based on a classification between apparent fault resistances deduced for faults on lines and at substations for systems for which such classification seemed warranted. Due to the fact that wood

**Table I—Modal, Median, and Average Values of Apparent Fault Resistance**

| System | Number of Cases | Apparent Fault Resistance | | | |
|---|---|---|---|---|---|
| | | Range | Mode* | Median** | Average |
| *B*— 33 kv | 181 | −9 to 87 | 8 | 22 | 25 |
| *C*— 33 kv | 89 | −9 to 160 | 24 | 28 | 30 |
| *E*— 44 kv | 1,031 | −10 to 720 | 13 | 23 | 57 |
| *I*—132 kv | 14 | 8 to 68 | 15 | 28 | 30 |
| *J*—220 kv | 60 | 5 to 132 | 25 | 31 | 34 |
| Average curve | | −10 to 720 | 19 | 25 | 35 |

* Value expected to occur most frequently.
** The median of a series of values is the midpoint of the series when arranged in order of magnitude.

pole lines were not of special design and frequently carried ground wires, and also to the relatively small differences between the curves for wood pole and steel tower lines just referred to in the case of systems *B* and *E*, values deduced for faults on all types of lines were lumped together in the average curves of figure 3. They show 18 ohms as the most frequently occurring value of apparent fault resistance for lines, and 5 ohms for substations.

Most of the data on apparent fault resistance were computed from values of neutral current measured 3 or 4 cycles after the fault started, which, in the majority of cases, allowed sufficient time for the disappearance of the unsymmetrical transient, if present. However, fault resistance frequently varied from cycle to cycle and in some cases, particularly on systems operating with neutral resistance, the fault cleared before breaker operation.

## Direct Measurement of Fault Resistance

A method of measuring fault resistance during accidental faults on a particular line has been suggested by W. A. Lewis as the result of his studies of distance relaying problems. The method requires the measurement, at each end of the transmission line under study, of the phase currents and the line-to-line or line-to-ground voltages, and the phase relationships among these quantities. From these measurements fault resistance and the location of the fault can be determined by solving, after some rearrangement, equations developed in connection with the theory of determining fault location in distance relaying.[2] In order to obtain measurements of required currents and voltages, at least one 6-element oscillograph is required at each end of the line.

Considerable difficulty was experienced in finding lines suitable and available for fault impedance measurements of the type described above. As a consequence, only one oscillograph installation which would provide data for this phase of the study was made, namely, that on system *D*. The oscillographs were located at each end of a 64-mile line. During the 30 months this system was under observation, 78 records of faults were obtained but only 7 were suitable for fault resistance determinations. The results are given in table II.

From the tabulation it is seen that the fault resistances determined from the 2 equations check reasonably well but that the fault locations are much less reliable, particularly for the higher values of fault resistance.

While these data are not extensive enough to add much to the information on fault resistance, the results are comparable with those given in figure 1. The observations indicated certain practical limitations in this method of measuring fault resistance. One difficulty encountered was that of adjusting the sensitivity of the oscillographs to give proper deflections for faults at any point on such a long line. Another was that of obtaining sufficiently accurate measurements of phase angles from the oscillograms. Also, with the sensitivity required to record fault currents, it was practically impossible to determine the magnitude of the load currents in the non-faulted phases, which may be a source of some error in the calculations.

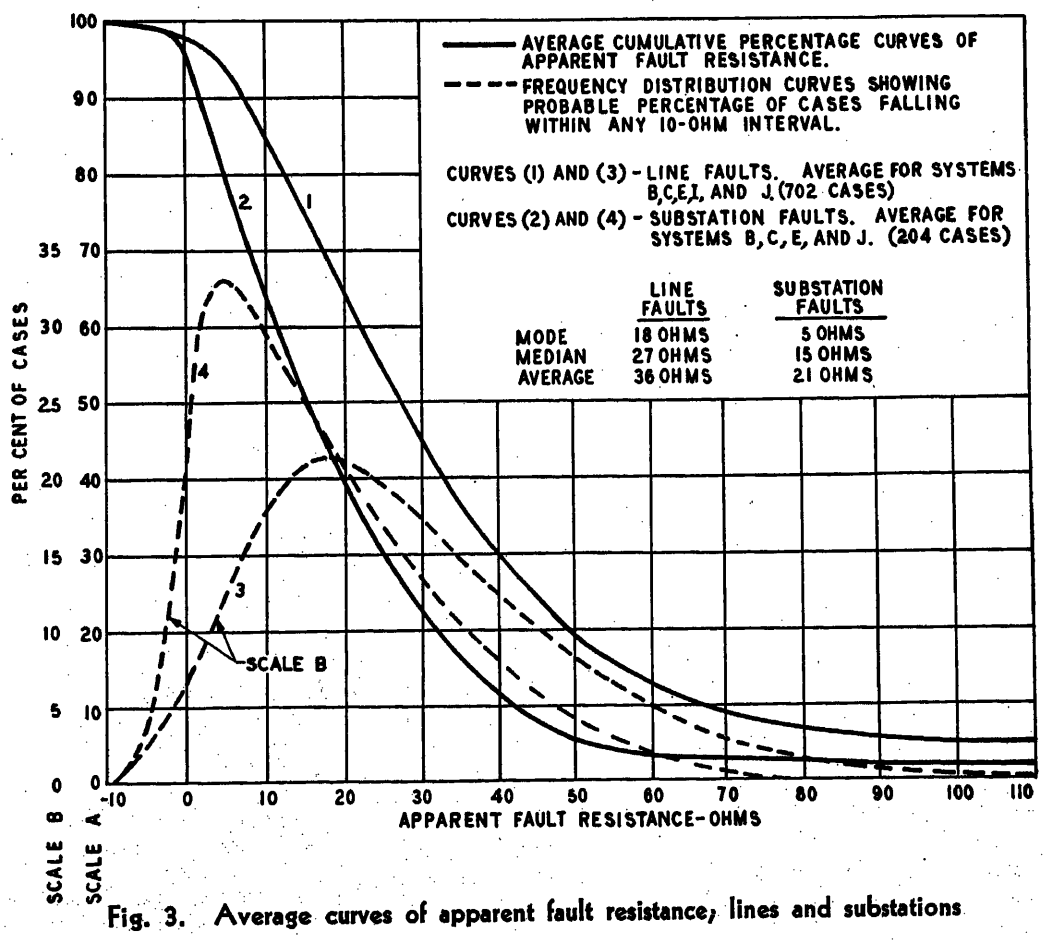



**Fig. 3. Average curves of apparent fault resistance, lines and substations**

**Table II—Fault Resistances Determined by Direct Measurements**

| Case No. | Computed Fault Location—Miles From Station G (1)* | (2)* | (Avg.) | Fault Resistance—Ohms (1)* | (2)* | (Avg.) |
|---|---|---|---|---|---|---|
| (*a*) | 40 | 25 | 33 | 16 | 12 | 14 |
| (*b*) | 65 | 22 | 44 | 45 | 45 | 45 |
| (*c*) | 44 | 43 | 44 | 7 | 7 | 7 |
| (*d*) | 20 | 22 | 21 | 7 | 22 | 14 |
| (*e*)** | | | 28 | | 36 | |
| (*f*)** | | | 28 | | 32 | 30 |
| (*g*)** | | | 28 | | 23 | |

* These values were obtained from 2 equations, each of which could be resolved into real and imaginary components and solved for fault location and fault resistance and the averages taken. The values under (1) and (2) give the results for the individual solutions.
** Stub-end feed, fault location known. (*f*) and (*g*) are reclosures on fault of case (*e*).

**Table III—Miscellaneous Arc and Fault-Impedance Tests**

| Type of Test | Minimum Length of Arcing Path—Inches | Fault Current—RMS Amps | Computed Fault Resistance—Ohms |
|---|---|---|---|
| (1) From a 132-kv system—tests of 1928 | | | |
| Arc across insulator | 52 (approx.) | 359 | 8.7 |
| Arc across insulator | 52 (approx.) | 348 | 9.4 |
| | Length in Contact With Ground—Feet | | |
| Conductor dropped on wet ground | 500 (approx.) | 356 | 9.0 |
| Conductor dropped on wet ground | 500 (approx.) | 365 | 9.6 |
| Resistances computed from readings taken at sending end of line. | | | |
| (2) 33-kv system—tests of 1927 | | | |
| Conductor dropped on dry ground | 5 | 180 (approx.) | 45 |
| Conductor dropped on dry ground | 45 | 200 (approx.) | 36 |
| Conductor dropped on dry ground | 100 | 200 (approx.) | 33 |

## Direct Measurement of Certain Items Entering Into Fault Resistance

In the course of the fault resistance study information on certain of the items entering into or related to fault resistance has been secured. While data on all items are not available, those given may be of interest in connection with certain types of problems.

### Arc Resistance

Certain investigations have indicated that for fairly large currents, the voltage gradient in an arc is independent of current. Consequently, if the voltage per foot of arc can be determined and the length of the arc path is known or can be approximated, the arc resistance is given immediately by:

$$\text{arc resistance} = \frac{\text{arc voltage gradient} \times \text{length of arc}}{\text{fault current}}$$

From time to time advantage has been taken of opportunities to determine arc resistances and arc voltage gradients experimentally. Certain of these arc measurements, of an incidental nature, were not suitable for determining voltage per foot of arc, as no special means of determining arc length were used. The conditions under which certain of these incidental tests were made and the over-all arc resistances measured at various stages of the arc are shown in figure 4. Some additional data on arc resistance and of the arc and contact resistance of a conductor dropped on the ground are given in table III.

Some arc resistance data were also derived from a series of relay tests made on system *J*. The faults were initiated by pulling a string, saturated with a salt solution, across the arcing rings of an insulator string. The approximate lengths of the arcs were determined from moving pictures taken with one camera. The voltage gradient derived from the measurements is shown in figure 5 by the small squares in the range between 2,000 and 3,000 amperes. An average arc voltage gradient of 360 peak volts per foot was deduced from these tests.

A more detailed study of the characteristics of arcs was made in another set of tests in which representatives of the joint subcommitee participated, the results of which have been given in an AIEE paper.[3] In those tests, arc length was determined from moving pictures of the arc taken with 2 cameras set at right angles to each other. It was found that for arc currents between 100 and 800 amperes peak, 67 per cent of the measurements of arc voltage fell

| | CURVE NUMBER | | |
|---|---|---|---|
| | 1 2 & 3 | 4 & 5 | 6 |
| NATURE OF TEST | ARC ACROSS INSULATOR STRING | ARC BETWEEN CONDUCTORS | ARC ACROSS PIN INSULATOR |
| ARC STARTED BY: | FUSE | FUSE | FUSE |
| SYSTEM KV: | 110 | 33 | 33 |
| MIN. ARCING DISTANCE | 74" | 36" | 10" |
| CURRENT RANGE (PEAK ÷ $\sqrt{2}$) | 300-440 | 40-150 | 390-450 |

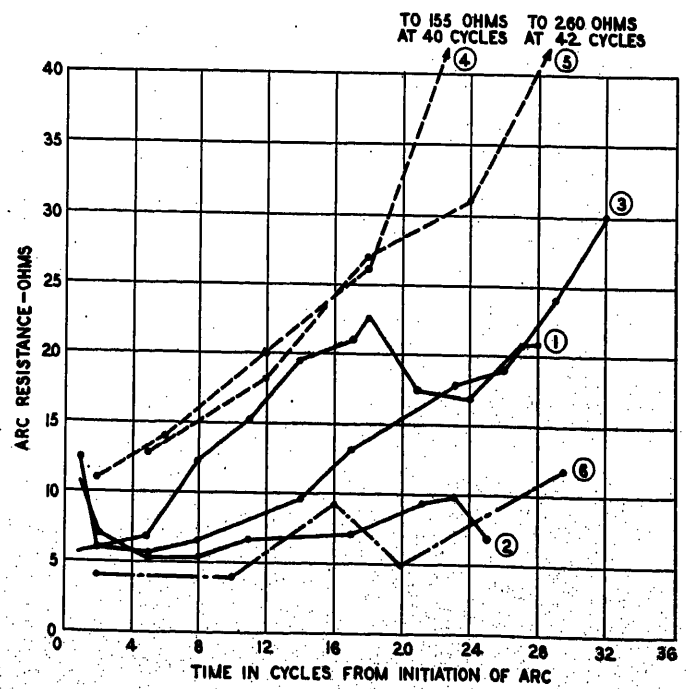



**Fig. 4. Arc resistance**

Results based on arc-voltage and fault-current measurements during staged tests on transmission lines

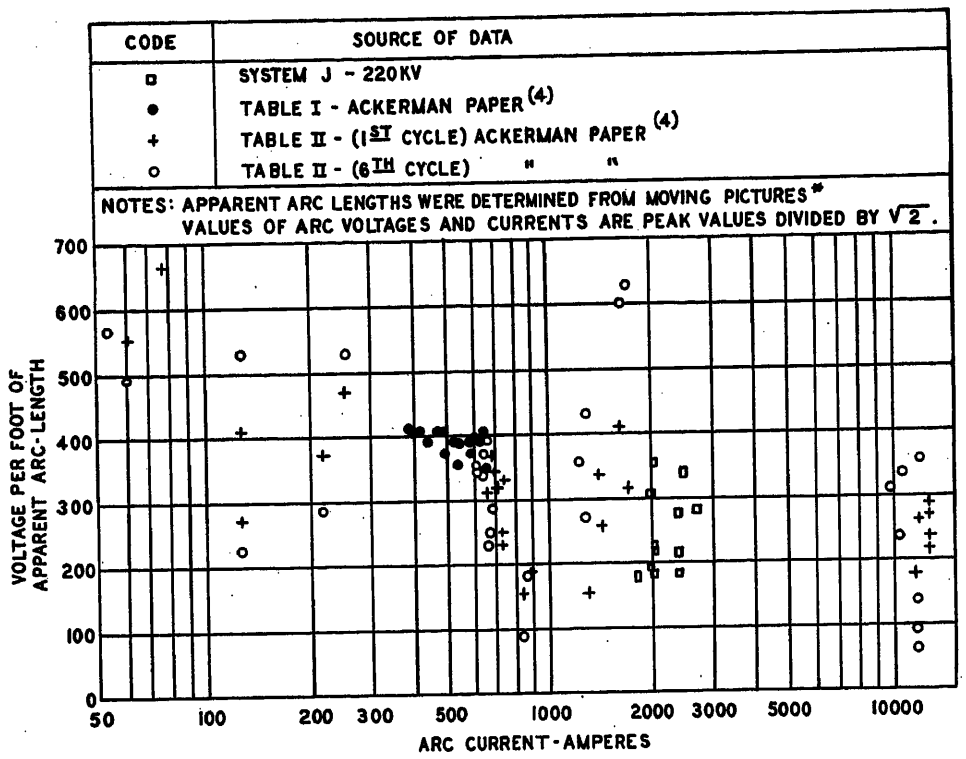



**Fig. 5. Volts per foot of arc versus arc amperes**

*Total initial arc voltage across pin type insulators for currents ranging from 70 to 10,000 amperes as given in Ackerman's paper were:

2.2-kv pin insulator—250 root-mean-square volts

27-kv pin insulator—500 root-mean-square volts

60-kv pin insulator—900 root-mean-square volts

within ±20 per cent of 300 peak volts per foot of arc length. Also 53 per cent of the cases were above 300 peak volts per foot and 47 per cent were below this value. Consequently, the average voltage gradient in an arc for currents from 100 to 800 amperes peak is concluded to be about 300 peak volts per foot.

Investigations by Paul Ackerman[4] have given valuable test data regarding the relationship between arc voltage, arc current, and arc length, the latter being determined from moving pictures of the arc (taken in one plane only). Arc lengths determined in this manner are generally greater, particularly in the case of small pin type insulators, than the striking distance across the insulator. Results from these tests, in so far as they relate to the voltage per foot of arc, have been plotted as a function of current in figure 5. On the basis of his tests Ackerman reaches the following conclusion regarding arc voltage: "The arc voltage is thus chiefly dependent on the arc length. . . . For practical purposes it may be assumed that for long stretched arcs, the arc voltage will be approximately 400 root-mean-square volts per foot length of arc, irrespective of short-circuit current."

The data from the various investigations cited above are in reasonably close agreement with regard to the voltage gradient of an arc, considering the necessary approximations in arc length. The range in average value of gradient is from 200 to 400 root-mean-square volts per foot of arc. (While root-mean-square values are quoted, it should be realized that arc current or voltage waves are usually distorted. Peak values divided by $\sqrt{2}$ were used in analyses.)

### Tower Footing Resistance

For faults to towers on lines having no ground wires, a single tower or pole footing resistance enters into the fault resistance, and unless data are available on footing resistances, the amount to allow is problematical. For lines provided with ground wires, the shunting effect of the other towers along the line becomes a factor and the importance of tower footing resistance in influencing fault current diminishes. It appears that, in a majority of cases encountered in practice, tower footing resistance on lines having ground wires, may be neglected without introducing appreciable error in fault current calculations if $l$, the length in miles of the section of line under consideration, is greater than

$$5\left(\frac{\sqrt{\text{average tower footing resistance}}}{\text{number of towers per mile}}\right)$$

This conclusion is based on a study of the effect of tower footing resistance on the zero-sequence impedance of power lines by a method given in an engineering report of the Joint Subcommittee of Development and Research, E.E.I. and Bell System.[6]

## Conclusions

(*a*) The most frequently occurring values of "apparent fault resistance" for the systems studied ranged from 5 to 25 ohms. Those determined for faults at substations were generally less than for faults on lines; those determined for faults on steel tower lines tended, for the 2 systems for which such separation could be made, to be somewhat smaller than for faults on wood pole lines, but taking the results as a whole there appears to be no marked difference for these 2 types of construction. The data indicate that, where fault resistance is to be allowed for in fault current computations, 20 ohms for line and 5 ohms for substation ground-faults are reasonable values to use.

(*b*) The direct measurement of fault resistance during accidental faults, while possible, is subject to numerous practical difficulties which make the accumulation of data by this method slow and rather expensive.

(*c*) Fairly comprehensive information on arc resistance indicates that, above about 100 amperes arc current, the

(*Concluded on page 474*)

# Relation Between Voltage Drop and Load Balance in an Open-Y Distribution Circuit

By S. D. APOSTOL
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WHEN supplying large lighting loads such as theaters, hotels, or department stores by the 4-kv primary circuits, in many cases it has been desirable to utilize only 2 phases of the 3-phase 4-wire system. These loads are fed by 2 transformers connected in open Y on both the primary and secondary. Such an arrangement is made in order to avoid connecting large lighting loads on only one phase of the 4-kv circuit, thus maintaining a better load balance on the primaries and also obtaining an economical 3-wire secondary distribution system.

With the introduction and widespread use of the a-c network system of Δ-Y transformation the connection of load to only 2 phases in open Y, in some cases, becomes necessary. This is particularly true when the load is cut from d-c to a-c and the old 3-wire system in the building is to be utilized. In both of these methods of distribution the secondary connections are essentially the same and serious voltage-regulation difficulties will arise unless the load is correctly—not generally equally—divided on the 2 phases.

It is a well-known fact that when load is fed from a 3-phase 4-wire system the most desirable arrangement would be to balance the load on the 3 phases. With balanced load, the neutral wire will carry no current and the voltage drop on all 3 phases will be equal. Any unbalancing of the load will cause the neutral wire to carry current with the result that the voltage drops will not be equal on all phases.

In this paper the effect of connecting load to only 2 phases will be considered. In figure 1, $V_A$ and $V_B$ represent the applied voltages for $A$ and $B$ phases, respectively, forming an angle of 120 degrees. Also, $I_A$ and $I_B$ represent the currents for the same phases and lagging their respective voltages. Then $I_N$ will represent the current in the neutral and its value will depend upon the magnitude and direction of $I_A$ and $I_B$. Its magnitude can be computed by the following formula

$$I_N = \sqrt{I_A^2 + I_B^2 + 2I_A I_B \cos\theta} \qquad (1)$$

where $\theta$ is the angle between $I_A$ and $I_B$.

The impedance drops on $A$ and $B$ phases are represented by $V_AE_A$ and $V_BE_B$, respectively. Also, the impedance drop on the neutral, causing the neutral point of the system at the load to be shifted to $N_1$, is represented by $NN_1$. Then the vectors $N_1E_A$ and $N_1E_B$ or simply $E_A$ and $E_B$ represent vectorially the voltages at the loads. Their magnitude and direction depend upon the impedance drop on each phase and the neutral and can be calculated by the following formulas:

$$E_A = V_A - I_AZ_A - I_NZ_N \qquad (2)$$

$$E_B = V_B - I_BZ_B - I_NZ_N \qquad (3)$$

where $Z$ is the impedance of the conductors.

A study of this vector diagram, which was drawn for equal loads and power factors on both phases, shows that the voltage on the leading phase at the load, $N_1E_A$ is considerably greater than the voltage on the lagging phase represented by $N_1E_B$. With the power factor of the load remaining constant, the voltages can be equalized by a definite unbalancing of the load on the 2 phases. The voltages can also be equalized by a change in the power factor of the load, as will be illustrated later.

With these fundamental characteristics of an open-Y circuit in mind it will be shown how they can be applied to produce good voltage regulation on wiring in buildings connected to 2 phases of the network system.

A study of various sizes of 600-volt rubber-insulated conductors installed in building conduits was made to determine the voltage drops at various power factors and various load balances. The resistance for these conductors was taken at 50 degrees centigrade and the reactance was calculated for an average position of the conductors in the conduit, using the formula

$$D = 2\left(\frac{S}{2} + \frac{\frac{1}{2}S}{\cos 30°}\right) = 2.153\,S$$

$$\therefore S = 0.465\,D \qquad (4)$$

where $D$ is the inside diameter of the conduit and $S$ the distance between centers of conductors.

Then, $X = 2\pi 60[14.051 \log (S/r) + 1.524]\ 10^{-5}$, $r$ being the radius of wire.

It was also assumed that the phase wires and the neutral were of the same size.

The calculated values for the reactance are shown in table I.

With the computed reactances and given resistances of these conductors, as shown in the table, calculations can be made using formulas 2 and 3 determining the voltage drops on the leading and lagging phases for various power factors and various load balances. Such calculations were made for number 4 wire with balanced load on both leading and lagging phases at various power factors, and the results were plotted as shown in figure 2. A study of these curves shows the following facts:

1. With the load remaining constant, an increase in power factor from 0.7 to unity results in an increase of voltage drop on the leading

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phase, whereas on the lagging phase the voltage drop decreases with an increase in power factor.

2. At 0.7 power factor the voltage drop on the lagging phase is more than twice the drop on the leading phase, while at unity power factor the voltage drop on the lagging phase is less than that on the leading phase. It is apparent that at approximately 0.98 power factor the voltage drops are equal on both leading and lagging phases.

Similar computations were made for number 4 wire with constant power factor of 0.9 on both phases and with various load balances on the 2 phases, based on 100-ampere total load. The results of these calculations

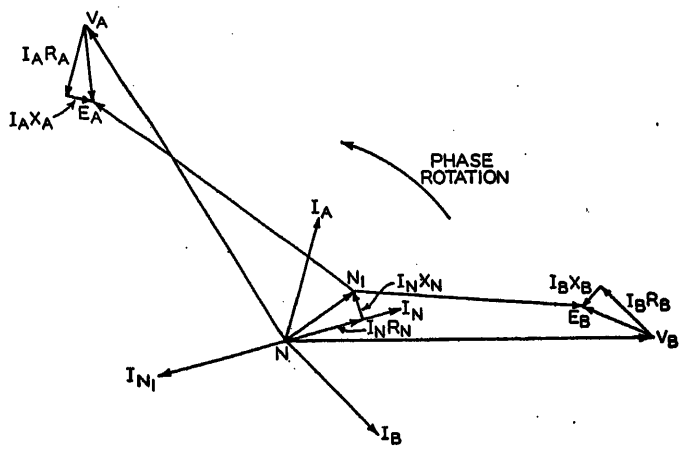



**Fig. 1. Vector diagram of an open-Y distribution circuit**

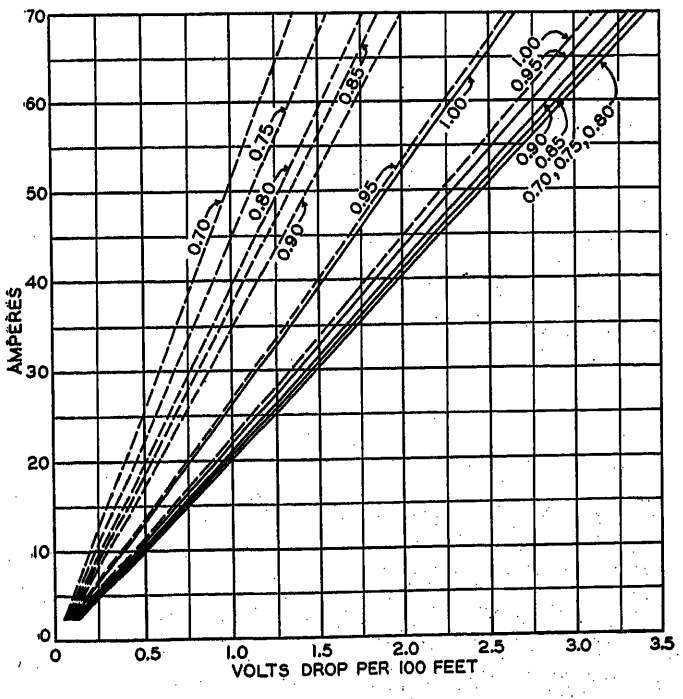
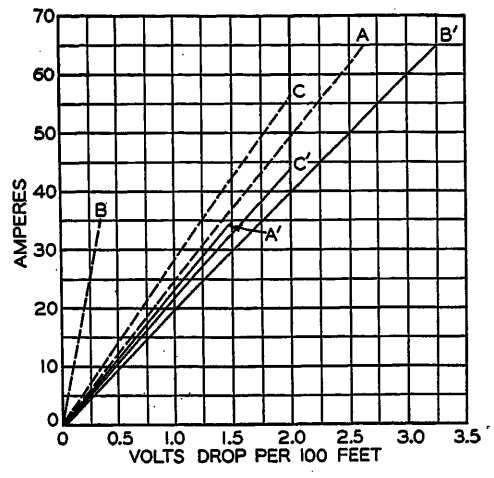



**Fig. 2. Voltage drops on leading and lagging phases at various power factors with balanced load and number 4 600-volt rubber-insulated conductors in $1^1/_4$-inch conduit**

Numbers on curves are power factors
Solid lines for lagging phase; dashed lines for leading phase

**Fig. 3. Voltage drops on leading and lagging phases at various load balances at 0.9 power factor and number 4 600-volt rubber-insulated conductors in $1^1/_4$-inch conduit**




Solid lines for lagging phase; dashed lines for leading phase

*A*—65 per cent of total load on leading phase
*A′*—35 per cent of total load on lagging phase
*B*—35 per cent of total load on leading phase
*B′*—65 per cent of total load on lagging phase
*C*—56 per cent of total load on leading phase
*C′*—44 per cent of total load on lagging phase

were plotted as shown on figure 3. It will be noted that for a load balance of 65 per cent on the leading phase and 35 per cent on the lagging phase the voltage drops are 2.65 volts and 1.5 volts, respectively. With a load balance of 65 per cent on the lagging phase and 35 per cent on the leading phase the voltage drops are 3.25 volts and 0.35 volts, respectively. The voltage drops on both phases can be equalized at 2.0 volts as shown by connecting 44 per cent of the load on the lagging phase and 56 per cent of the load on the leading phase.

Of course, unbalancing the load will increase the copper losses in the wiring but this increase has little significance when compared with the improvement in voltage regulation. It can be shown that by unbalancing the load to a point where one phase carried 30 per cent and the other phase 70 per cent of the total load, such as would be the limit of unbalancing in application, the increase in copper losses amounts to 26.6 per cent.

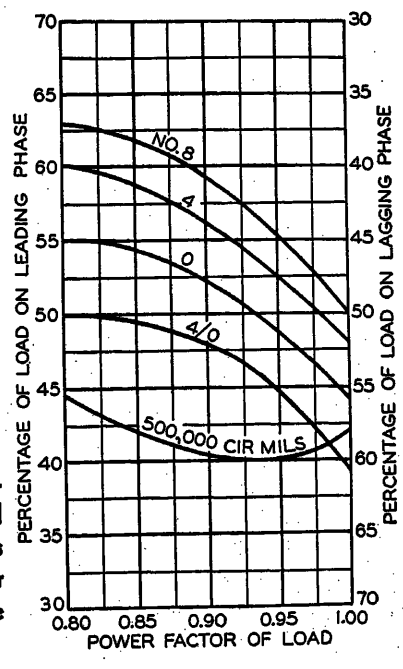



**Fig. 4A. Chart showing the proper load division between phases at a given power factor to give the same voltage drop on each phase**

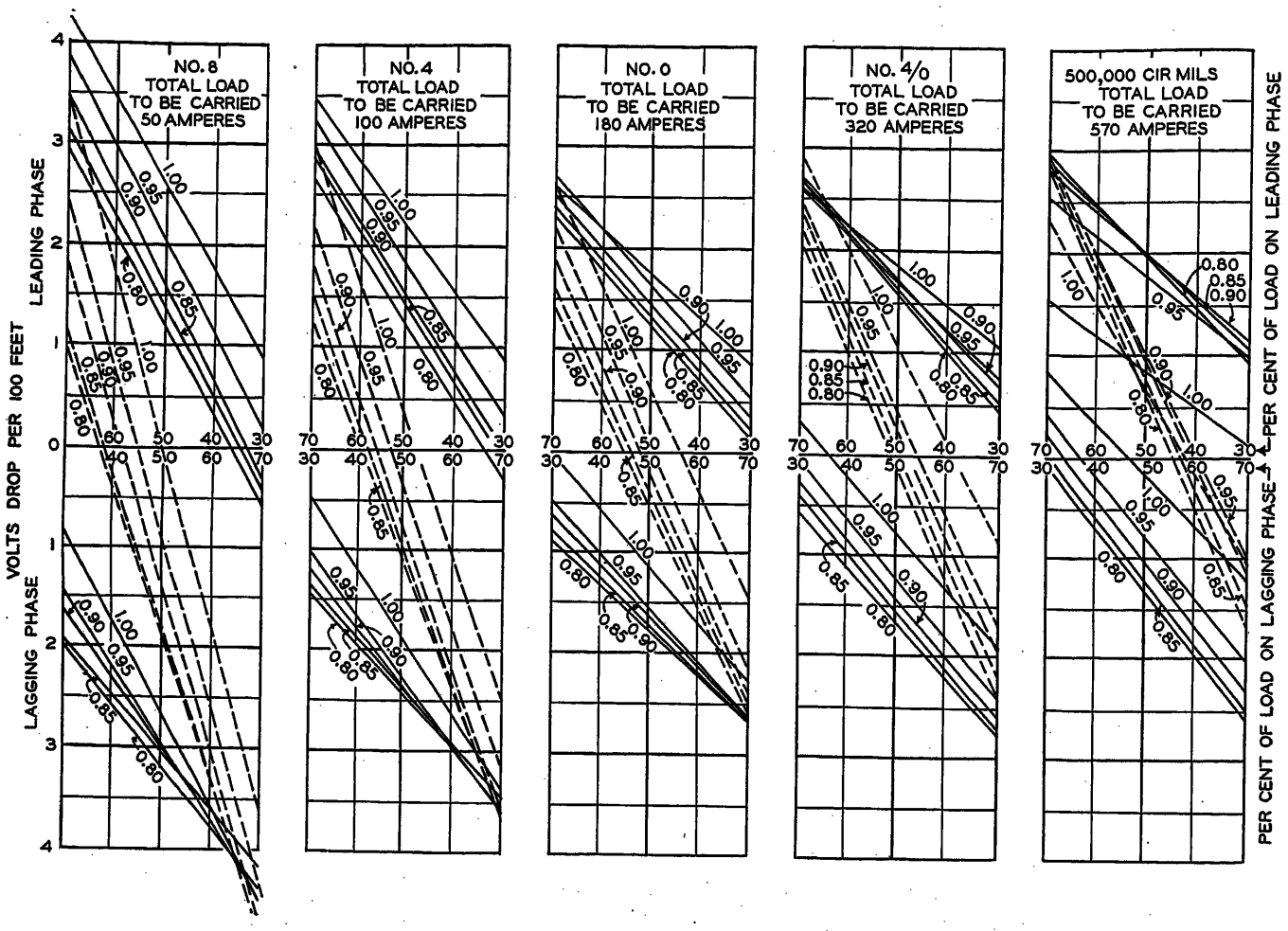



**Fig. 4. Relation between voltage drop and load balance for load connected to only 2 phases of 3-phase 4-wire secondary network for various power factors, 600-volt rubber-insulated conductors**

Numbers on curves are power factors

Solid lines are voltage drops; dashed lines are differences in voltage drops between leading and lagging phases

It has been shown that the voltage drops on both phases can be equalized by changing either the power factor of the load or the load balance. In practical application, however, the power factor is generally fixed and attention must be given to load balance. To determine the correct load balance for various sizes of conductors curves such as shown in figure 4 can be drawn. These curves show the voltage drops at various power factors and various load balances for the more generally used wire sizes. The calculations for the voltage drops on figure 4 are also based on formulas 2 and 3. Considering one phase only, say the lagging phase, and with the impedance of the phase and neutral wires equal, the formula

$$E_B = V_B - I_B Z_B - I_N Z_N$$

can be transformed by the vectorial addition of the phase and neutral currents into

$$E_B = V_B - (I_B + I_N)Z$$

or

$$E_B = V_B - I_{BN} Z \qquad (5)$$

The graphical representation of this vectorial addition for a power factor of unity is shown in figure 5. To illustrate, it is assumed that 60 per cent of the total load is connected to the lagging phase and 40 per cent to the leading phase. The vector $OP$ represents the load on the lagging phase and $OQ$ the load on the leading phase. Then $OR$ represents the neutral current for this load balance. Combining $OP$ and $OR$ vectorially, $OS$ is obtained representing the current $I_{BN}$ of formula 5.

In a similar way combining $OQ$ and $OR$ the vector $OT$ is obtained, which is the resultant of the neutral and leading phase currents. Resultants of all possible load balances, from one limiting condition where the entire load is connected to the lagging phase, to the other extremity where the entire load is connected to the leading phase, line on lines $KU$ and $LM$.

Continuing to figure 6, the lines $KU$ and $LM$ are the loci of the resultant of the current components as shown in figure 5 at unity power factor. By allowing the power factor to vary from unity to 0.8 on both phases these 2 lines will revolve about point $O$ of figure 6. The portions of the loci of the resultant currents for the neutral and lagging phase, having practical application, lie within the area bounded by the vertical lines $DD_1$ and $FF_1$ indicating

Fig. 5 (below). Diagram showing loci of neutral current and of resultant currents of neutral and phase currents for all load unbalances at unity power factor

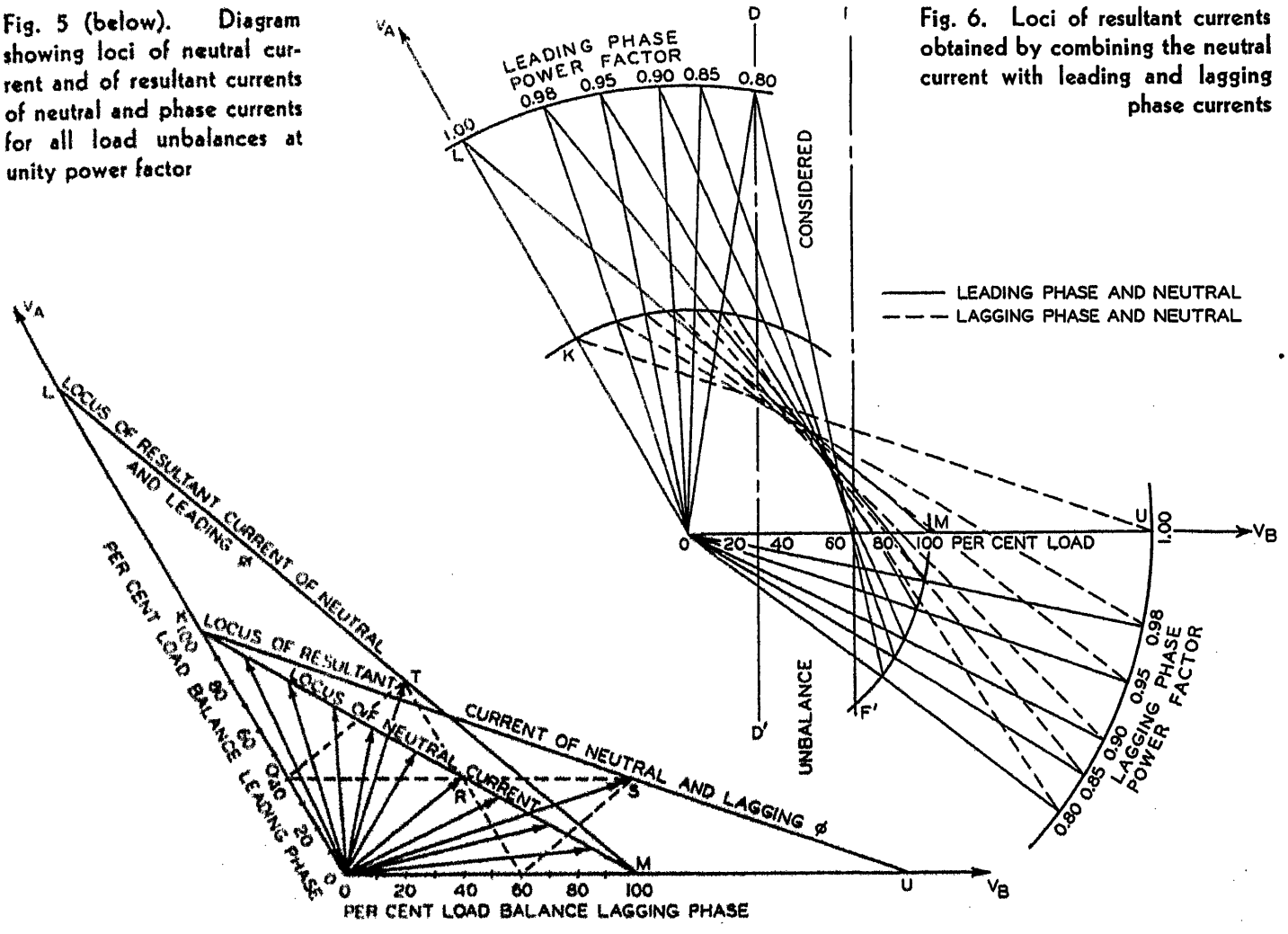



Fig. 6. Loci of resultant currents obtained by combining the neutral current with leading and lagging phase currents

load balances between 30 per cent and 70 per cent. Similarly the portions of the loci of the resultant currents for the neutral and leading phase for load unbalances between 30 per cent and 70 per cent could be segregated by lines drawn vertically to *OL* with the correct scale.

Multiplication of the resultant currents by the impedances of the conductors would give the impedance drops. Since the impedance of the conductors is a fixed value and the locus of the resultant currents is a straight line, for a given power factor, the locus of the impedance drops would also be a straight line.

The loci of the impedance drops of the various power factors will be related to one another in a manner similar to the relationship which exists between the loci of the resultant currents. From the impedance drops the voltage drops, which are desired in the final analysis, can be obtained by subtracting algebraically the voltage of the load from the applied voltage. Consequently, the loci of the voltage drops at various power factors are straight lines still maintaining the relationship with one another that existed between the loci of the resultant currents in figure 6.

From the preceding analysis the reason for the apparent inconsistency in relationship of the loci of the voltage drops shown in figure 4 is evident. It is also evident that, as the loci of voltage drops are straight lines, the determination of only 2 points on any line is necessary, thus making the drawing of the family of curves a relatively simple matter.

The curves shown in figure 4 are plotted for an unbalance of load between phases from 30 to 70 per cent. Such extreme unbalancing of the load between the 2 phases might not be practicable but it was considered for illustration purposes. As shown by the curves for a number 8 conductor and a power factor of 0.8, with the load divided equally between the leading and lagging phases, the voltage drop for the leading phase per 100

(*Concluded on page 474*)

Table I

| Wire Size | Wire Diameter, Inches | Minimum Size Conduit, Inches | Average Spacing, Inches | Reactance per 1,000 Feet | Resistance at 50 Deg. C. per 1,000 Feet |
|---|---|---|---|---|---|
| 10 solid | 0.1019 | 3/4 | 0.348 | 0.0499 | 1.117 |
| *8 solid | 0.1285 | 3/4 | 0.348 | 0.0445 | .7023 |
| 6 solid | 0.162 | 1 1/4 | 0.581 | 0.0510 | .4416 |
| 4 solid | 0.2043 | 1 1/4 | 0.581 | 0.0456 | .2778 |
| 2 solid | 0.2576 | 1 1/2 | 0.697 | 0.0446 | .1747 |
| 0 stranded | 0.373 | 2 | 0.93 | 0.0427 | .111 |
| 0,000 stranded | 0.528 | 2 1/2 | 1.16 | 0.0398 | .0558 |
| 250,000 cir mils stranded | 0.575 | 2 1/2 | 1.16 | 0.0378 | .0473 |
| 500,000 cir mils stranded | 0.814 | 3 | 1.395 | 0.034 | .0237 |
| 1,000,000 cir mils stranded | 1.152 | 4 | 1.86 | 0.0327 | .0118 |

* The Commonwealth Edison Company permits the installation of 3 number 8 wires in 3/4-inch conduit.

# Special Uses for the Automatic Oscillograph

By G. A. POWELL
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THE automatic oscillograph has been available for about 7 years,[1,2] but until 8-cycle oil switches and 1-to-6-cycle relays were in general use, the automatic oscillograph was not used extensively because the performance of the slower relays and switches could be checked at low cost by various forms of high-speed graphic meters. With the present high-speed relays and oil switches, the automatic oscillograph is considered almost a necessity.

Automatic oscillographs are of great assistance in analyzing system disturbances[3,4] because they provide at reasonable cost an accurate record of what happens electrically during each disturbance. For instance, the oscillogram of a disturbance shows the duration of the disturbance, the time required for relay and oil-switch operations, the phases involved, the minimum values of voltage, any tendency toward instability, the blowing out and restriking of arcs, the amount of short-circuit current, and the amount of current in the neutral of transformer banks.

The general nature and benefits of the automatic oscillograph are well known. However, it is sometimes difficult to justify the installation of one if its only use is to analyze disturbances. The purpose of this paper is to describe other uses and to give the operating results which have been obtained.

The 3 special uses described are:

1. Fault location on transmission circuits.
2. Testing carrier-current-controlled relay system.
3. Keeping a check on the operation of the relays controlled by carrier.

The first is applicable to most systems and has been used to some extent, but little has been published on the results obtained.[5] The second is a typical example of the possibility of using the automatic oscillograph for special tests instead of requiring a portable laboratory oscillograph. The third is not applicable to many systems, but it indicates a method of obtaining additional information.

In 1931 an automatic oscillograph was installed at the Rotterdam substation of the New York Power and Light Corporation. Experience with this instrument was so favorable that in 1934 another was installed at the Pleasant Valley substation, for use in connection with the operation of the 132-kv transmission circuits to New York City.

Figure 1 shows the diagram of the transmission circuits centering at Rotterdam and Pleasant Valley.

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G. A. POWELL is engineering assistant of power control, New York Power and Light Company, Albany; R. E. WALSH is an engineer with the same company.

1. For all numbered references see list at end of paper.

The Pleasant Valley oscillograph is initiated by an overcurrent relay in the neutral of the transformer banks, and by a high-speed undervoltage relay. It records the following quantities:

(*a*) Three phase-to-phase 110-kv voltages.
(*b*) Current in *A* phase of Pleasant Valley-Millwood number 9,825.
(*c*) Current in *C* phase of Pleasant Valley-Millwood number 9,826.
(*d*) The total current in the neutrals of 4 transformer banks.

The Rotterdam oscillograph is started by an overcurrent relay in the neutral of the transformer banks, and records the following quantities:

(*a*) Three phase-to-phase 110-kv voltages.
(*b*) Current in *A* phase of Spier-Rotterdam number 2.
(*c*) Current in *C* phase of Inghams-Rotterdam number 9.
(*d*) The total current in the neutrals of 2 transformer banks.

## Fault Location on Transmission Circuits

The current flowing in the Pleasant Valley and/or Rotterdam transformer bank neutrals has been calculated by the method of symmetrical components for faults at the terminals of each 110-kv and 132-kv circuit, and at several intermediate points along each circuit. These calculations were started in 1932. Curves have been made for each circuit plotting Pleasant Valley or Rotterdam transformer bank neutral current versus tower number. Figure 2 shows these curves for both Pleasant Valley and Rotterdam neutral currents for faults on one of the Rotterdam-Pleasant Valley circuits. For each pair of circuits on the same towers, there are the following curves:

(*a*) Single circuit single-phase-to-ground faults.
(*b*) Double circuit single-phase-to-ground faults.
(*c*) Single circuit 2-phase-to-ground faults.
(*d*) Double circuit 2-phase-to-ground faults.

Since all calculations have been for faults of zero impedance, the actual current in the transformer bank neutrals measured by the automatic oscillographs deviates slightly in some cases from the calculated value. When a fault is found, its location is plotted on the curve sheet to show the relation between actual and calculated tower number. The phase-to-phase voltages shown on the oscillograms have been used on several occasions to calculate the approximate location of 3-phase faults.

As soon as possible after a fault occurs, the films are developed by a member of the substation crew, in dark rooms provided at Pleasant Valley and Rotterdam. The values of the 6 elements shown on the film are carefully

measured at the substation and telephoned to the power control office. Figure 3 is a typical oscillogram. The measured values on the oscillograms are converted to actual system voltages and currents from calibration curves for each oscillograph. From the voltage records on the oscillogram, the phase or phases involved is ascertained. The curve for that type of fault is then referred to, and the tower number determined. Maps showing a profile of the terrain traversed by the circuit, and the tower-footing resistances are studied to see if these factors are likely to change the location of the fault as determined from the curves. The tower number and phases involved are given to the system operator who orders the circuit patrolled 5 miles each side of this tower.

This procedure has been followed since May 1935, although calculation of the location of faults was started in 1932. Previous to 1935, it was the practice to patrol the whole circuit after a trip-out. During 1935 and 1936, a total of 200 man-days were saved in patrols by this procedure. A summary of results for the last 5 years is shown in table I.

**Table I**

| | 1932-34 | 1935 | 1936 |
|---|---|---|---|
| Number of cases calculated | 35 | 25 | 18 |
| Fault within 10 towers (approx. 1.2 miles) of calculated location | 10 | 14 | 5 |
| Fault within 2 miles of calculated location | 7 | 3 | 4 |
| Fault within 4 miles of calculated location | 7 | 3 | 5 |
| Fault more than 4 miles from calculated location | 3 | 1 | 0 |
| Fault not located | 8 | 4 | 4 |

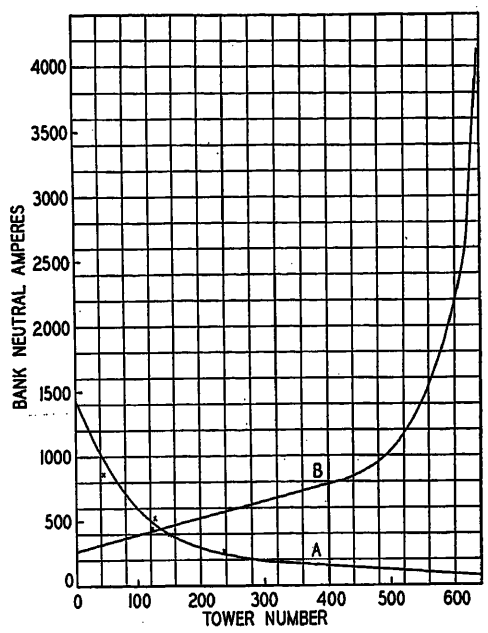



**Fig. 2. Rotterdam - Pleasant Valley number 19 and number 20. Single circuit—single phase to ground fault**

*A*—Rotterdam banks neutral current

*B*—Pleasant Valley banks neutral current

Crosses indicate actual faults

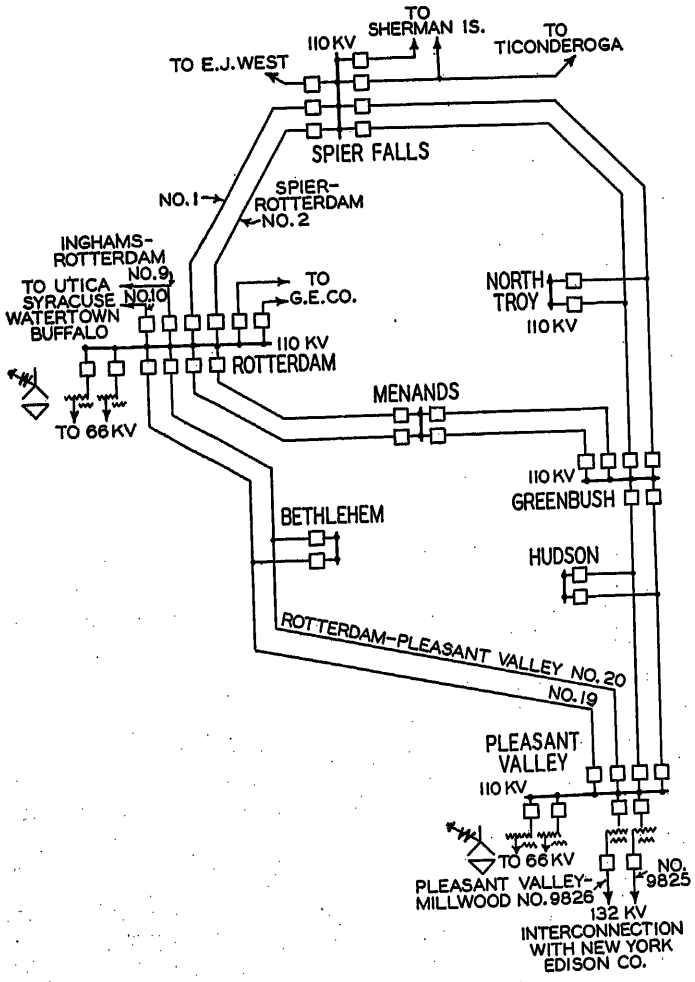



**Fig. 1**

## Testing Carrier-Current-Controlled Relay System

In 1933 2 parallel 132-kv circuits were equipped with carrier-current-controlled relay protection.[6] Standard power-directional and ground-directional relays are used for this protection. There are 2 ground-directional relays, one for starting carrier transmission and one with 2 sets of contacts. One set of contacts is for tripping and the other set for preventing the starting of carrier transmission, in case the power-directional relay should operate incorrectly, due to a large amount of through load current at the time of an internal phase-to-ground fault. For phase-to-phase faults a power-directional relay is provided for starting carrier, and in conjunction with an induction-type overcurrent relay, is used for tripping. To increase the sensitivity and the speed of the power-directional relay at the time of a fault, the voltage restraint on this relay is supplied through the normally closed contacts of an instantaneous overcurrent relay.

The relay tripping times with this scheme of protection are approximately 6 cycles. If a fault is external to the section protected, it is necessary for either the power-directional or ground-directional carrier starting relays to operate and start transmission of carrier current, and for the carrier current to operate the receiver relay at the remote end to block tripping, before the tripping relays close their contacts. This means that for correct operation of the protective scheme all of the relays must be closely co-ordinated to be selective within 6 cycles. This selective action is not difficult to obtain if the relays are all properly adjusted as the carrier starting relays open normally closed contacts while the tripping relays are circuit closing. However, after each individual relay was

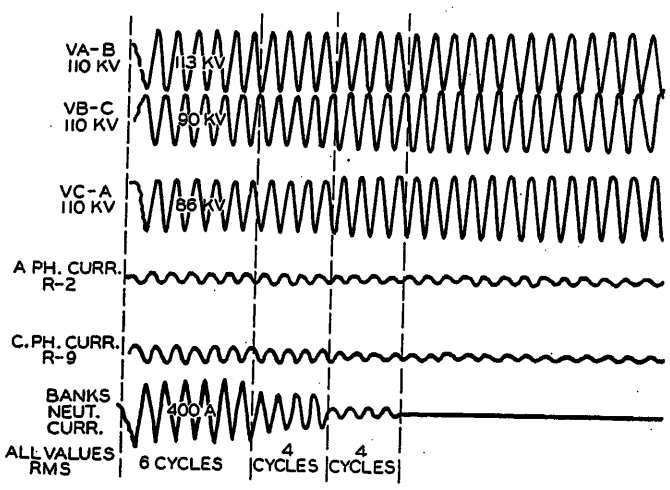



Fig. 3

carefully calibrated and set, it was felt there was no definite check on their combined operation as a group or the margin of selectivity between the groups.

In order to obtain this information the automatic oscillograph is used after each periodic calibration and check of the individual relays, to show the operation of each individual relay at that station and their combined operation as a group. One set of tests is made on the ground relays and one on the phase relays. The oscillograph is started by hand and current of proper magnitude and phase angle to simulate faults at various locations is passed through the relays and one element of the oscillograph. The relays actually remove voltage restraint from the power-directional relay, start carrier, operate the carrier receiver relay, open the trip circuit and finally close the trip circuit exactly as in actual operation, except that each set of contacts also energizes or de-energizes (depending on whether it is circuit closing or circuit opening) an element of the oscillograph from a 125-volt d-c source. One element of the oscillograph is energized with 110 volts alternating current, to give a timing wave. As soon as the tripping contacts close, the test current is removed, relays reset, and the oscillograph stopped. This procedure gives a record of the resetting of the relays as well as a record of their operation. A record of the reset

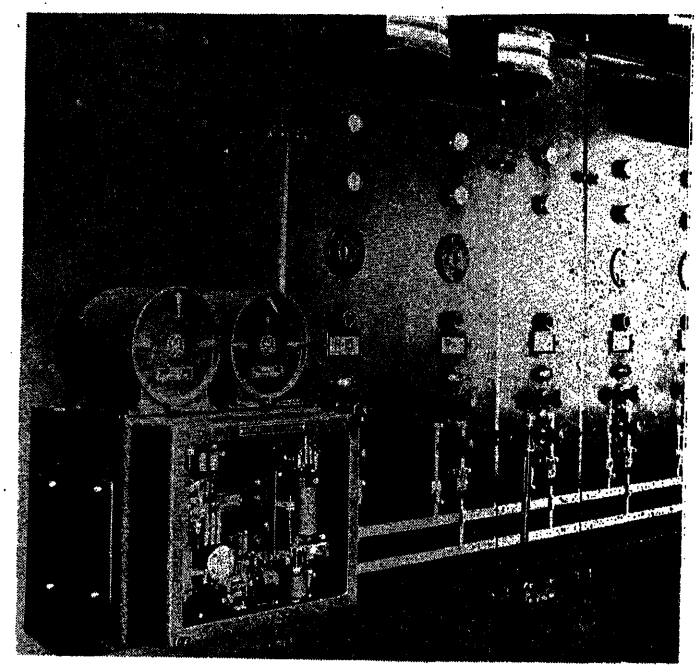


Fig. 5. Automatic oscillograph on switchboard panel in Rotterdam substation

is very important as in most cases the margin for insuring correct operation is less during reset than during operation.

## Keeping a Check on the Operation of the Relays Controlled by Carrier

After the carrier-current pilot relays had been in service about a year it was felt that although the operations had all been correct, it would be desirable to have a check of the operation of the relays oftener than the yearly periodic calibration and test. The carrier receiving relay has 2 sets of contacts; one set is circuit-opening and opens the trip circuit; the other set is circuit-closing and is used to energize an auxiliary alarm relay which lights a light and rings an alarm.

While this arrangement indicated whenever the trip circuit was locked out, it did not give any information as to the time required to lock it out or the length of time it remained open. A scheme was worked out for using the automatic oscillograph to give this information. A second auxiliary relay is connected with its coil in series with coil of the auxiliary alarm relay. The contact of this second auxiliary relay is connected in series with a 6-volt battery, a resistor, and one element of the oscillograph. The element of the oscillograph is one which is used to record one of the phase-to-phase voltages on the

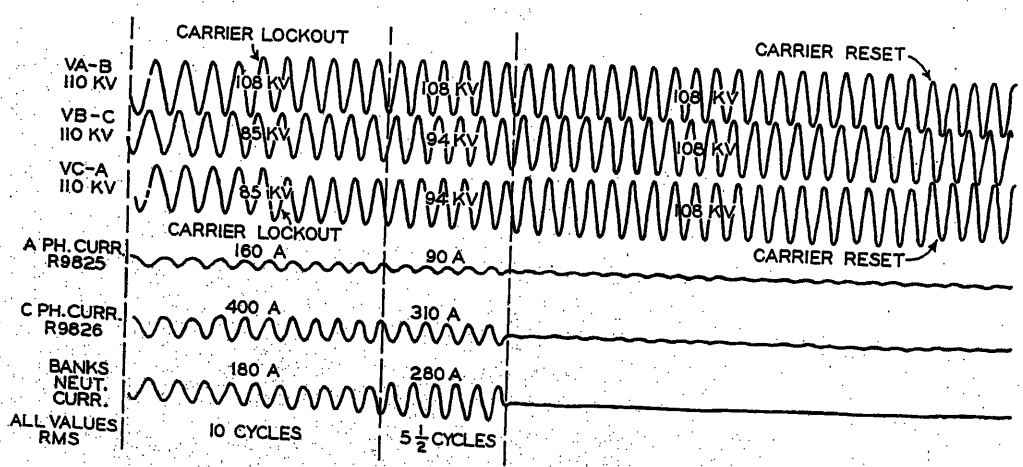



Fig. 4

(*Concluded on page 476-7*)

# A New Magnetic Flux Meter

By GEORGE S. SMITH
MEMBER AIEE

## Summary

THE MEASUREMENT of magnetic fields in air gaps by the existing methods, is almost as cumbersome as light measurements were before the introduction of the photronic cell or photoelectric tube into that field. This paper describes a meter for the measurement of magnetic flux which seems to parallel the advance made in the lighting field.

About 2 years ago a problem arose in connection with some research work in which continuous measurement of somewhat varying magnetic flux values in air gaps was desired. A survey was made of the methods available, and no method was found suitable for the problem at hand. This problem then became the subject of somewhat extended research, the results of which are given in this paper.

A variety of schemes have been used or suggested for the measurement of air-gap flux, most of which are of value only in some very special type of problem. The 2 most popular methods in use today are first by means of a galvanometer and a search coil and, second, by means of the change in resistance a bismuth wire exhibits when placed in a magnetic field. The first of these methods requires movement of the search coil and an instantaneous reading of the resulting galvanometer deflection. The second requires careful measurement of the resistance offered by the bismuth wire in the field, as well as that in zero field; the percentage change in resistance thus obtained is referred for interpretation to a calibration curve. As is evident, both methods are cumbersome for general use, and require care and skill for accuracy. This is especially the case in the use of bismuth, since a small change in temperature between measurements will often result in a considerable error in the results. Neither of these methods is well adapted to continuous measurements.

After this research problem was well under way the author's attention was called to a publication by F. S. Dellenbaugh, Jr.,[1] describing a miniature d-c generating armature for use in the continuous measurement of magnetic fields, varying or constant. However, this method also has many disadvantages, especially from the standpoint of construction, where it is to be used in fields of very limited area, or in very small air gaps.

The first attempt in this problem was to make an instrument using the Hall effect.[2,3,4,5] This effect appears to be a distortion of the normal current path in a thin flat disk of metal in the presence of a magnetic field. Since various metals have differing Hall-effect factors, this effect seems to depend also upon some property of the material. The Hall effect for bismuth is much higher than for most other metals except tellurium. This approach appeared very hopeful until higher flux densities were approached; then the readings became less, and finally reversed in direction. Figure 1 shows the wiring diagram of the apparatus used and the curves taken for 21 degrees centigrade and 48 degrees centigrade. As has been suggested by Craig[6] and Beekert,[7] this method might be of value in the measurement of low values of flux density.

The next step contemplated was to amplify the change in the resistance of bismuth by means of a vacuum-tube circuit, but this too appeared to offer many obstacles. Finally it appeared possible to obtain the desired results by using a bismuth resistor in each of the 2 diagonally opposite arms of a Wheatstone bridge, as shown in figure 2, and placing both of these in the magnetic field to be measured.

This research has resulted in a very satisfactory method of obtaining a direct and continuous reading of the flux density of magnetic fields, either steady or slowly varying. The same instrument can be calibrated for ranges from full-scale reading of a thousand gausses or less to as high flux densities as may be desired to measure. The calibration curves for 2 ranges on the bridge are shown in figure 3. Figure 4 shows the meter with the bridge removed from its compartment, ready for use.

A study of many of the researches[8] in connection with the behavior of bismuth and other metals in the presence of magnetic fields revealed many points of value. The greatest amount of useful information was furnished by the curves shown in figure 5, plotted from data in the Smithsonian tables. These show the variations to be expected in the use of bismuth at varying temperatures and varying flux densities. Fortunately the variation over the usual working range of temperatures is not very great, so that correction need be made only when more than ordinary accuracy is desired.

Since bismuth is very brittle and is not easily worked, it is usually found pure only in lump or granular form. However, its melting point is rather low (271 degrees centigrade) and it forms well in a cast. Accordingly, it was first cast in a double spiral groove, machined in the face of a brass plate and so arranged that the resulting spiral would be noninductive. A great deal of difficulty was encountered in obtaining any great length with a small cross-section, but after many attempts 2 such spirals were obtained, of about 3.7 ohms each. These were built into a bridge, with very fine copper wire interwound between

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1. For all numbered references see list at end of paper.

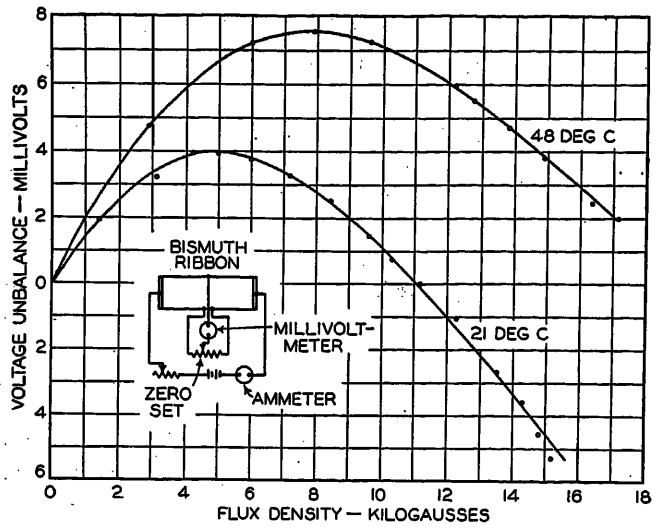



**Fig. 1. Voltage unbalance due to Hall effect**

the bismuth turns to form the remaining arms. This bridge gave such consistent results in the calibrations and various checks that still better results seemed likely from a bridge with higher resistance in the arms. Hence some bismuth wire was imported from Germany, and a bridge was constructed with 50 centimeters of 0.17-millimeter diameter wire in each spiral. Each arm measured about 28.25 ohms.

In the construction and tests on this bridge, a number of problems arose which were either partially or wholly solved.

First, since bismuth has rather high thermoelectric effect when joined to most other metals, a considerable amount of error might result if the junctions of the various ends of the spirals were not kept at the same temperature. To avoid this the support for the bridge was made of a thin sheet of copper covered on either side with a very thin sheet of mica. To each side of this support were cemented the 3 thin flat copper leads; the spirals and balancing resistors were securely attached to the one end, and a bakelite terminal block to the other. The assembly of bridge and its leads was then covered on each side by a sheet of mica, for protection. The arrangement is clearly shown in figure 6. All junctions were made as near each other as possible so that very little difference in their temperatures could exist. The resulting thickness beyond the terminal block is 1.25 millimeters. No errors from this source have been detected, so that the temperature-equalizing strip may not be necessary.

A second problem arose in the zero shift of the flux meter when the temperature of the bridge was increased or decreased. To overcome this a search was made for some metal having the same temperature coefficient as bismuth, but none could be found. By using a metal of higher temperature coefficient of resistance than bismuth, and using only enough so that its resistance change would always be equal to the corresponding resistance change in the bismuth, the zero shift could actually be made zero. The remainder of the balancing resistance for each arm can be made of manganin resistor which may be placed in the meter case. A portion of one of these should be made variable, in order to correct any possible zero displacements.

The equation used to determine the value of such balancing resistors is as follows:

$$ {}_xR_0 = {}_bR_0\alpha_b/\alpha_x $$

where

${}_xR_0$ = resistance of the balancing resistor at the assumed base temperature
${}_bR_0$ = resistance of the bismuth resistor at the assumed base temperature
$\alpha_x$ = temperature coefficient of the balancing resistor material at the base temperature
$\alpha_b$ = temperature coefficient of bismuth at the base temperature

In this research the final adjustment had to be made by trial. Since some number 40 Brown & Sharpe silk-covered nickel wire was available, it was used for the balancing resistance, though some very fine lead wire would probably be more desirable, since its specific resistance is much higher, it is entirely nonmagnetic, and it would be very easily formed in spirals.

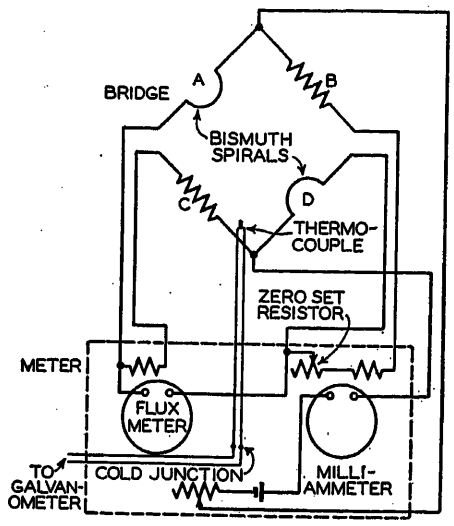



**Fig. 2. Wiring diagram for magnetic flux bridge**

The several spirals were wound separately, and each was wound noninductive. The 2 spirals of bismuth were placed between those of nickel. With this arrangement quick changes in temperature often result in uneven heating of the various spirals, and thus a temporary shift of the zero. This could be greatly reduced by interwinding the turns of bismuth and its balancing spiral.

Figure 7 shows curves of several of the tests made in studying the zero drift and in correcting it. From the great amount of data taken before the zero drift was corrected the conclusion was evident that this tendency for the zero to shift caused no noticeable error in the measurements, provided the meter was carefully set on zero before the reading, and was checked again after it. The chief difficulty arose when the zero was set in a region of zero field and then the bridge was placed near some metal whose lower or higher temperature would slowly alter the temperature of the bridge.

A third problem presents itself when the temperature of the bridge varies any considerable amount from that at which the bridge is calibrated. A study of the curves in figure 5 will show that when great difference in temperature is involved some corrections must be made, if any great accuracy is desired. In order to determine the variation to be expected in the bridge readings, a small thermocouple was built into the bridge, with the one junction placed between turns, as far into the bismuth spiral as possible. The other junction was carried back into the meter case where a thermometer could be placed in contact with it. The thermocouple was then calibrated for the difference in temperature between these junctions, and it proved to be very sensitive and very accurate. The galvanometer used was external to the meter, though the galvanometer could be built in as an integral part of the meter.

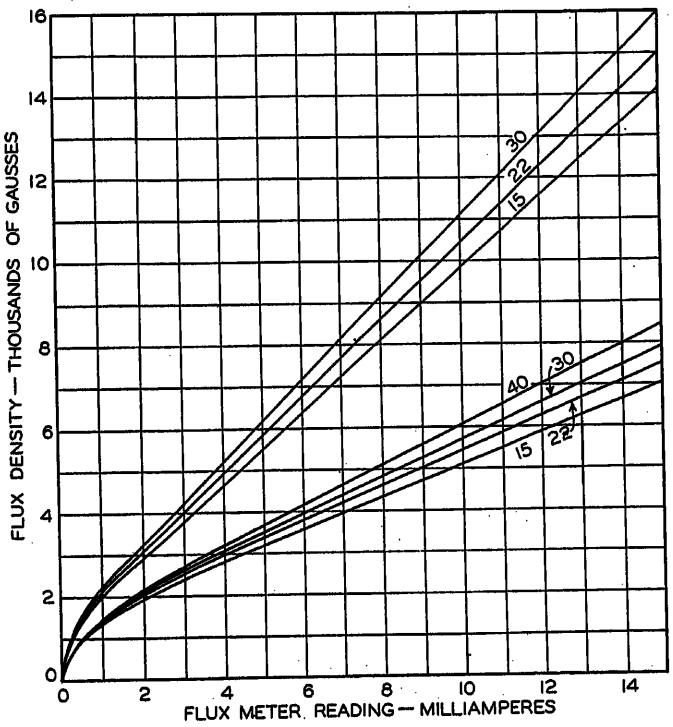



**Fig. 3. Calibration of magnetic flux bridge**

Using a model 280 Weston 1.5-milliampere d-c meter having 27 ohms resistance as flux meter
Bridge current 21.3 milliamperes for 0–7,500-gauss range; 9.8 milliamperes for 0–15,000-gauss range
Bismuth arms at 23.7 degrees centigrade—28.21 and 28.25 ohms
Nickel arms at 23.7 degrees centigrade—21.80 and 21.78 ohms
Manganin wire in meter case used for remainder of nickel arm balancing resistances
Numbers on curves are temperatures in degrees centigrade

Figure 3 shows such calibrations for several temperatures. The flux meter itself could be calibrated for the usual temperature at which it would be used, say 22 degrees centigrade, and curves could be supplied for enough temperature points above or below so that the reading could easily be interpolated for any temperature within this range.

A mathematical study of the resulting unbalance was made by assuming varying resistance values in the arms and varying currents supplied to the bridge. The wiring diagram is given in figure 8, and symbols are indicated for each of the values. The general equation for the unbalanced current in the flux meter in terms of the resistance in the arms, the flux meter resistance, and current supplied to the bridge, is

$$I_M = I_B \frac{R_4R_1 - R_3R_2}{R_1R_3+R_2R_3+R_3R_4+R_4R_1+R_1R_M+R_2R_M+R_3R_M+R_4R_M}$$

In the construction of the bridge the resistances of the 4 arms are made so nearly equal at zero flux that they may be considered equal. If then $x$ be substituted to represent the resistance of each of the 2 bismuth arms, and if $y$ be substituted to represent the resistance of each of the constant arms, the equation simplifies to

$$I_M = I_B \frac{x - y}{x + y + 2R_M}$$

For this study the bridge was assumed to be unbalanced by a flux which increased the resistance of the bismuth arms 50 per cent. Assuming the supply current to the bridge as constant, the equation was solved for varying values of arm resistance from 5 to 100 ohms and for $R_M$ values of 10 ohms and 27 ohms. The results are shown in curves $A$ and $B$, figure 8.

However, in the operation of a bridge too much heating would result if the same $I_B$ values are kept for the higher resistances, unless the size and thus the heat-dissipating capacity are altered accordingly. A second set of computations was made assuming the heat loss as constant, and thus the $I_B$ will be greater than 20 milliamperes for low arm resistances and less than that for high arm resistances. Curves $E$ and $F$ were calculated assuming a heating loss of 0.0112 watt. This was the loss allowed in the meter built, and also the resulting loss in curves $A$ and $B$ when the arm resistance was assumed to be 28 ohms.

Curves $C$ and $D$ assumed half this loss, or 0.0063 watt; curves $G$ and $H$ assumed double the loss, or 0.0252 watt.

Evidently little is to be gained by using an arm resistance more than 2 or 3 times the flux-meter resistance, even if the bridge current is kept constant for all values. As is also evident from curves $C$ to $H$, with a constant loss the arm resistance should be about equal to the flux-meter

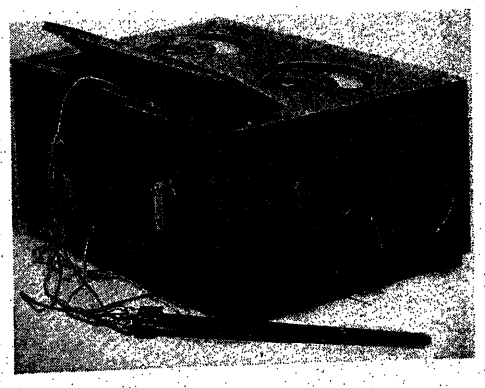


**Fig. 4. Magnetic flux meter**

resistance. Thus a desirable flux meter will have a resistance as small as possible, providing it is at the same time sufficiently sensitive. With such a meter, a bridge can be made which will be both sensitive and very small in size. Such a bridge would be well adapted to measure fields of rather small dimensions, and would give more accurate results in nonuniform fields. Since flashlight batteries would commonly be used as the source of voltage in the bridge, the current value should be kept as low as possible to give the results desired. Also 2 bridges might be used with the same meter: one with very small total area, wound of small diameter wire, the other with heavier wire and thus a much larger total area. The diameter of such a small bridge might be limited to 5 millimeters or less; that of the larger one might be 25 millimeters or more. The former would take less current, would be less sensitive, but could be used in very small field areas. The latter could be made very sensitive by using a large bridge current, but its use would be limited to uniform fields of much larger areas.

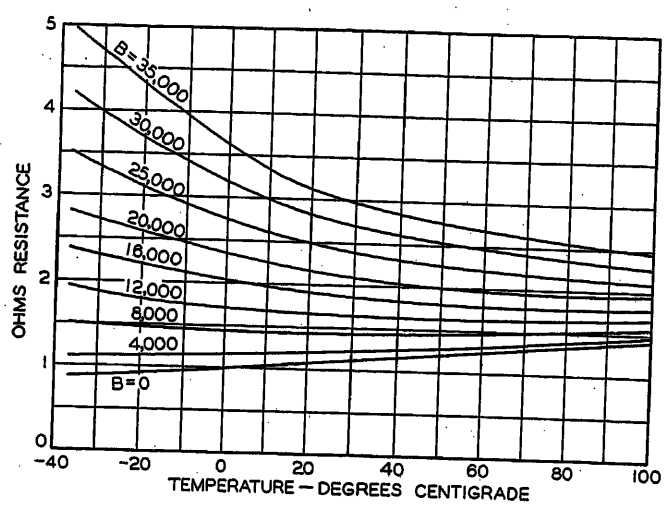



**Fig. 5. Variation of bismuth resistance with temperature at various flux densities**

Using a resistance of one ohm at zero degrees centigrade and zero flux density (from Smithsonian tables)

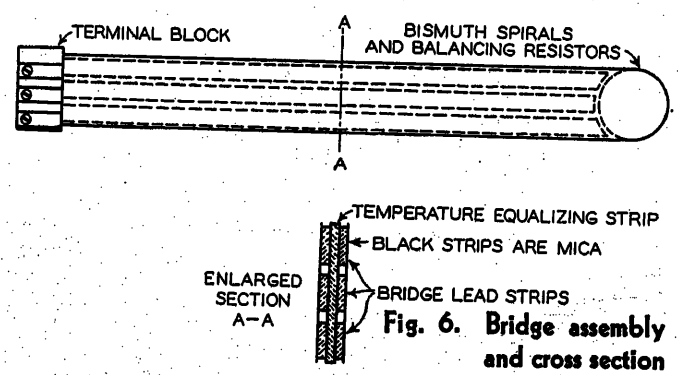
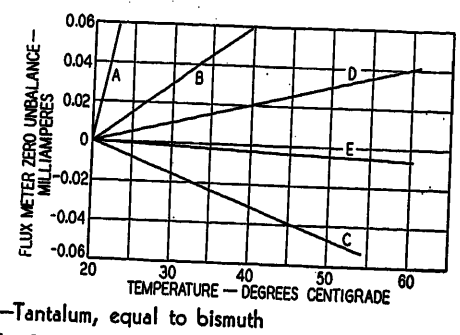



**Fig. 6. Bridge assembly and cross section**

A given meter may be calibrated to be used for a wide range of measurements. For the calibrations shown in figure 3, the range of the instrument was doubled by a reduction in the current supplied to the bridge. In a similar manner the range could be still further increased to a maximum as high as is desired. However, to obtain a lower range with the same bridge, either a greater bridge current must be used, or a flux meter of the same or greater sensitivity but with lower resistance.

The same bridge used for the curves in figure 3 had a full scale range of approximately 2,000 gausses when used with a Weston model 322 meter, having a resistance of 18.4 ohms and a full scale reading of 0.1 milliampere. By increasing the current to the bridge from 21.3 to 30 milliamperes the full scale range was further reduced to approximately 1,700 gausses.

**Fig. 7. Zero drift with temperature change**




Type and value of balance arm resistors:

*A*—Manganin, equal to bismuth

*B*—Tantalum, equal to bismuth

*C*—Copper, equal to bismuth

*D*—Nickel, approximately 18 ohms each

*E*—Nickel, approximately 22 ohms each

The final balance was too near zero to be shown on curves

Some work was done in determining the amount of current which could be used before the heating is noticeable or dangerous. A piece of the 0.17-millimeter bismuth wire was soldered to light copper leads, and was formed into a small loop with a thermocouple inside the loop. The whole was cemented between thin mica sheets. The results showed that up to 50 milliamperes no appreciable temperature rise was noticed, and that at 75 milliamperes the temperature increased only about 2 degrees centigrade above a room temperature of about 21 degrees centigrade. The current was increased to 800 milliamperes; after about 20 minutes the wire was very hot, but still was in no danger of melting or burning out. In operating the bridge at 20 milliamperes no noticeable temperature rise takes place, and possibly higher currents could be very safely used.

For calibration purposes an electromagnet was built to give a flux density of at least 20,000 gausses between the parallel circular pole pieces, 3.8 centimeters in diameter, when the air gap between them is set at 5 millimeters. From this diameter the pole pieces taper outward at the Ewing optimum angle of 51 degrees to a final diameter of 7.6 centimeters. This setting results in a very uniform air-gap flux between the parallel faces. A one-turn search coil 2.9 centimeters in diameter is hinged on an arm and, by means of a catch, is held well within the uniform portion of the field. Beside it may be placed other measuring devices for comparison or calibration. Upon release of the arm, the search coil is automatically swung out into

**Fig. 8. Bridge sensitivity curves**

Variation of $I_M$ with varying resistance in the bridge arms

$R_M$ = 10 ohms for all full-line curves

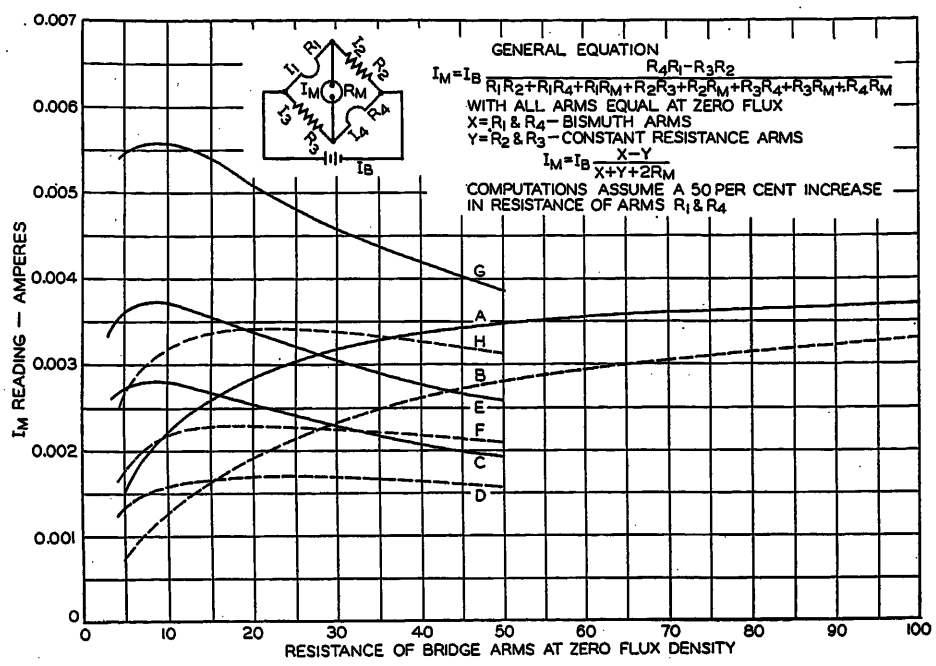
$R_M$ = 27 ohms for all dashed-line curves

For curves *A* and *B*, $I_B$ was assumed constant at 0.02 ampere for all values of resistance. The $I_B$ current values for the other curves were computed to maintain the $RI$ constant

Curves *C* and *D*—$RI_B^2$ = 0.0063 watt

Curves *E* and *F*—$RI_B^2$ = 0.0112 watt

Curves *G* and *H*—$RI_B^2$ = 0.0252 watt




a zero-flux field by means of a spring, and the impulse due to the induced voltage is read on a ballistic galvanometer.

To calibrate the galvanometer, a standard solenoid was very carefully constructed with length 174 centimeters and diameter 7.9 centimeters, giving a ratio of length to diameter of 22 to 1. The calibration constant of the galvanometer and search coil obtained by means of the standard solenoid was 1,844 gausses per unit deflection on the galvanometer. This appeared to be fairly constant for deflections up to 4 or 5 units, but decreased by small measurable amounts at the higher values.

A calibrated bismuth spiral just received from Germany was used as a check on the ballistic method. Table I gives the results of a very careful check made between the 2 methods.

The lowest flux-density value results in a constant slightly over 2 per cent greater than the calculated one; values at the higher densities more nearly check the calculated values. As appears in table I and as was previously mentioned, the constant becomes smaller at the higher galvanometer deflections. As a compromise between the 2 methods, a curve was plotted of constants against galvanometer deflections, the values of which were taken as a reasonable mean between the 2 methods.

A considerable number of calibration data were obtained on the various bridges tried, under various temperatures and other conditions. Unusual care was taken in obtaining the curves shown in figure 3. Several check curves were taken at 22 and 30 degrees centigrade, some by means of the German spiral only and others by means of the galvanometer. Very few of the points thus obtained varied more than 1.5 per cent of full scale value above or below the mean curves, and most of the values fell on or very near the curves shown. From all the experience gained in the use of the bridge the conclusion seems reasonable that the meter will duplicate its readings to a greater degree of accuracy than can be expected from the usual calibrating apparatus, which probably ranges close to 2 per cent.

A summary of the advantages and disadvantages of the meter—most of which have been indicated in this discussion—makes evident that by the use of 2 bismuth elements instead of one, the indication for a given flux density value is very greatly increased, and that it arrives at its final value almost as soon as the element is placed in the field, remains constant if the field is constant, or varies with the field if the change is not too rapid for the meters to follow. If the various arms of the bridge are so constructed that the changes due to temperature are similar in each, small temperature changes, so troublesome with a single spiral, are entirely, or almost entirely, obviated. A single bridge and meter may be calibrated for a very wide range of flux densities, from the lowest the meter-and-bridge combination will give to the highest desired. By including more than one bridge with the same meter, the combination can be adapted for measurements in very small areas, as well as for larger areas of comparatively low densities. Probably the greatest disadvantage of the meter is the change in the indication for a given flux density when the bismuth temperature is changed either above or below that at which the meter is calibrated. Where great accuracy is desired readings must be corrected

**Table I**

| Flux Density by Bismuth Spiral | Galvanometer Deflection by Search Coil | Resulting Galvanometer Search Coil Constant |
|---|---|---|
| 2,490 | 1.32 | 1,885 |
| 7,500 | 4.00 | 1,874 |
| 10,270 | 5.55 | 1,850 |
| 11,300 | 6.14 | 1,843 |
| 14,500 | 7.83 | 1,851 |

(*Concluded on page 475–6*)

# A Suggested Course on Industrial Economics and Business Methods

By R. E. HELLMUND
FELLOW AIEE

## Synopsis

IN VIEW of the frequent criticism of engineers to the effect that they do not pay sufficient attention to economic and business factors, a brief review of the present activities of engineers is given. It is pointed out that they are extensively and successfully handling economic problems relating directly to their specific line of work but that they are inclined to overlook other economic and business factors equally important but somewhat removed from their daily tasks. In order to stimulate the interest of the younger engineers in economics and to give them a broader viewpoint of the business enterprises in which they will be engaged, a brief but fairly comprehensive course on "industrial economics and business methods" is advocated to be given in preference to some of the highly specialized technical courses now forming part of the undergraduate curricula. The paper outlines the type of subjects which seem suitable for this course and further recommends that analytical methods of attack be employed to a greater extent than is now customary in economic studies.

The general criticism of engineers during recent years to the effect that they have not paid sufficient attention to economic and business factors surrounding their work is a challenge to the engineering profession. This criticism has almost created an impression that economic considerations are more or less foreign to practicing engineers. However, even a cursory examination of actual conditions shows that this is far from the truth. An industrial plant engineer, for example, when considering the installation of a power plant, will make very extensive and detailed economic calculations covering various plans. His studies probably would include a comparison of the economic merits of power purchased from a public utility and that generated in a privately owned plant, as without this information it is not likely that any management would appropriate funds for the undertaking. In fact, an appreciable part of the time of most plant engineers who deal with the purchase and installation of any equipment is devoted to economic studies of some kind or other. If we now turn to the design engineer, we find that he too spends a large part of his time in working out the most economic designs and in analyzing items affecting costs. A designer of household refrigerators, for instance, would not hold his position very long if he did not devote a great deal of his time to economies in design. When it is considered that with the quantities produced by some manufacturers a one-cent saving on each unit means an annual saving of $1,000 to $4,000, the need for this is obvious. Similarly, the manufacturing engineer tries continually to find ways and means for reducing manufacturing costs and in so doing makes numerous comparative economic studies. The utility engineer, in considering the extension of a distribution line to reach new customers, will as a matter of course make calculations to see whether the extension is justified from an economic point of view. In general, the time of most engineers is taken up to a great extent with economic considerations, and the majority of engineers have furthermore proved well able to cope with problems and calculations of this nature. The analytical methods required for this purpose are much simpler from a theoretical point of view than many other problems that engineers have to solve in their daily work.

Nevertheless I am in accord with those who feel that engineers should interest themselves to a greater extent in economic factors, and the suggestion frequently offered that the curricula of engineering schools be modified to bring this subject to the foreground seems a step in the right direction. Engineers who successfully handle certain economic problems too often entirely overlook other economic and business aspects, or at least do not sufficiently appreciate their importance. It is not at all uncommon to find designers who spend much of their time in devising machines that can be economically built and operated advocating commercial or engineering ventures which as a whole are economically unsound. As an illustration: In these days when air conditioning is receiving wide attention, endless schemes which could not possibly be commercialized within a reasonable period of time are being proposed by serious and capable engineers. Proposals are being made, for instance, to install internal combustion engines in homes or small commercial establishments for the purpose of furnishing both heat and electric power, and extensive studies are being made to improve the thermal and electric efficiencies of these arrangements. At the same time, the fact that this apparatus at present cannot be manufactured, marketed, and installed under a cost of several thousand dollars is being entirely overlooked. This in turn means that the interest on the investment and the allowance for depreciation and maintenance would about equal the cost at which these services can now be obtained more conveniently by using one of the existing methods of heating and by buying power from a public utility. The proponents of

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1. For all numbered references see list at end of paper.

these arrangements will at times give consideration to the cost of the production of the equipment but will often entirely ignore the expense involved for sales effort, warehousing, shipping, installation, and servicing of the equipment. If this is brought to their attention, they will pass it over by stating that the distribution costs can be held low and they seem to have no appreciation of the fact that the reduction of these expenses is more difficult than the reduction of manufacturing and other more tangible factors of expense.

Similarly, the engineer who purchases equipment often acts contrary to sound economic laws by ordering special apparatus when standard apparatus would be satisfactory and more economical. The sales engineer in his eagerness to secure business will agree to furnish specials when it is obvious that this means additional expense to the manufacturer and that in the long run these expenses will be passed on to the purchaser. This practice of increasing the manufacturing cost is frequently followed by engineers who will on the other hand go into the most minute details in calculating economies in their own part of the undertaking.

This inclination on the part of the engineer to study economic factors having a direct bearing on his own work and to pay so little attention to other equally important ones entering into an enterprise is, of course, not greatly different from that found in other forms of human endeavor. It is a common failing of human nature to give undue emphasis to factors of direct and immediate interest and to overlook others of equal or even greater importance. The most natural way of eliminating this shortcoming would seem to be to give the engineer a broader point of view of industrial economics during his early education. Some schools have departments for industrial engineering in which courses relating directly or indirectly to specific phases of industrial economics are given. The titles of some of these courses indicate a rather broad study, but they are often found to be limited in scope. Nevertheless, industrial engineering students whose programs include a number of these specific courses may carry away with them a reasonably broad conception of the important factors entering into industrial economics. A review of the curricula of other engineering departments, such as the electrical, mechanical, and civil engineering, indicates that but one or 2 courses relating to a more or less specific phase of industrial economics are listed as electives, and that in a few isolated cases one or the other of these courses is compulsory. This practice, however, falls short of the previously indicated need for giving the student a broad point of view in industrial economics. In order to satisfy this need, a fairly comprehensive course on "industrial economics and business methods," relating primarily to the problem of the supply and use of manufactured goods or articles, should be given to students of electrical, mechanical, and chemical engineering. This course may also be helpful to students of civil engineering, although the interest of civil engineers is more or less confined to the use of manufactured goods and problems relating to their production are of less importance to them. It is evident that a course of this nature cannot possibly cover all phases of economics, nor can it treat any phase in detail because of the endless variety of economic problems arising in industry. Nevertheless it is believed that in a 2-hour course carried through 2 semesters, many important subjects can be covered and the student given a fairly broad perspective. An attempt will be made here to outline such a course and to indicate the type of economic studies that seem desirable as a part thereof. Frequent reference will be made to publications and textbooks containing material that seems to be suitable for supplementing the brief remarks and principles stated in the following.

The essential factors of industrial economics include:

*Supplying* goods
- Direct labor
- Works overhead
- Materials
- Test and inspection
- Design, engineering development, dies, and fixtures
- Storage, distribution, and servicing
- Installation

*Using* goods
- Interest charges on investments
- Depreciation
- Operating expenses
- Maintenance expenses
- Scrap value

Factors of interest to both *supplier and user*
- Statistical methods
- Standardization
- Organization
- Personnel questions, etc.

Problems relating to the *over-all operating results* of the individual economic units
- Price limitations
- Business volume
- Expense control
- Budgeting, etc.

## A. Economics of Using Goods

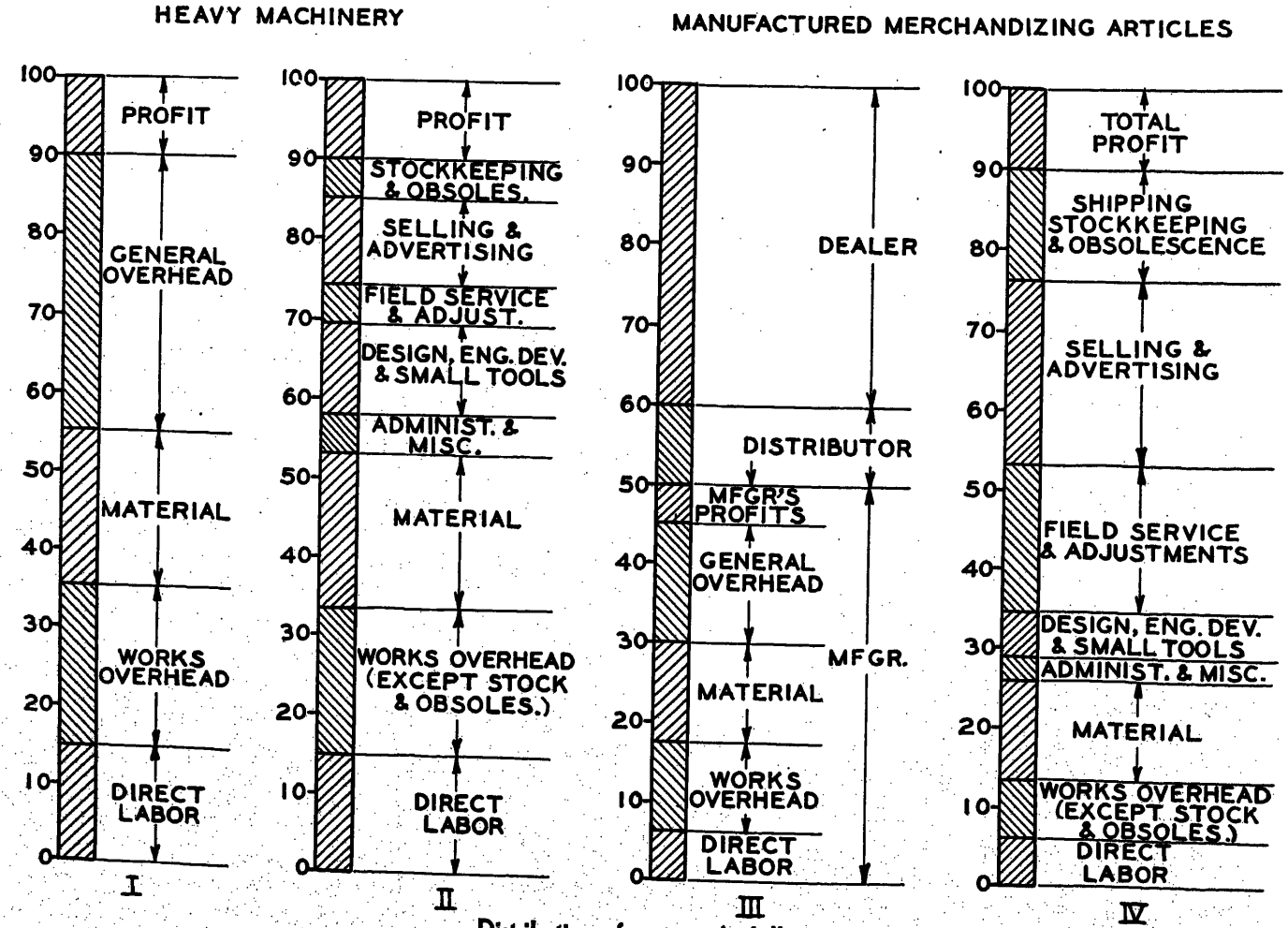
Although, chronologically, the supplying of goods precedes the use of them, the supplier should give consideration first to their use. Goods are created for some use or other and only those goods which accomplish their intended purpose in the most economical manner are worth creating and marketing. The user of goods is, of course, interested primarily in this phase of economics. Often his problem is to determine whether goods purchased for a given purpose represent an economic undertaking on his part, and he should in all cases select from a number of possible choices the goods that will most economically serve his specific purpose, regardless of whether a business problem or his personal comfort or pleasure is involved. The basic principles governing these considerations are well set forth in available textbooks and therefore need not be covered here in detail. (See references 1 and 2; an abbreviated version giving the essentials presented in chapters 1 to 10 of reference 1 seems well suited for presenting this material. See also chapter 2 of reference 27 for a brief treatment of the subject.) The considerations of the user relate in the majority of cases either to

but one or to a limited number of specific applications, but the supplier's problem is much more complex. He is often confronted with the necessity of considering a great many uses of a proposed article of manufacture under various conditions of application and as affected by many economic factors. It is necessary for him to make a rather complete market analysis in order that he may supply goods which will be applicable by many users and which can therefore be manufactured in quantities sufficiently large for successful commercial exploitation. The manufacturer's point of view and methods of analysis are covered in some of the available textbooks. (See in particular reference 14, chapter 4. The considerations given in this reference apply essentially to equipment used in industry but the fundamentals apply equally well to manufactured goods of the so-called "merchandising" type used by the public at large.)

## B. Economics of Supplying Goods

### 1. Cost and Expense Factors

In a study of the economics of supplying goods, the cost factors entering into the manufacture of industrial goods should be briefly reviewed. (See, for example, chapter 7 of reference 3.) However, the distribution of goods also is very important from an economic viewpoint and the discussion should be extended to cover this phase as well. Graph I shows the cost distribution as it may apply to the manufacture and marketing of a heavy piece of machinery. This graph is in accordance with the customary accounting practice but gives only the major divisions, showing the 3 major cost factors relating to works production and giving as a single item all other factors entering into the total cost to the manufacturer under the assumption that he sells directly to the ultimate user. In graph II, the items given as "general overhead" in graph I are further subdivided, and the expense for stocking and obsolescence of stock usually involved in the handling of certain part stocks in the works organization is combined with the other expenses for stocking and obsolescence. The principal purpose of showing the expense in this manner is to stress the fact that there are, in addition to the usual manufacturing activities in industry, a number of other very definite and unavoidable functions presenting economic problems of great practical importance. Graph III shows the segregation of expenses as they quite commonly apply to merchandising articles, which require the service of distributors and dealers in addition to the function of the manufacturer in order to meet the demands of a broad market. With articles like this, certain selling and advertising expenses may be encountered by the manufacturer, distributor, and dealer, and therefore graph IV has




Distribution of customer's dollar

been drawn combining these expenses as a single item; shipping, stocking, and obsolescence as another; and field servicing and adjustment expenses as a third. This again shows that expense items other than those for manufacturing are of even greater importance than those shown in graph II. Because of the difficulty in obtaining accurate data from all 3 parties involved, no claim can be made for the accuracy of the proportions shown; however, it is believed that they are nearly correct for certain merchandising articles. These graphs are given because no suitable references could be found elsewhere.

Each of the items shown in graphs II and IV involves a number of further subdivisions, each having its own economic aspects, and it is obviously impossible to discuss all of them in a brief course. However, it seems desirable to exemplify the general principles involved by an analysis of some of the more important subdivisions and merely to mention some of the other problems of an economic nature.

## 2. Direct Labor

In the labor item, rate setting for the shop personnel is one of the most important factors subject to economic study. A great deal has been written about this (references 4, 5, and 6) and excellent results are now being obtained in this work. This subject should be covered briefly in the course (see reference 4, chapters 16 and 17). Closely tied in with the subject of rate setting is that of incentives (briefly covered in reference 4, chapter 39; see also reference 27, chapter 21). In this connection, the economic influence which incentives for speed may have upon quality and the consequent need for additional inspection and field adjustment expense, should be carefully considered. In the labor study, certain relations between production factors and the law of diminishing returns are of practical importance (chapter 8, reference 3) and may be discussed here although the broad principle applies to many activities. Another item of importance in labor costs is the determination of lot sizes giving the most economic results (reference 7). Consideration of suitable methods and equipment for all manufacturing operations and the economics of handling parts and complete pieces of apparatus in their flow from one manufacturing operation to another (reference 27, chapters 13 and 14), as well as comparisons of the merits of centralization and decentralization of some maufacturing operations (reference 24), are all essential in studies of labor expense.

## 3. Works Overhead

Equipment for manufacturing purposes represents an important item affecting works overhead. A plant engineer in considering the installation of equipment for manufacturing operations usually acts as the user of products manufactured by others and he thus makes use of methods previously referred to in the "Economics of Using Goods." In addition, he must of course compare the overhead expense caused by different types of equipment with the savings in labor costs that can be realized with each type. (See reference 27, chapter 8.) These calculations, which must allow for such factors as interest, depreciation, maintenance, cost of power, replacement, etc., are usually specific for each case, but there are basic principles which apply to all of them. (See references 1 and 8; also chapters 9, 10, 11, and 12 of reference 27.) New manufacturing equipment is an item in works overhead which must be taken into account at rather frequent intervals. There are also many other items, such as depreciation in buildings, insurance, lighting, cleaning, supervision, which require analysis less frequently but which must be reviewed at the proper time. As an example, the construction of a plant and its best geographical location involve a great many economical problems, some of which have an important bearing on works overhead expenses (reference 27, chapter 3).

## 4. Material Costs

The material content of any manufactured article is essentially a question of design, with problems more or less specific to each case. However, important general economic considerations enter into this, such as methods of standardizing and stocking raw materials which will make available a sufficient variety of materials to permit satisfactory and economical design and at the same time limit and rationalize available types and sizes of materials. This is of prime importance in reducing expenses for storage and investment and makes possible the purchase of material in large quantities, with corresponding reduction in price. (See reference 9; also chapters 6 and 7 of reference 27.) The purchase of material again involves numerous economic considerations. The methods of purchasing and the underlying basic principles represent an extensive study in themselves; only a brief reference to some of the basic considerations seems justified. (See second half of chapter 6, reference 27; for additional material see reference 22, chapters 1 and 2, and possibly reference 23, chapters 8 and 9.)

## 5. Test and Inspection

Proper inspection and testing methods for manufactured articles and parts require detailed study and are referred to separately because the expense for these activities is at times considered part of the labor cost, at times part of the cost of materials, and in other cases as a works overhead item. It is evident that articles should not be marketed without assurance, through inspection and test, of satisfactory field service in the majority of cases. Any appreciable amount of difficulty in the field will lead to uneconomical results through field expense and adjustment and the loss of the goodwill of the customer and, as a consequence, to increased sales resistance and sales expense. On the other hand, a method of inspection and testing giving 100 per cent satisfaction in the field may prove so costly as to be uneconomical from an all-round point of view. It is therefore highly desirable to devise inspection methods which strike the proper balance between the 2 extremes. Through the proper utilization of statistical data, a good deal has been done recently to put inspection activities on a more or less scientific basis and a brief study of material of this nature as part of a course on economics seems desirable. (See references 10 and 11.) While in-

spection activities are usually associated with the manufacture of goods, suitable methods are also of value to the users, who quite frequently find it expedient to undertake inspection and check tests of their own.

### 6. Design, Engineering Development, Dies and Fixtures

It is obvious that many economic considerations enter into design and engineering development activities. It has always been the major activity of the design engineer to develop apparatus which not only is effective and economical for the intended purpose but which also, through minimum expense for labor and material, can be produced cheaply. Apparatus must also be designed so that it requires the minimum expense for shop equipment and consequently low works overhead. The considerations vary to a great extent with the type of apparatus involved and can hardly be made the subject of a general study. However, a general activity which is becoming of increasing importance in economical design is that of carefully planning the design of an entire line of apparatus with all anticipated variations. With the continually increasing variety of sizes and ratings required, the multitude of service conditions to be met, and many other factors adding to the complexity of the problem as a whole, this procedure is essential. Not so long ago it was customary to design more or less independently the various sizes of a line of apparatus to meet the usual and standard requirements and subsequently to modify such designs to meet special requirements. This method of attack may still be satisfactory in cases where one type of design and possibly a few sizes or ratings represent the major part of the entire demand and where special requirements are the exception rather than the rule. In these cases, consideration of the standard variety should predominate and the few exceptions can be made the subject of secondary consideration. However, in the majority of cases such conditions no longer apply and a much better method of attack consists in designing a line of standard parts which are flexible in their use and permit the assembly of the many varieties demanded by the market. In planning a line of parts, a great deal of attention must be given to the simplification of stocking and routing of the parts so as to permit quick delivery of almost any reasonable combination and to the possibility of combining parts readily in a number of assembly plants or in the field, as the case may be. The necessity for meeting the more complex present-day problems should be recognized to an increasing extent by the designer. With the proper appreciation of this, it will usually be found possible through the choice of a rational line of parts of evenly spaced dimensions or characteristics to realize the most economical production of an entire line of apparatus with all reasonable variations rather than the production of a few so-called "standard assemblies" at a minimum cost. This can best be illustrated to the student by a few examples of specific apparatus designed in accordance with the principles previously mentioned (references 12 and 13).

Closely tied in with the development and design of a line of apparatus and usually considered as part of the development cost are the tools, such as dies, fixtures, molds, etc., needed for manufacturing the specific line as distinguished from the general-purpose tools. The expense for these tools can also be materially influenced by the planning of the entire line (see reference 27, chapter 12). Numerous problems arise in the planning of tools best suited to and most economical with the anticipated volume of manufacture, life of the design, interchangeability of parts, etc. As part of all development activities, it is very essential to determine whether the development costs can be recovered within a reasonable period from the sale of the device, the estimated sales volume being based upon previous experience or on a recent market analysis. The engineer's own work must, of course, be so planned that it can be carried on economically, and in addition to the design work, economic methods of making estimates in answer to customers' inquiries must be worked out. It is often difficult to decide whether this work should be carried on more or less completely for each individual project as it comes up or whether it is more economical to prepare extensive data which will facilitate the work in general and reduce the expense for estimating on the individual inquiries. (For additional discussion on estimating, see reference 27, chapter 5.) As part of the estimating and bidding on special apparatus, it is frequently necessary to decide whether it is more economical to accept orders involving highly specialized requirements or to forego such business. Although the decision in these cases is frequently influenced by competitors' practices, a good fundamental rule for the engineer to follow is to assume a sympathetic attitude toward those requirements for which there is economic justification or a real need and which therefore warrant a price sufficiently high to cover at least part of the extra costs of development or manufacture. (For additional discussion on engineering work, see reference 27, chapter 4.) Industrial research can be considered as part of engineering and it also has its economical aspects (see reference 27, chapter 16). However, as it is usually difficult to find a definite measure for the benefits derived from research work, it is not easy to determine just how much an industrial enterprise can afford to appropriate for this purpose.

### 7. Storage, Distribution, and Servicing

The economic problems relating to marketing and its subdivisions, such as selling and advertising, shipping, stocking, and obsolescence, installation and field service and adjustments, are often less tangible and therefore more complex and difficult than those previously discussed. This is no doubt one of the reasons why they have been subject to less analytical treatment, as a result of which less progress has been made in finding economic solutions for the many problems and in the reduction of the high costs of distribution. This, however, only emphasizes the importance of these problems and the advisability of giving them an appreciable amount of time in a comprehensive course on economics, which is further supported by the fact that a large percentage of engineering graduates take up this work after entering industry. Although there is a good deal of literature available on

the marketing of so-called "merchandise" and various business courses given at the colleges treat this subject extensively, comparatively little has been written regarding the marketing of industrial goods. However, a few good books covering this subject have been published recently and liberal use should be made of their contents in bringing before the engineering student the importance of marketing problems relating to equipment originated by engineers. (See references 14, 15, and 16; in particular, chapters 5, 6, 8, and 9 of reference 14 and chapter 2 of reference 16; also chapter 17 of reference 27.) The references given relate to the marketing of industrial equipment to industry, but it seems that there is practically nothing available on the marketing of highly technical industrial goods, such as refrigerators and electrical heating devices, to the public, though the problems in connection with this activity are becoming of increasing importance. It is evident that the methods of marketing these articles to the public differ greatly from the marketing of regular consumption merchandise, such as food, articles of apparel, and the like, and that they therefore deserve separate and thorough consideration.

In the sale of industrial products, which activity in the case of industrial products is carried on principally by engineering graduates, the success of the sales engineer depends to a great extent upon his ability to analyze his customers' problems properly from an economic point of view. It is therefore essential that he be familiar with a great many of the factors and methods of analysis outlined for the proposed course.

### 8. Installation

The installation and also the proper application of industrial products may in many cases be a major, or at least an appreciable item of expense. This expense will be incurred by the manufacturer, distributor, dealer, contractor, or user. Important economic problems may be involved but these are so varied and numerous that it is difficult to outline even the more important considerations in the brief course under discussion.

## C. Interrelation of Economic Factors

The divisions given in the graphs and discussed in the foregoing, as well as the divisions of most accounting practices and systems, represent an attempt to segregate various major types of costs or expenses and to place the responsibility for these various expenses upon the different departments of an industrial organization, such as the works, engineering, sales, and executive departments. However, these purposes are accomplished only to a limited extent, and it moreover appears to be practically impossible to devise any system which permits even an approach to a clean-cut division of responsibility among the various functional divisions of an organization. It is true that items such as labor, material, and works overhead are usually considered the major responsibility of the works organization, but the previous discussion indicates quite clearly that these items are about equally dependent on the activities of the design engineers. (Additional evidence supporting this can be found in reference 17, for instance, or reference 27, pages 52 to 58.) Similarly it can be shown that the engineering department's work appreciably influences the economic factors relating to marketing. The engineer's success in meeting, or his failure to meet, the requirements of the market and in designing for sales appeal will greatly influence the market acceptance or the sales resistance encountered and consequently will materially affect the sales expense and also the volume of sales. The latter, in turn, will indirectly influence the cost of production and so forth. The engineer also influences to a marked degree expenses for field service, field adjustments, and installation. Finally, the engineer, particularly in his ability to design parts and devices permitting flexibility of assembly and application, may affect expense for stocking, shipping, etc., appreciably and also the possibility of quick deliveries, which will directly affect sales volume and, indirectly, various production cost factors. There are few economic factors in industrial activities which are not influenced to some degree by the design and development engineer. The same holds true of the activities of the works organization. Faulty workmanship or material will result in expenses for field adjustments and will increase sales resistance and other unfavorable influences; similarly, inability to make quick deliveries because of some shortcoming of the works organization will bring with it unfavorable economic results. The sales organization in turn can materially increase engineering and development expenses by requesting estimating when there is no reasonable prospect of obtaining orders, or by accepting orders for special apparatus when standards might be sold. Examples of the influence of the activities of one division upon the economic operation of other divisions could be cited almost indefinitely. This very condition, which is practically unavoidable in modern organizations with functional activities, makes a comprehensive course on industrial economics and business methods highly desirable in an engineering curriculum. As pointed out in the beginning of the paper, almost any department can handle its own major economic problems satisfactorily, but much improvement seems possible through appreciation by any one department of the effect of its activities upon the economies of other departments.

## D. Miscellaneous Factors of Economic Importance

In addition to the activities discussed, there are a number of others the responsibility for which it is difficult to place with any one division of an organization. In these cases, results can be obtained only through the cooperation of several divisions, or perhaps even though the co-operative action of persons throughout the entire industry. Under these conditions, it is of course difficult to work out an economic solution of the problem at hand. The most outstanding item of this nature is standardization, and no course in industrial economics can be considered complete if it does not devote appreciable time to the economic possibilities of proper standardization. Not

only should the value of standardization be pointed out (see reference 3, chapter 9), but methods facilitating standardization also should be given, such as the use of simplified practice and the application of preferred numbers (references 18 and 19; also chapter 15 of reference 27). An essential step in standardization frequently consists in the choice of proper standard sizes and ratings with satisfactory steps between. This is very important from an economic viewpoint (reference 20 or 21). Some problems involved in standardization have been previously referred to in the discussion of the standardization of materials (reference 9) and the standardization and design of parts permitting flexible assembly (references 12 and 13).

Another factor which is of economic importance and which cannot be handled by the individual units is that of organization and the proper correlation of the various units to facilitate the work. The course, therefore, might make reference to different types of organization (reference 3, chapter 11). Unfortunately various treatments on organization in available textbooks are merely of a descriptive nature and some authors of articles or papers are prone to advocate in a controversial manner organizations of some particular type. In considering various types of organization, it is essential to recognize that any one of them may result in the best economic results under certain conditions, and, furthermore, that within the larger industrial organizations nearly all types of organization can be used to advantage for different activities and at different levels of the organization. For example a large company may be divided into various units, each producing a certain line of products while within each unit the organization may be along functional lines. In addition, it may be and usually is advisable to have a staff for co-ordinating certain functional activities of the various units as well as certain centralized functional activities. It is most essential that any treatise on organization should give, in addition to a description of the various types, some consideration to the factors influencing the choice of one rather than the other type of organization for any set of conditions.

Other activities usually not associated with economics nevertheless have economic aspects which may be pointed out briefly. Examples are: personnel questions, educational and training activities, and even social and welfare arrangements. (See chapter 20 of reference 27, also chapters 13 and 19 of reference 25 or chapters 14, 17, and 20 of reference 26.) The expenditure for educational activities, for instance, should be in keeping with the subsequent savings derived from having the work performed by a personnel which has benefited from such education.

## E. Analytical and Mathematical Treatment of Economic Studies

In reviewing material available on industrial economics, it has been observed that too much of it is of a descriptive nature and that there has not been much attempt to attack the problems in an analytical manner. As just indicated, the treatments of organization, for instance, are frequently descriptive or of a controversial nature and lack the objective and analytical point of view which the engineer should have in all of his work. In many instances it is quite possible to attack a problem by mathematical methods, and this is advisable even though a complete mathematical solution is not possible. Frequently even a partial mathematical solution establishes certain facts, which with the use of good judgment regarding other factors is much more likely to give better results than relying entirely on judgment. (For examples of this see references 7 and 20 or 21, also some chapters of reference 27.)

The analytical treatment of many economic problems will eventually be dependent upon statistical data and statistical methods of using these data, and for this reason some time should be given to a study of such methods, reference to which has already been made in the discussion of test and inspection (references 10 and 11). Other presentations of statistical methods for engineering problems have been published (see reference 1, chapter 14).

## F. Basic Considerations for Economic Units

An economic unit as referred to here may be an individual, a household, partnership, or a company; again, it may be a municipality, a state, a society, etc. The previous outline clearly indicates that economic considerations enter into nearly every activity connected with an industrial product, from its inception, design, or development to the time it is used up and ready for the scrap pile or to be disposed of in some way or other. Various and typical examples of economic questions have been discussed. Assuming that all industrial activities are carried out with due consideration to economy, it is further most essential that the over-all picture be sound from an economic point of view. If we assume, for instance, the simplest case where all activities are carried on within a single industrial unit, this means that the cost of creating a product must be equal to or below a value justified by its use. In addition, it is necessary that the concern involved either has the funds required to finance the venture or can convince others of the soundness of the venture and thus obtain funds from them as an investment or a loan. In most cases, however, conditions are not quite so simple inasmuch as several economic units are involved—sometimes a manufacturer and a user; again, both of these and a dealer or distributor, or both; or there may further be contractors, contractor dealers, and several other types of economic units having a place in the over-all picture. In all these cases it is necessary not only that the over-all picture of the product be sound but also the part of the work carried on by any of the individual units and the operation of each unit as a whole be on a sound economic basis. No type of unit can survive unless the other types necessary for the complete picture are able to do their part; for example, a manufacturer unwilling to give his dealers a discount which will enable them to carry on their part of the activities with a reasonable profit cannot hope to survive.

As previously pointed out, the most important economic factors of the entire picture to be considered first are those

determining the amount which the user can or will pay for a product. In the case of well-established goods for which there is a general demand, the price obtainable by any supplier is usually fixed by competitive prices, with proper allowance for difference in quality, serviceability, and similar factors. Such competitive prices as a rule drift around a level where the more efficient suppliers make a reasonable average profit. If the user is an industrial concern, the price must further be such as to make the purchase a profitable economic venture for the purchaser, based on the considerations covered under "Economics of Using Goods." In the case of individuals or homes, additional limitations are imposed by the income of the purchaser, which is comparatively low in the majority of cases. The price obtainable and the volume of sales at such price depends upon the number who are willing to pay and the amount they are able to spend for conveniences, comforts, and luxuries after paying for absolute necessities.

In view of all these and other factors limiting the price obtainable, the supplier's principal economic problem is to bring the cost of all his operations sufficiently below such price to allow a fair profit. Whenever several units, such as the manufacturer, distributor, dealer, and others, are involved in the marketing of a product, the first problem is to determine the proper distribution of the customer's dollar among these units. Subsequently each unit is confronted with the problem of carrying out its part of the functions at a cost sufficiently below the part of the customer's dollar allotted to it to insure a reasonable profit, or at least sufficient to give a fair return on the capital required for carrying on the particular activity. There are always a few exceptions to every rule, and in the case of new products of low cost and great usefulness it is sometimes possible to secure larger profits. This, as a rule, is only a temporary condition, because the very possibility of larger profits encourages competitive enterprises and consequent reduction in price. At times patent protection makes it possible to maintain larger profits for an extended period, but even in these cases attractive profits usually stimulate competitive inventive activities which eventually lead to the manufacture of similar products by others, with a resultant reduction in prices. Even during the periods when it is possible to secure large profits on the individual article, better all-round economic results can often be obtained by the manufacturer through the lowering of prices, with subsequent greater sales volume, lowered cost of production, and increased overall profits.

An outline of these considerations seems essential as a part of the proposed course and is given here in some detail because no suitable references could be found. The growing appreciation of the fact that prices and profit margins in most industries are continuously decreasing and likely to change into losses, especially during business depressions, has developed a tendency toward budgetary control of all expense and cost items, such as those shown in the graphs and many others. Continually changing business conditions naturally make it difficult to budget expenses in advance. Furthermore, too rigid a budget control carries with it the danger of interference with freedom of action when circumstances arise making departures

## Table I

| Period Number | Subject | Part of This Paper | Numbers of Typical References | Numbers of Alternate and Additional References |
|---|---|---|---|---|
| 1, 2, 3, 4 | Introduction and standardization | Introduction and first part of *D* | 3, chapter 9; 19 and 20 | 27, chapter 15; 18 and 19 |
| 5, 6 | Organization and personnel | Part of *D* | 3, chapter 11; 25, chapters 18 and 19 | 26, chapters 13, 17, and 20; 27, chapter 20 |
| 7, 8, 9 | Engineering application of statistical methods | *E* | 1, chapter 14 | |
| 10, 11 | Inspection and test | *B*-5 | 10 and 11 | |
| 12, 13, 14, 15, 16 | Economics of using goods | *A* | 1, chapters 1–10; 14, chapter 4 | 1 and 2; 26, chapter 2 |
| 17 | Expense factors | *B*-1 | 3, chapters 7, 8; and 4, chapters 16, 17, and 39; 7 and 24 | 27, chapters 13, 14, and 21; 5 and 6 |
| 18, 19 | Labor | *B*-2 | | |
| 20, 21 | Works overhead | *B*-3 | 27, chapters 3 and 8; 8; 1, chapters 1–10 | 27, chapters 9, 10, 11, and 12 |
| 22, 23 | Materials | *B*-4 | 22*i*, chapters 1 and 2 | 27, chapters 6 and 7; 23, chapters 8 and 9 |
| 24, 25 | Design, development—dies and fixtures | *B*-6 | 12 and 13; 27, chapter 5 | 27, chapters 4 and 16 |
| 26, 27, 28, 29 | Storage, distribution, servicing, and installation | *B*-7 | 14, chapters 5, 6, 8, 9; 16, chapter 2 | 27, chapter 17; 14, 15, and 16 |
| 30 | Interrelation of economic factors | *C* | 17 | 27, pages 52–58 |
| 31, 32 | Economics of units—budgeting | *F* | 29, chapters 5, 6, and 7 | 22-*k*; 28 |
| | General references | | | 22, *a*–*k*; 30 and 31 |

The order of subjects in this table is somewhat different from that in the text; it is here arranged to give in the first semester subjects of interest to both users and suppliers and also on the economics of using goods; in the second semester, the economics of supplying goods is covered.

and changes desirable during a budgetary period. Nevertheless a gradual evolution toward methods of expense control which are sufficiently flexible to take care of changing conditions but not so flexible as to make the control ineffective seems a step in the right direction. Therefore a brief study of this subject of budgets is desirable as a part of the course under discussion. (See references 22*k*, 28, and chapters 5, 6, and 7 of reference 29.)

## G. General Discussion

No mention has been made in this outline of the economic problems applying specifically to the central station industry and its production and rate-setting activities. The outline suggested has been worked up with the idea of its being of use to all branches of engineering, such as electrical, mechanical, chemical, etc. Each of these in turn may involve economic problems more or less specific to it, such as the central station situation, which is of specific interest to electrical engineers entering the utility field. Possibly a number of courses of interest to specific types of engineering students should be offered as electives in addition to the more general course covered here; for example, a course relating to the economics of construction work might be desirable for the students of civil engineering.

Scarcely any reference has been made to economic laws and factors as, for instance, price fluctuations as influenced by the law of supply and demand, which are usually covered in existing courses on classical economics. It is assumed that the student has previously taken a course of this nature.

While this entire paper emphasizes economic considerations, care should be taken not to leave with the student the impression that all activities and practices in industry can be governed entirely by economic aspects. There are other factors which must be taken into account and several of the references given introduce points of view other than the purely economic. However, it is usually good practice in any problem or undertaking to analyze the economic situation fully and subsequently give consideration to other factors.

A review of the material given in this paper for use in a course on industrial economics and business methods might give the impression that it cannot be readily covered in a weekly 2-hour period extending through 2 semesters. However, by properly condensing the material of the references this is quite possible. Although the author has not given a course exactly as outlined here, he has given similar courses and has accumulated experience definitely demonstrating the possibility of this. Table I gives a tentative outline indicating the time which might be devoted to the various subjects. In choosing material from the references and from the content of the paper, it is more important to select it so as to illustrate sufficiently the types of economic problems and proper method of attack than it is to give an exhaustive treatment of any one of them. It also seems advisable to make predominant those economic problems which can be handled or are influenced by the rank and file of an organization in order to avoid a rather common impression among younger engineers that most economic problems are essentially a function of the management group. It has been impossible for the author to review completely all material published which might be used for the course, and the references are given principally for the purpose of suggesting the kind of material which seems desirable for this purpose; no doubt other publications of similar nature can be found which at least in some instances may prove to be more suitable for class work than that given. (See reference 22, *a* to *k*, for additional material; reference 31 gives a broad and most interesting study of American industry.)

This paper is intended merely as a contribution by one who has had practical engineering experience, and outlines subjects regarding which the young engineer entering industry should have an appreciation and understanding. It may be true that much of this material will come to the attention of most practicing engineers over a period of years, but frequently the younger engineer will be placed for extended periods in specialized work with but little contact with other divisions of the organization and he would be greatly benefited in carrying on his specialized tasks if he could bring with him some knowledge of the typical economic factors of importance in industry. (See reference 30.) It also seems that with an increased interest in economics the engineering profession could through its analytical methods of attack assist in working out more nearly correct solutions for the many perplexing economic problems in industry.

There certainly can be no doubt that a course as here proposed will be of benefit to a vastly larger number of the younger engineers than some of the specialized technical courses on such subjects as transmission engineering, electric railway engineering, communication engineering, etc., which are now taking a part of the student's available time in college. This fact cannot be ignored and steps should be taken at least to make such a course available as an elective subject and to encourage the students to take an early interest in the economic and business side of their future work.

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(*Concluded on page 475*)

# End-Winding Inductance of a Synchronous Machine

By B. H. CALDWELL, JR.
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## Introduction

IN PREVIOUS PAPERS it has been found necessary to consider the armature inductance of salient-pole synchronous machines under several divisions. The most useful and generally accepted divisions are as follows:

1. Inductance of armature reaction
2. Inductance due to space harmonics in the core length or differential leakage, which is subdivided into
   - *a.* Belt leakage inductance
   - *b.* Zigzag leakage inductance
3. Slot leakage inductance
4. End-winding inductance

The first 3 divisions have been adequately treated by both Alger[1] and Kilgore,[2] who have derived formulas which apply accurately for most commercial machines. Formulas for the end-winding inductance have also been given, but all of them involve approximations which have not been adequately investigated.

It will be the purpose of this paper to develop formulas for calculating the end-winding self-inductance and leakage inductance on as sound a theoretical basis as possible and to obtain a direct experimental check of the resulting formulas for the single-phase, static case. The formulas for the 3-phase case will also be derived, but no experimental check will be given at this time.

## Historical Review

Doherty and Shirley[3] were the first to develop formulas for the calculation of the armature inductance of salient-pole synchronous machines which held for a wide range of machines. Later Doherty and Nickle[4] introduced the concept of resolving the armature magnetomotive force wave into its rotating space harmonic components; and with the aid of Blondel's[5] concept of resolving such harmonics into components along the direct and quadrature axes, they developed formulas for the inductance of armature reaction and for the differential leakage inductance. They also proposed new and precise definitions for the inductances of armature reaction and the armature leakage inductance. Following the basic ideas developed in this paper Park and Robertson[6] proposed to standardize the definitions of the various types of inductances of synchronous machines, including the transient and subtransient inductances, and described methods of measuring them. At about the same time Wieseman[7] applied the technique of field plotting to salient-pole machines, which allowed an accurate determination of the constants necessary to calculate the inductances of armature reaction. With this basis Alger[1] developed more accurate formulas for armature inductance, and introduced the belt leakage and zigzag leakage inductance terms as used by Adams[8] in his treatment of induction machines. Later Kilgore[2] published a paper wherein he developed formulas for calculating armature inductance. He used essentially the same definitions as Alger, but his results were given in a slightly different form, and he gave formulas for calculating the transient inductances, and proposed the use of a saturation factor.

## Theoretical Development

The approach which will be employed in the solution of this problem follows the same general scheme as that used by Doherty and Nickle[4] in calculating the inductance of the armature in the core length. That is, the magnetomotive force will be resolved into space harmonics, and the corresponding flux density wave will be found. The linkages will be determined with the aid of the equation

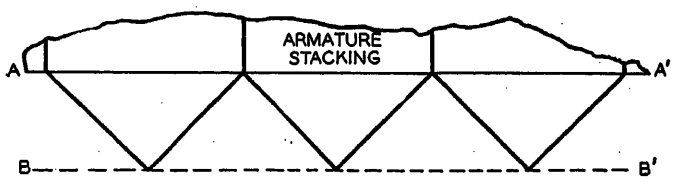



**Fig. 1. Development of simplified end winding**

of the flux density wave, from which the inductances will be found. The problem in this case differs from the core length solution in that the magnetic circuit is composed of air, and the magnetic field is 3-dimensional.

Since writing this paper attention has been called to "Potentialfelder der Electrotecnik" (a book), F. Ollendorf, Julius Springer, Berlin, wherein a similar approach is made to this problem, but the solution obtained is not so complete in detail or results.

As in the method used by Doherty and Nickle,[4] it will be assumed initially that the conductors are concentrated and have zero cross-sectional area. It will also be assumed that the end-winding coils are V-shaped. Then the end-winding will have been simplified to the winding shown in figure 1. It will also be assumed that the end-winding conductors lie in a plane which is the plane of the development of the armature surface.

The end-winding region is the region enclosed by the 2 planes $AA'$ and $BB'$ as shown in figure 1, which cut the

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1. For all numbered references see list at end of paper.

plane of the end-winding coils at right angles. The plane $AA'$ passes through the end of the armature core; thus, it is the boundary formed by the iron of the armature and field. The plane $BB'$ passes through the apices of the V-shaped end-winding coils.

In order to investigate the field in this region it is necessary to make some assumptions regarding the character of those boundaries. The iron of the armature

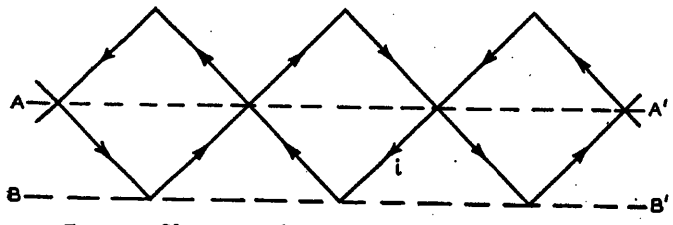



**Fig. 2. Showing substitution of a second V-shaped conductor for the armature stacking**

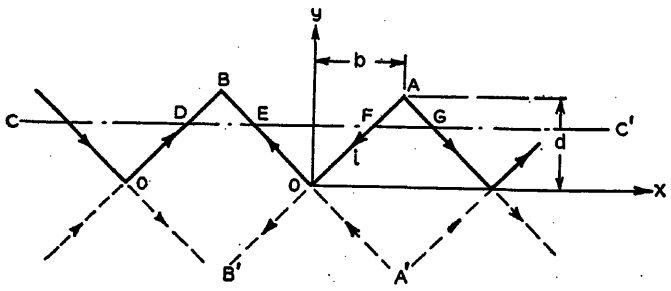



**Fig. 3. Development of simplified end winding showing the assumed image OA′ of OA, etc.**

core which forms the boundary $AA'$ will contain eddy current paths, and the flux entering it from the end-winding region must enter at approximately right angles to these eddy current paths; therefore the iron will act somewhat as a magnetic shield. In view of this fact the component of flux which is normal to the end surface of the armature core will be neglected, and the lines of flux will be assumed to be parallel to the end of the armature core at this boundary. The same boundary condition will be obtained with the configuration shown in figure 2 where a second V-shaped coil is substituted for the armature core.

The boundary condition at the plane $BB'$ will be approximated by assuming that the end-winding conductors are produced as shown in figure 3; that is, $OA$ is produced as $OB'$, etc. This assumption is made primarily to simplify the solution. It will introduce an error proportional to the coupling between coils $OAB$ and $OA'B'$ which will be discussed later.

The field in the end-winding region is symmetrical about the plane of the coil, and the problem is more easily treated by considering only the field on one side of the plane of the end-winding conductors. Because of this symmetry it is obvious that one-half of the total magnetomotive force is effective for either side of the plane of the conductors.

In obtaining a solution it is desirable to make the following simplifying assumptions and apply corrections later. These assumptions are:

1. That the end winding can be approximated by the V-shaped configuration as shown in figure 1.
2. That the conductors are of zero cross-sectional area.
3. That the end-winding conductors $AO$ and $BO$ as shown in figure 3 are produced as $OB'$ and $OA'$ and that these produced conductors carry the same current as the actual end-winding conductors.
4. That the component of flux normal to the end surface of the armature core is zero.
5. That the end-winding conductors lie in a plane which is the development of the cylindrical armature surface.
6. That the conductors in each phase group are concentrated.

Select a rectangular system of co-ordinates as shown in figures 3 and 4 with $O$, the apex of the coil, as the origin. Let $x$ be measured in the peripheral direction, $y$ in a direction parallel to the axis of the shaft, and $z$ in the radial direction perpendicular to the plane of the development. All distances are measured in centimeters. The positive direction from the $x$ co-ordinate is taken as the direction of rotation; the $y$ co-ordinate is measured positive toward the armature core; and the positive direction of the $z$ co-ordinate is taken in such a direction that a right-hand system of co-ordinates is formed. The dimensions $b$ and $d$ are measured in centimeters as illustrated in figure 3.

Select the magnetic reference potential as that existing along any line segment such as $DE$ and $FG$ of section $C$-$C$ as shown in figure 3, or in other words, the plane bounded by $OBO'B'$. In traversing a flux line $efgh$ as shown in figure 4, a magnetomotive force drop of $4\pi ni$ is experienced, where each of the $n$ conductors in the coil side $E$ carries $i$ abamperes of current. Since the field is symmetrical about the plane of $DEFG$, the magnetomotive force drop experienced in traversing $efg$ is $2\pi ni$.

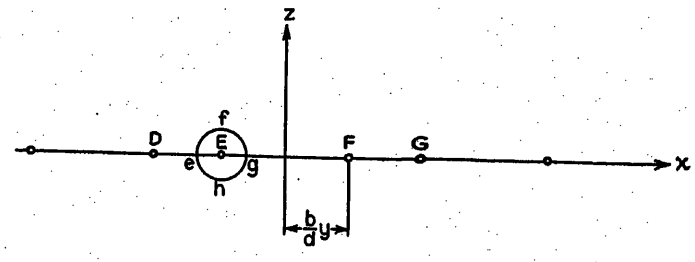



**Fig. 4. Section of the end-winding region taken perpendicular to the developed plane of the end-winding conductors**

If this magnetomotive force along a typical line formed by the intersection of the plane of section $C$-$C$ and the $x$-$y$ plane is plotted as ordinates against the distance along the line as abscissas, a curve as shown in figure 5 is obtained. The wave of the magnetomotive force along the $x$ axis for several values of $y$ is shown in order to demonstrate the variation along the $y$ axis.

If $k = (P/D)(b/d)$ and $\gamma = (P/D)\,x$, where $P$ is the number of poles and $D$ is the diameter, then the equation

of the rectangular magnetomotive force wave of figure 5 may be written as a Fourier series of the form

$$a = \sum \frac{A_q i_q}{m} \sin mky \cos m\gamma \tag{1}$$

where $m$ is the order of the space harmonic, and takes the values $2jq + 1$; $j = 0, 1, 2, 3, \ldots$ and $q$ is the number of phases. The values of $A_q$ for single-phase and balanced 3-phase windings are

$$A_1 = 8n \tag{1A}$$

$$A_3 = 12n \tag{1B}$$

The next step is to determine the flux density wave corresponding to each of the components of the magnetomotive-force wave such as

$$a_m = \frac{A_q i_q}{m} \sin mky \cos m\gamma \tag{2}$$

Let $B$ be the flux density in gausses at any point corresponding to the $m$th space harmonic of magnetomotive force, and let the subscripts $x$, $y$, and $z$ indicate the components of $B$ in the $x$, $y$, and $z$ directions. For the region

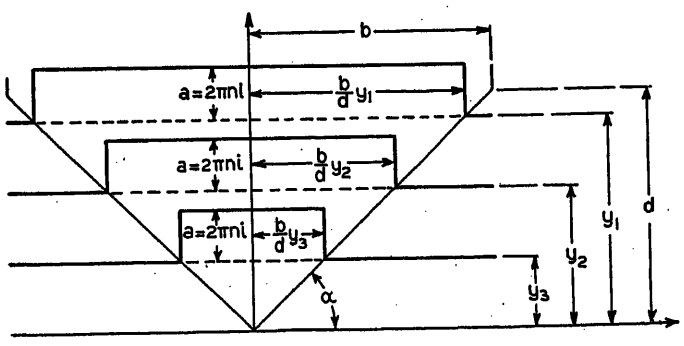



**Fig. 5. Diagram showing magnetomotive force wave for various values of y**

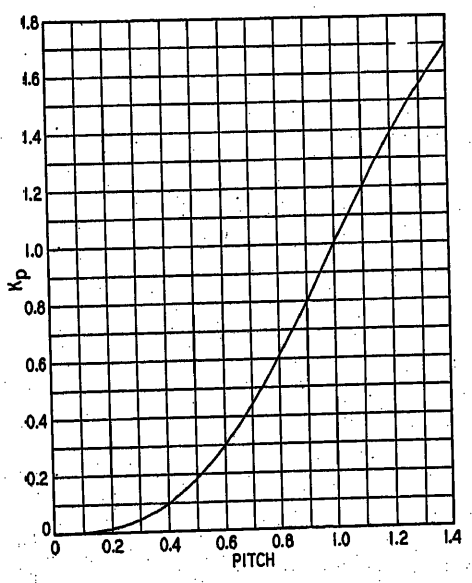



**Fig. 5A. Pitch factor**

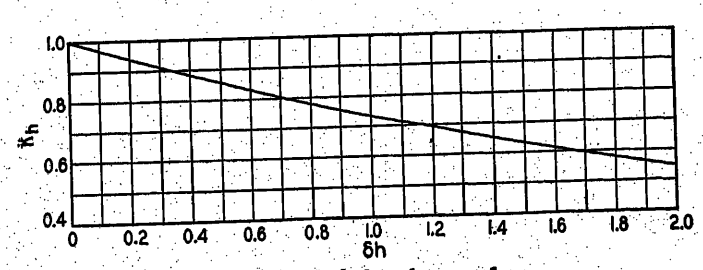



**Fig. 5B. Radial distribution factor**

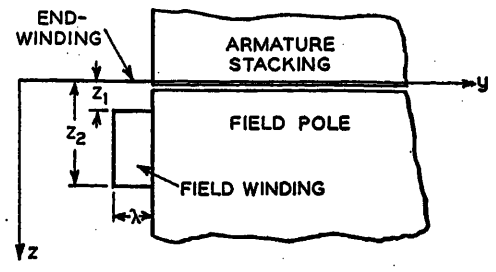



**Fig. 6. View of armature and field taken perpendicular to the plane of end - winding coils**

corresponding to positive values of $z$ in which there is assumed to be no magnetic medium and no current carrying conductors, the equations

$$\nabla . B = 0 \tag{3}$$

and

$$\nabla \times B = 0 \tag{4}$$

must be satisfied subject to the boundary conditions

$$\left.\begin{aligned} B_x &= -\frac{\partial a_m}{\partial x} \\ B_y &= -\frac{\partial a_m}{\partial y} \end{aligned}\right\} \text{When } z = 0 \tag{5, 6}$$

and

$$B \to 0 \text{ as } z \to \infty \tag{7}$$

The desired solution for positive values of $z$ is readily found by usual methods to be

$$B_z = B_m e^{-m\delta z} \sin mky \cos \frac{m\pi x}{D}, \tag{8}$$

where

$$\delta = \frac{P}{D} \csc\alpha \quad (9) \quad \text{and} \quad B_m = \delta A_q i_q \tag{10}$$

where $\alpha$ is the angle shown in figure 5.

The linkage $\psi_m$ in abampere-henries per phase per pole for the V-shaped end-winding which has $n$ conductors connected in series, is

$$\psi_m = n \int_0^d \int_{\frac{-b}{d}y}^{\frac{b}{d}y} \beta_m \, dx \, dy \times 10^{-9} \tag{11}$$

where $\beta_m = B_z$, when $z = 0$. Substitute the value of $\beta_m$ from equation 8 into equation 11, and integrate to obtain

$$\psi_m = \frac{\pi n D^2 \tan\alpha}{2mP^2} B_m K_{pm} \times 10^{-9} \tag{12}$$

where $K_{pm}$ is the pitch factor and is given by the equation

$$K_{pm} = p\left[1 - \frac{\sin mp\pi}{mp\pi}\right] \tag{13}$$

The inductance $L_m$ in henries corresponding to these linkages is

$$L_m = \frac{\psi_m}{iq} \tag{14}$$

where $i_q$ is the current in each of the $n$ conductors of the end winding. Substitute the values of $\Psi_m$ and $i_q$ into equation 14 to obtain the total inductance per pole per phase. The result is

$$L = \frac{\pi F_q n^2 D \sec \alpha}{P} \sum \frac{K_{pm}}{m} \times 10^{-9} \tag{15}$$

where

$$F_1 = 8 \tag{16}$$

and $m = 1, 3, 5\ldots$, for the single-phase case, and

$$F_3 = 12 \tag{17}$$

and $m = 1, 5, 7\ldots$, for the 3-phase case.

This derivation is based on the 6 assumptions previously listed. It is now necessary to develop corrections for these assumptions. First, consider the assumption that the phases are concentrated. In general the phases consist of several groups of conductors, each group of which occupies a different slot, and these slots are spaced around the periphery of the armature. The space waves of magnetomotive force due to these coils are out of phase by an angle determined by the angle between slots and the order of the space harmonic. Therefore the resultant magnetomotive force is less than for the case of concentrated phases, and the reduction factor $K_{dm}$ is applied to correct for this. Its value is given by the equation

$$K_{dm} = \frac{\sin m\frac{s\theta}{2}}{s \sin m\frac{\theta}{2}} \tag{18}$$

where $\theta$ is the angle measured in electrical radians between slots, and $s$ is the number of slots per pole per phase. Also the electromotive forces induced in the armature conductors by the rotating space waves of flux will be out of phase for the same reason, hence the reduction factor $K_{dm}$ must be applied again, or the total reduction factor is $K_{dm}^2$.

The factor, which applies to correct for the fact that the conductors have a dimension other than zero measured along the periphery of the armature, is equal to the ordinary distribution for a uniformly distributed phase which is distributed over the peripheral dimension $c$ of the rotor surface. Thus,

$$K_{cm} = \frac{\sin \frac{mPc}{2D}}{\frac{mPc}{2D}} \tag{19}$$

The derivation of this relation is based on the assumption that the current is uniformly distributed over the cross section of the conductor.

It should be noted at this point that the product $K_{dm}$ $K_{cm}$ is approximately equal to $C_m$, the distribution factor

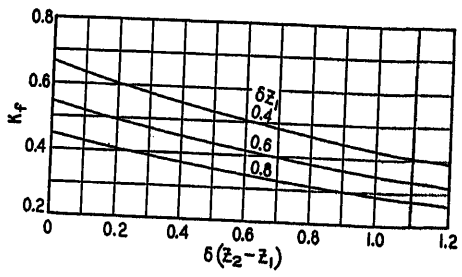



**Fig. 7A. Mutual inductance factor**

for a uniformly distributed winding, when spacing between the end-winding conductors is small as is usually the case. This is a good approximation particularly for the space fundamental.

The inductance is further reduced by the fact that the coil side has a depth or radial dimension $h$ which is greater than zero. The derivation of this reduction factor $K_{hm}$ is based on the result of equation 8 and the assumption of uniform current distribution over the coil side cross section. With the aid of equation 8 the flux density which is established at some point along $h$ by an infinite number of current filaments spaced equally along $h$ may be computed. Then the average of this flux density over the dimension $h$ divided by the flux density resulting from a concentrated conductor carrying the same current as the distributed conductor gives the desired reduction factor. The result is

$$K_{hm} = \frac{2}{m\delta h}\left(1 - \frac{1 - e^{-m\delta h}}{m\delta h}\right) \tag{20}$$

If

$$K_m = K_{pm} K_{dm}^2 K_{cm}^2 K_{hm} \tag{21}$$

then the formula for the end-winding inductance may be written as

$$L = \frac{\pi F_q n^2 D \sec \alpha}{P} \sum \frac{K_m}{m} \tag{22}$$

If the approximation $K_{dm}\, K_{cm} = C_m$ is made, then

$$K_m = K_{pm} C_m^2 K_{hm} = K_{pm} \frac{C_1^2}{m^2} K_{hm}' \tag{23}$$

and the end-winding inductance is

$$L = \frac{\pi F_q n^2 D \sec \alpha}{P} \sum \frac{K_{pm}\, C_1^2\, K_{hm}}{m^3} \tag{24}$$

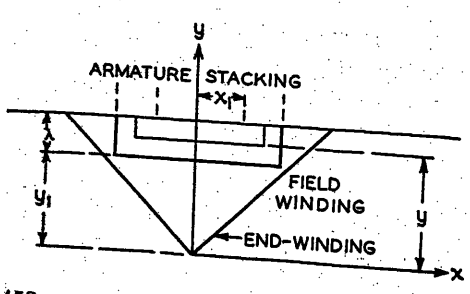



**Fig. 7. Development of end winding showing the field winding**

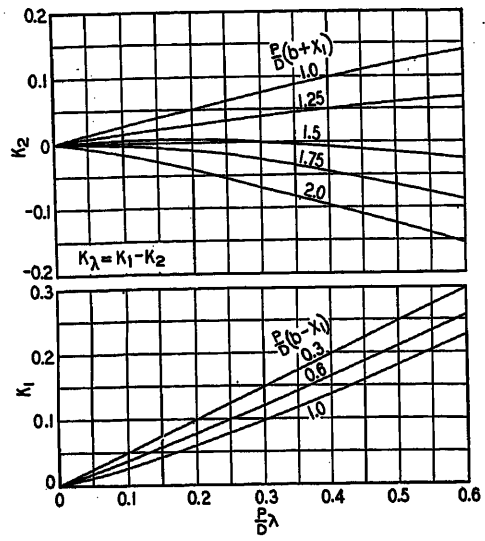



**Fig. 7B. Mutual inductance factor**

This series converges rapidly, and only the first term is necessary in computing for the usual case with the possible exception of the single-phase case where the third harmonic appears. In order to facilitate computation, curves of the factors $K_{pm}$ and $K_{hm}$ are given in figures 5*A* and 5*B*.

The assumption regarding the V shape of the end-winding coils is fairly close to the actual case except for that portion of the winding near to the armature core. However, the length of the conductor which extends straight out from the slot is usually small compared with the total length, and it seems that little error is introduced by this approximation.

The effect of the remaining assumptions has been investigated experimentally, and will be discussed later.

An important consideration, which has been completely ignored by previous writers, is the mutual linkage between the field coils and end winding. This is important; since, even though this mutual linkage may be a very small percentage of the total mutual linkage between the field and armature, it may be appreciable compared with the end-winding linkage thereby causing the end-winding *leakage* inductance to differ considerably from the total self-inductance of the end winding.

The field winding ordinarily extends an appreciable distance beyond the end of the field pole, hence this winding links some of the flux set up by the end winding. Figures 6 and 7 show a typical design for a salient-pole machine. According to assumption 4 none of the end-winding flux enters the field pole core, therefore, the only flux to be considered is that in the region occupied by the field winding which extends into the end-winding region.

The method to be employed in calculating this mutual linkage will be, first, to calculate the average component of flux perpendicular to the plane of the end winding over the radial depth and within the boundaries of the field coil by the use of equation 8. Next, it will be assumed that the field winding is uniformly distributed. Then the mutual linkage will be found by integration.

Select the same co-ordinate system as used in the derivation of equation 8 and as illustrated in figures 6 and 7.

Let the dimensions $z_1$, $z_2$, $x_1$, and $\lambda$ be measured in centimeters as shown in the diagram. Consider the case where the pole axis coincides with the phase axis, and the resulting mutual linkage will be the maximum value.

The average of $B_z$ from $z_1$ to $z_2$ as found from equation 8 is given by

$$B_z = B_m K_{fm} K_{dm} K_{cm} \sin mky \cos \frac{mPx}{D} \tag{25}$$

where

$$K_{fm} = \frac{1 - e^{-m\delta h}}{m\,\delta\,h} \frac{[1 - e^{-m\delta(z_2 - z_1)}]e^{-m\delta z_1}}{m\delta(z_2 - z_1)} \tag{26}$$

The corresponding linkage is found by integration. Thus the linkage $\Psi_m$ of the field coil due to the $m$th harmonic of the flux density wave set up by the field of the end winding is

$$\psi_m = \frac{D^2 n_f B_m K_{fm} K_{dm} K_{cm} K_{\lambda m} \times 10^{-9}}{m^2 P^2} \tag{27}$$

where $n_f$ is the number of turns per field pole, and

$$K_{\lambda m} = \frac{\sin \frac{mP}{D}(b - x_1)}{1 + \frac{b}{d}} + \frac{\sin \frac{mP}{D}(b + x_1)}{1 - \frac{b}{d}} + \frac{\cos \frac{mP}{D}(b - x_1) - \cos \frac{mP}{D}\left[b - x_1 - \left(1 + \frac{b}{D}\right)\lambda\right]}{\left(1 + \frac{b}{d}\right)^2 \frac{mP}{D}\lambda} - \frac{\cos \frac{mP}{D}(b + x_1) - \cos \frac{mP}{D}\left[b + x_1 + \left(1 - \frac{b}{d}\right)\lambda\right]}{\left(1 - \frac{b}{d}\right)^2 \frac{mP}{D}\lambda} \tag{28}$$

The corresponding mutual inductance in henries per pole per phase for both ends of the end winding is

$$M_0 = \frac{2F_q n n_f D \csc\alpha}{P} \sum \frac{K_{fm} C_1 K_{\lambda m}}{m^2} \times 10^{-9} \tag{29}$$

This is the maximum value of mutual inductance. In general only the first term of the series is required. The factors $K_{fm}$ and $K_{\lambda m}$ are rather complicated for computing purposes and they contain too many parameters to be given conveniently in the form of curves. However, if we neglect the effect of the term containing $h$ in the expression for $K_{fm}$ of equation 26, $K_{fm}$ may be conveniently given in curve form as shown on figure 7*A*. Likewise a constant value of $b/d = 0.577$ ($\alpha = 60$ degrees) is assumed in plotting the curves for $K_{\lambda m}$ as shown in figure 7*B*.

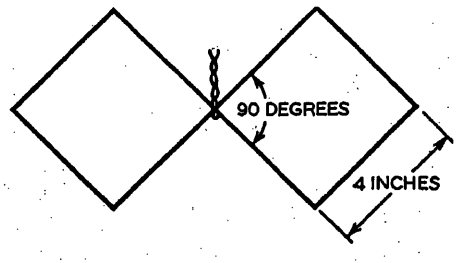



**Fig. 8. Sketch showing diamond-shaped coils used in mutual inductance measurement**

For a machine with a "sine wave winding"; that is, a machine which eliminates all effect on the terminal voltage of space harmonics of flux and magnetomotive

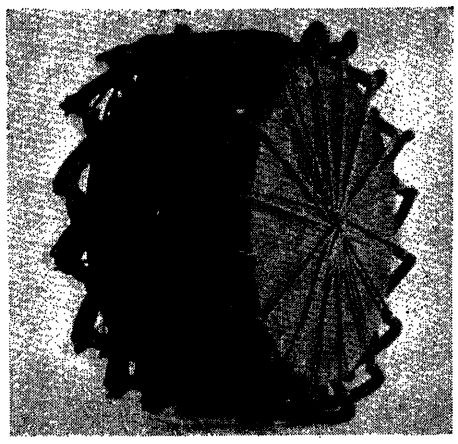


Fig. 9. End-winding model

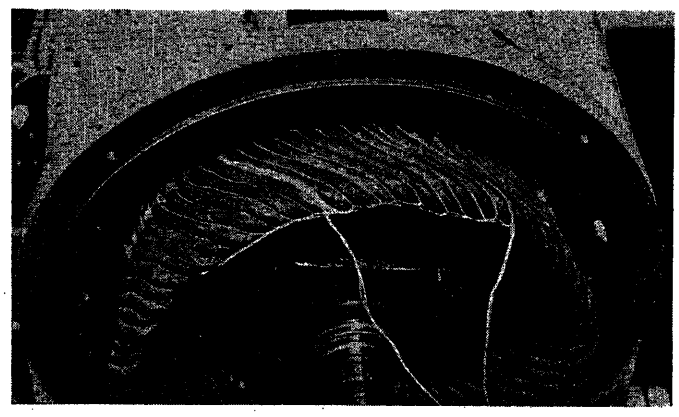


Fig. 10. View of exploring coils

force, this mutual inductance varies sinusoidally from its maximum value to zero as the pole moves through 90 electrical degrees. Blondel[5] first introduced the concept of expressing the armature inductance of such a machine by its values along the direct and quadrature axes, and most of the subsequent studies have employed this concept. It is desirable then to write the end-winding inductance along the direct or pole axis as

$$L_{ld} = L - \frac{n}{n_f} M_0 \qquad (30)$$

where $L$ is given by equation 22, and $M_0$ is given by equation 29.

## Experimental Techniques

Several experiments were performed to determine the accuracy of the assumptions. In so far as seemed feasible, the experiments were so arranged that each assumption was checked separately.

In order to determine the order of magnitude of the error introduced by the assumption that the end-winding conductors were produced as shown in figure 3, the mutual inductance of 2 diamond-shaped coils as shown in figure 8 was measured. With the 2 coils connected in series, the inductance differed by 1.5 per cent from the sum of the 2 self-inductances. The mutual inductance will of course vary with the shape and size of the coils, but its magnitude is negligible compared with the self-inductance, so the assumption appears reasonable.

An experimental check on the accuracy of formula 22 was obtained by measuring the inductance of models as shown in the photograph of figure 9 and comparing the result with the calculated value. The coils were connected as a single-phase 4-pole winding. The models were equipped with 4 coils per pole and each coil had 20 turns in series. The coil connections were arranged so that measurements could be made with 1, 2, 3, or 4 coils per pole.

This agreement is reasonably good; and since the model duplicated the actual end winding except for the effect of the iron in the armature stacking, these results indicate that the total error introduced by assumptions 1, 3, and 5 and the errors in the factors, which were developed to correct for assumptions 2 and 6, as previously listed is approximately ± 3 per cent.

The next experimental check consisted in measuring the inductance of the end winding of an actual machine. The tests were made on a 15-horsepower 220-volt 1,800-rpm 60-cycle 4-pole 3-phase salient-pole synchronous motor. The armature winding was reconnected single-phase.

Exploring coils were used to measure the inductance. They were placed on the end winding as shown in figure10 with a single turn of the exploring coil around each end-winding coil of a phase belt per pole. A 60-cycle voltage approximately sinusoidal in wave shape, was impressed on the armature circuit through an ammeter. The exploring coils were connected in series and the terminals were brought out to the input of a calibrated amplifier and voltmeter. The end-winding inductance was measured with the field axis and quadrature axis coinciding and with the field axis and the direct axis coinciding. Thus measurements were obtained for the conditions of maximum and minimum effect of the iron of the field stacking. The variation was found to be ±3.75 per cent from the average value.

The same arrangement was used in the measurement of the mutual inductance. In this case the field was

**Table I—Comparison of Calculated and Measured Values of Inductance of the Models as Shown in Figure 9**

| Coils per Pole | L in Millihenries: Calculated | Measured | Per Cent Error |
|---|---|---|---|
| **Model No. 1** | | | |
| 4 | 3.55 | 3.48 | 2.0 |
| 3 | 2.83 | 2.79 | 1.4 |
| 2 | 1.76 | 1.73 | 1.7 |
| 1 | 0.685 | 0.670 | 2.2 |
| Coil pitch = 1.0, single-phase, 4-pole, $D$ = 31 centimeters, $b$ = 12.2 centimeters, $d$ = 12.1 centimeters, $c$ = 1.34 centimeters, $h$ = 1.14 centimeters. | | | |
| **Model No. 2** | | | |
| 4 | 2.98 | 3.02 | 1.3 |
| 3 | 2.34 | 2.44 | 2.9 |
| 2 | 1.49 | 1.52 | 2.0 |
| 1 | 0.635 | 0.630 | 1.0 |
| Coil pitch = 0.75, single-phase, 4-pole, $D$ = 44 centimeters, $b$ = 12.95 centimeters, $d$ = 11.35 centimeters, $c$ = 1.34 centimeters, $h$ = 1.14 centimeters. | | | |

excited with a known current, while the machine was rotated at normal speed, and the voltage induced in the exploring coils was measured. Then

$$M_0 = \frac{E}{\omega I} \tag{32}$$

where $E$ is the maximum value of the exploring coil voltage in volts, $I$ is field current in amperes, and $\omega$ is the angular velocity in electrical radians per second.

A tabulation of the values of $M_o$ and $L_{la}$ as determined from test and calculation is shown in table II along with the value end-winding leakage as calculated from the formula given by Alger.[1]

## Conclusions

Let us consider now the effect of the primary assumptions previously tabulated. Accurate corrections have been developed for assumptions 2 and 6, and the probable error introduced by them is negligible.

The error introduced by assumption 3, regarding the continuation of the end-winding conductors beyond the apex of the V-shaped conductors, was determined by the measurement of the mutual inductance of 2 diamond-shaped coils. The error due to this assumption is approximately 1.5 per cent.

The errors introduced by assumptions 1 and 5 were evident in the measurement of the inductance of the end-winding model. The error due to assumption 3 was also included here, and the comparison of the calculated and measured value of inductance indicates an error of approximately ± 3 per cent.

The assumption that the component of the flux normal to the plane of the end of the armature core is zero is equivalent to assuming that none of the flux from the end-winding field enters the armature core. Since the ultimate aim of this study is to compute the end-winding *leakage* inductance, suppose that we assume instead that only the end-winding *leakage* field is unaffected by the iron of the armature stacking, and review the theoretical development on the basis of this assumption instead of the assumption that none of the flux from the end-winding field enters the armature core.

Physically the meaning of this assumption is apparent from a survey of the 2-dimensional sketch shown in figure 11. If there were no iron in the armature core the flux line at the boundary of the armature stacking would be vertical. Because of the iron the flux lines near the boundary are distorted as shown, but as the distance from the boundary increases the distortion due to the iron decreases, and this distortion of the field is apparently small beyond the boundary of the field pole winding; that is, the distortion is small in the region of the end-winding *leakage* field. It follows that this assumption is less radical than the assumption initially made, and only the simpler assumption is involved in the final result.

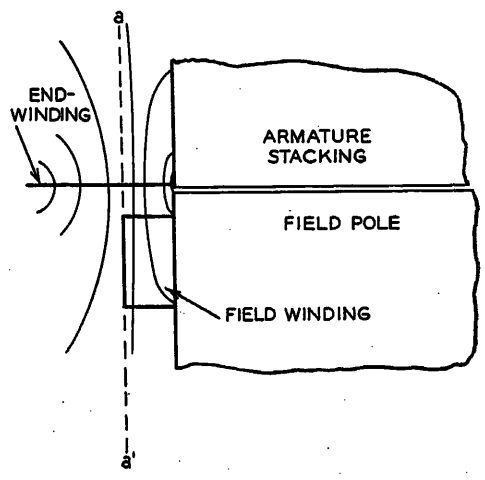



**Fig. 11. Sketch of end-winding field in a plane through the shaft axis and perpendicular to the plane of the end - winding coil**

It is believed that equation 30 is a step nearer to an accurate formula for the end-winding leakage inductance than any previously published. An effort has been made to indicate the nature and consequence of the assumptions involved and the effects of these assumptions have been investigated from an experimental viewpoint. An important part of the result is the expression for the flux density given by equation 8. This equation should serve as a basis for studying the effects of iron in the end-winding region. For example, the analysis may be extended to calculate the end-winding inductance of turbine generators where the rotor extends well into the end-winding region and to calculate the end-winding inductance of d-c machines where the conductors are supported by an iron ring.

**Table II—Winding Data, 18 Slots per Pole, 4 Turns in Series per Slot**

| | $M_o$— Milli-henries | Error— Per Cent | L— Milli-henries | Error— Per Cent | $L_{ld}$— Milli-henries | Error— Per Cent |
|---|---|---|---|---|---|---|
| Test value | 3.81 | | 0.892 | | 0.460 | |
| Calculated value | 2.70 | 29.1 | 0.774 | 13.2 | 0.468 | 1.8 |
| Calculated value from Alger's formula | | | | | 0.469 | |

$P = 4$, $D = 29.0$ centimeters, $b = 6.93$ centimeters, $d = 8.13$ centimeters, $h = 1.10$ centimeters, $p = 0.61$, $n_f = 635$ turns per pole, $z_1 = 3.81$ centimeters, $= 3.81$ centimeters, $z_1 = 2.54$ centimters, $z_2 = 5.72$ centimeters.

## Nomenclature

- $a$ = magnetomotive force in gilberts
- $\alpha$ = angle shown in Figure 5
- $A$ = constant as defined by equations 1$A$ and 1$B$
- $B$ = vector flux density in gausses corresponding the $m$th space harmonic of magnetomotive force as a function of the space co-ordinates, and the subscripts $x$, $y$, and $z$ indicate the components of $B$ in the $x$, $y$, and $z$ directions
- $\beta$ = value of $B$ when $z = 0$
- $b, d$ = end-winding dimensions measured in centimeters as shown in figure 3
- $C$ = reduction factor for a winding which is uniformly distributed over the phase belt
- $c$ = peripheral dimension in centimeters of the conductors
- $D$ = diameter of armature winding in centimeters
- $\delta = \frac{P}{D}\sqrt{\left(\frac{b}{d}\right)^2 + 1}$

*(Concluded on pages 475–5)*

# An Alternator-Voltage Regulator Utilizing a Nonlinear Circuit

By HARRY W. MAYNE

ALTHOUGH several different types of alternator-voltage regulators are in successful operation at present, the purpose of this paper is to describe a regulator which is believed to have several outstanding advantages over any of the present types. The inherent limitations of the various types of moving-contact regulators are well known, and a perusal of the circuit diagrams[1] of the different types of electronic regulators will indicate the complexity of such circuits, even though they are superior in most respects to the moving-contact-type regulators.

The regulator to be described here is of the electronic type, and is capable of the same degree of accuracy as the best of its type. It promises even faster operation than existing types and these characteristics are obtainable with a circuit utilizing 2 mercury-vapor control tubes combined with a small inductance, capacitance, and resistance.

## Nonlinear Circuits

The eccentricities of circuits containing capacitance and saturable core inductance have long been known to engineers. The particular phenomenon which first attracted attention was the so-called inversion or instability of the neutral of a 3-wire star-connected bank of transformers feeding a highly capacitive transmission line. Considerable material[2] was written on the peculiarities obtained, but it was not until 1931 that publications discussing simple single-phase circuits appeared.[3] Only the simple series circuit shown in figure 1 will be discussed. In figure 2 we have the effective volt-ampere characteristics of the circuit for various values of the resistance. From these curves we see that as the resistance is decreased, the slope of the curve increases so that it is possible to obtain a very large change in the effective value of the current with a negligible change in the effective value of the impressed voltage. Of course further reduction of the resistance produces a characteristic which is double-valued in current over a certain range of voltage, but these properties are of no utility in this particular application except as a limiting case.

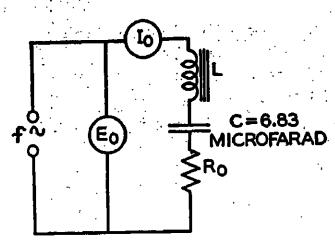



**Fig. 1. Nonlinear series circuit**

$R_0$ represents total d-c resistance of circuit

Because of the presence of the iron-cored coil, the wave form of the current in such a circuit is not sinusoidal, and is subject to considerable change as the effective value changes. Figure 3 is an enlarged drawing of superimposed oscillograms which illustrates the variation for the particular circuit used. Referring to figure 3, $I_1$ represents an effective value of 0.21 ampere, and the voltage required was 110 volts. When the voltage was increased to 111 volts, $I_2$, with an effective value of 0.43 ampere was obtained. The resistance in the circuit was 125 ohms, and the frequency 60 cycles per second. From the drawing we see that when the lower value of current is flowing, the crossing points of the current wave lag those of the voltage wave by approximately 20 degrees, and the peak current of 0.414 ampere occurs at 139 degrees. When the impressed voltage is increased from 110 to 111 volts effective value, or less than 1 per cent, the peak current increases to 0.908 amperes, or more than 100 per cent. In addition the wave is shifted so that the crossing points of the current wave are in the phase with those of the voltage wave. The peak current is also shifted by the same angle, approximately 20 degrees.

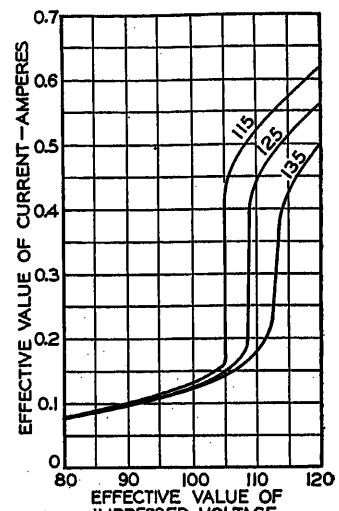



**Fig. 2. Effective volt-ampere characteristics for circuit of figure 1 at 60 cycles per second**

Numbers on curves are values of $R_0$ in ohms

## Application

With these general properties of the circuit in mind, the circuit shown in figure 4 was developed and tested. The alternator used was a 7.5-kva 60-cycle machine synchronously driven from a source having a frequency variation of ±0.3 cycle in 60. With a 7.5-kva load at

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1. For all numbered references see list at end of paper.

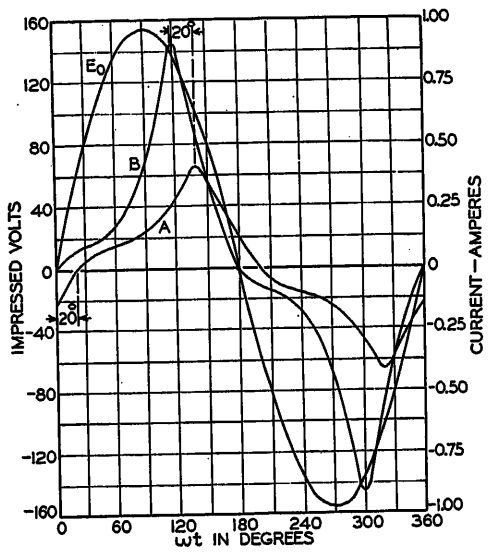



**Fig. 3. Variation of wave form of current in nonlinear circuit with impressed voltage**

A—$I_1$ = 0.21 ampere, $E_1$ = 110 volts, effective values

B—$I_2$ = 0.43 ampere $E_2$ = 111 volts, effective values

$R_0$ = 125 ohms, frequency = 60 cycles

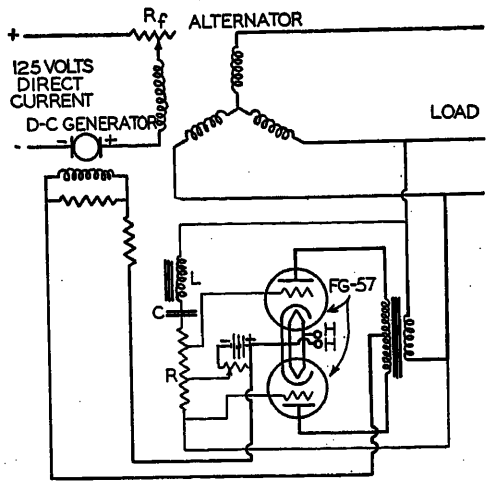



**Fig. 4. Circuit diagram of counter - electromotive-force regulator using nonlinear - circuit control**

0.85 power factor, the alternator regulation was 12 per cent and a 25 per cent decrease in field current was necessary to maintain normal voltage from full load to no load. The d-c end of a small a-c to d-c motor-generator set was used as a counter-electromotive-force generator in the alternator field circuit, and the drive was floated across the line to maintain constant speed. Type *FG-57* thyratrons were used as grid-controlled rectifiers supplying the counter-electromotive-force field. As these tubes are negative control tubes, it is necessary to use a d-c

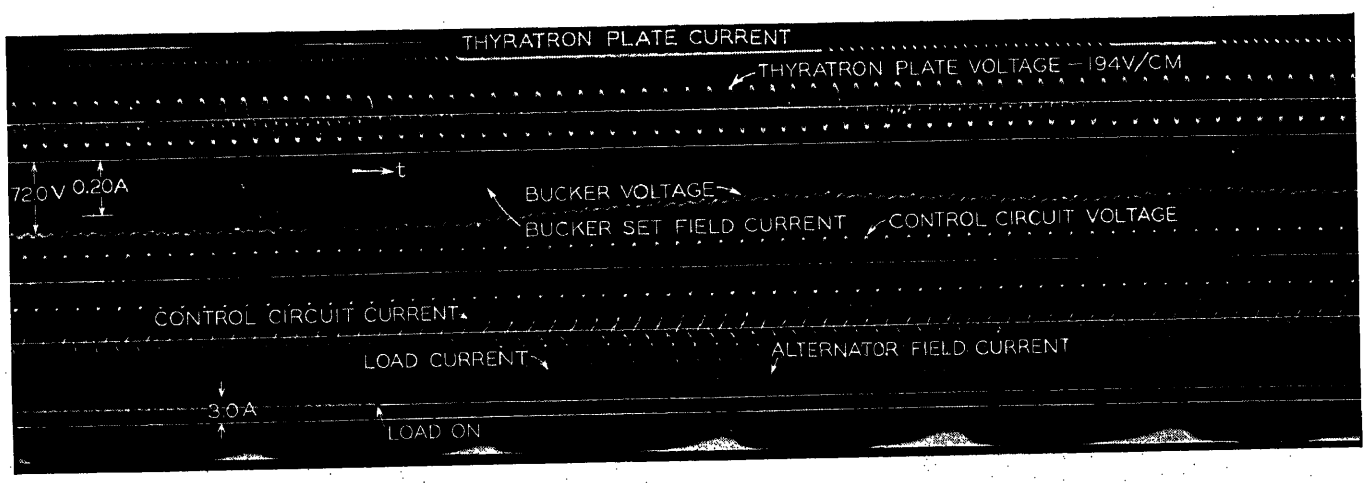



**Fig. 5a. Operation of regulator of figure 4 when load is applied**

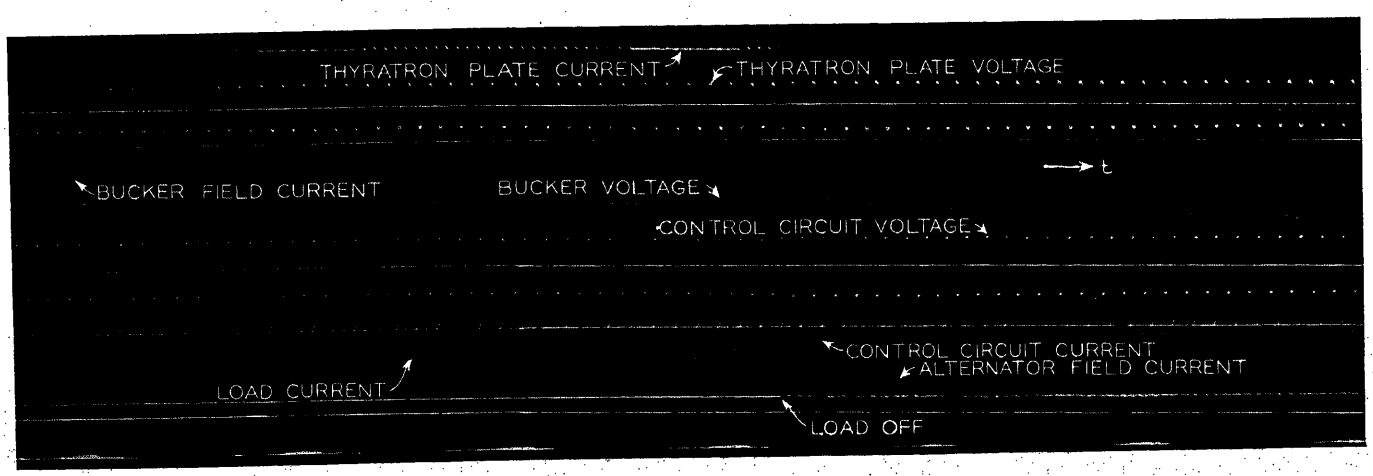



**Fig. 5b. Operation of regulator of figure 4 when load is removed**

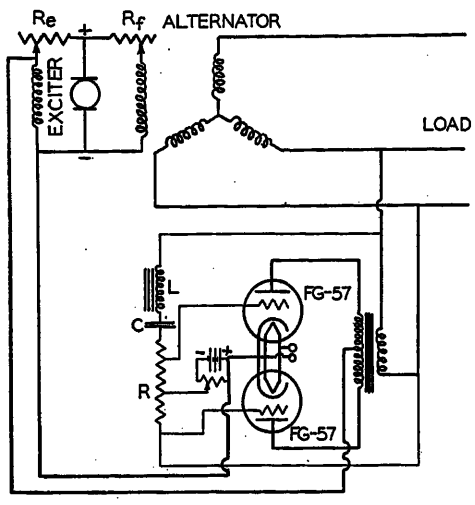



**Fig. 6. Circuit diagram of non-linear - circuit regulator operating on field of main exciter**

grid bias in addition to the a-c component. The use of the proper type of positive-grid-control tube would dispense with this grid battery.

The following preliminary adjustments are necessary to put the regulator in operation. The nonlinear circuit is adjusted so its characteristic is very steep at normal voltage on the alternator. With full load on the machine the field excitation is increased until the alternator voltage is just below the sensitive portion of the nonlinear circuit characteristic. The d-c grid bias on the rectifiers is then adjusted so the tubes are barely firing, and the field excitation further increased to provide the desired reserve capacity above full load.

After these adjustments have been made, suppose that the load is dropped suddenly. The terminal voltage will rise, producing a large rise in the nonlinear-circuit current, with the attendant phase shift referred to earlier. Since the circuit is connected so that the phase relation of the grid voltage to the thyratron plate voltage is the same as shown in figure 3, both changes produce a large increase in the average value of the rectifier plate current. This increases the terminal voltage of the counter-electromotive-force machine, with a corresponding decrease in alternator field excitation, thus tending to decrease the abnormally high alternator voltage. Any decrease, however, will react on the control circuit and tend to decrease the current again, so that the final equilibrium condition for no-load will be at a slightly higher voltage than at full load. With the machines used a regulator sensitivity of ± 0.2 per cent was obtained. The frequency variation of the source increased the variation to ± 0.3 per cent. The operation of the regulator is illustrated by the oscillograms shown in figures 5*a* and 5*b*. These show the variations when full load is applied and removed respec-

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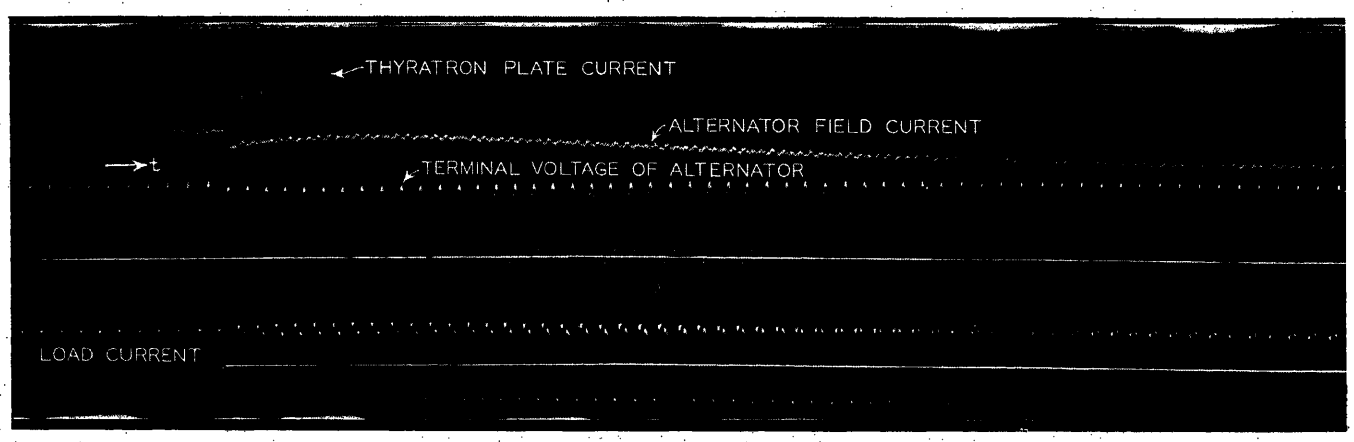



**Fig. 7a. Operation of regulator of figure 6 when load is applied**

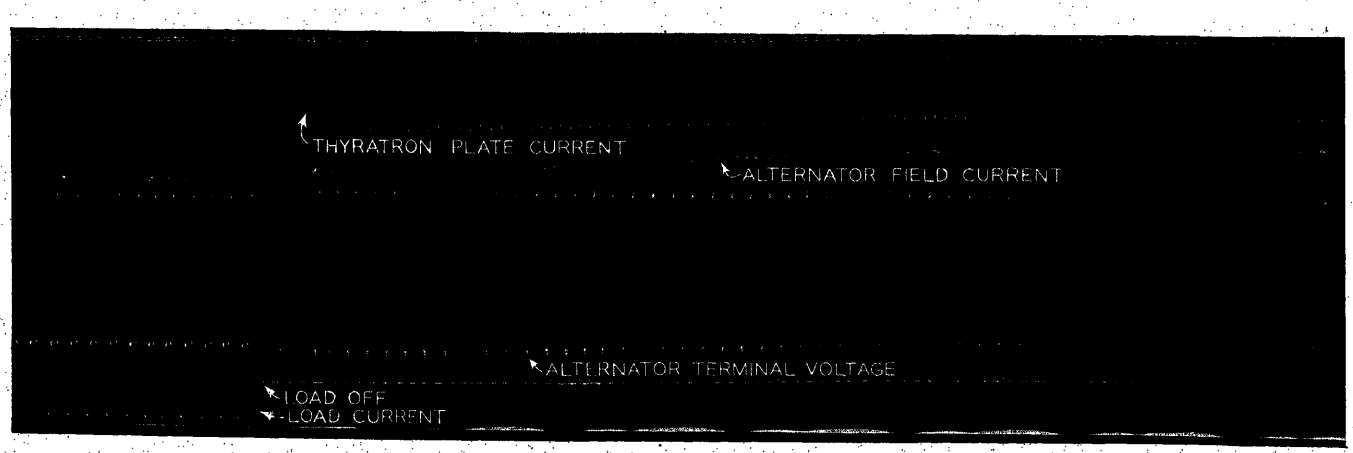



**Fig. 7b. Operation of regulator of figure 6 when load is removed**

# Oxidation in Insulating Oil

By J. B. WHITEHEAD
FELLOW AIEE

F. E. MAURITZ
ENROLLED STUDENT AIEE

## I. Introduction

IT is generally agreed that of the component parts of impregnated paper, the impregnating oil is most susceptible to deterioration. There is, however little definite knowledge of the processes leading to instability. Instablility manifests itself in changes in electrical properties. An increase in dielectric loss, if allowed to continue, ultimately leads to failure. Marked chemical changes often accompany these changes in electric properties, but whether or not the changes are caused by electrical stress, as related to the inherent chemical structure of the oil, or by residual impurities, as related to stress and structure, or by both jointly is as yet unknown. Obviously oxidation, with its generation of acids and consequent increase in chemical dissociation and electrical conductivity is a powerful cause of instability. Although careful provision is made for the elimination of oxygen in the manufacture of insulation, it is recognized that traces of oxygen must remain under all circumstances, and the determination of the degree of its activity as a cause of insulation instability becomes a matter of great importance.

To the electrical engineer, the electrical stability of an oil is measured not in terms of the specific chemical changes that are taking place, but in changes in its electrical properties, i.e., its conductivity, dielectric loss, power factor, or phase difference, dielectric constant and breakdown strength. Extensive studies of the variations of these quantities over the life of impregnated insulation have been made, and a highly developed technique is available. Characteristic changes in the electrical properties, through the life of the insulation, are often traceable to changes in conductivity and ionic content,[1] and there are other conspicuous evidences of chemical changes. But as stated, there is still great uncertainty as to the original cause of these changes and of their subsequent progress. Many studies have been made of the process of oxidation in mineral and in other oils as used for insulation. It is a highly complex process involving many end products, as is natural in view of the complexity of the oil molecule itself. However, while much information is now available as to the process of oxidation and its various end products, there is little available material correlating the oxidation of an oil with its electrical properties.

In this paper we report a series of studies of accelerated oxidation in a highly refined insulating oil as used in oil-filled cables, with particular reference to the correlation between oxidation and electrical properties. For certain of these properties there is a marked correlation. The tests have been made at higher temperatures than normal for insulation, in order to accelerate the complete program. There are definite indications, however, that reliable deductions may be made for the behavior of the oil at lower temperatures and in the presence of smaller amounts of oxygen.

## II. Scope of Studies

The literature on oil oxidation often indicates erratic electrical correlation due to uncertainty as to the degree of the oxidation.[2] In studies of this character empirical methods have often been used,[3] as for example oxidation

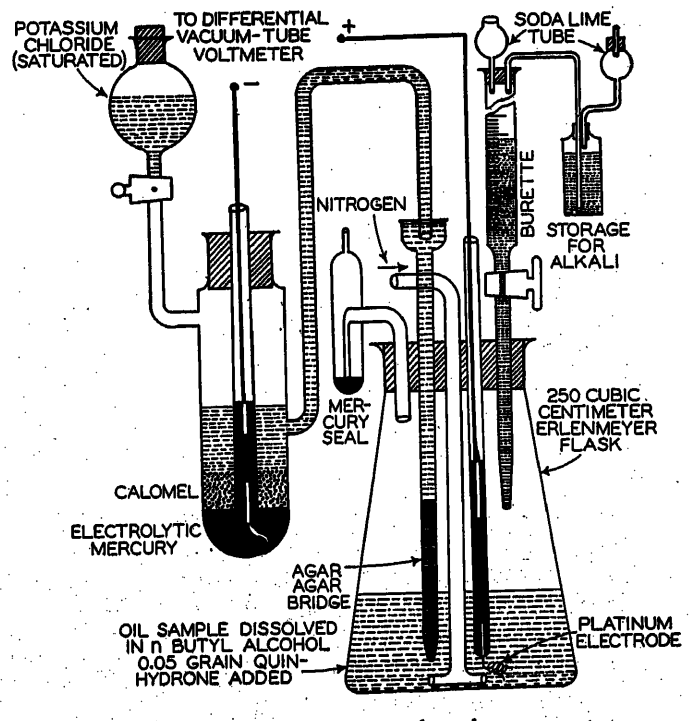



**Fig. 1. Schematic diagram of acidity apparatus**

is measured by the number of hours of heating in air or oxygen. Obviously more accurate methods are necessary.

The chemical quantities here measured are as follows: (*a*) the amount of oxygen chemically absorbed, the rate of absorption, and the reaction constant $k$, at the 3 temperatures 120, 135, and 150 degrees; (*b*) the activation energy as deduced from the results under (*a*); (*c*) acid number; (*d*) saponification number; and (*e*) carbon dioxide evolved; all as related to the amount of oxygen absorbed.

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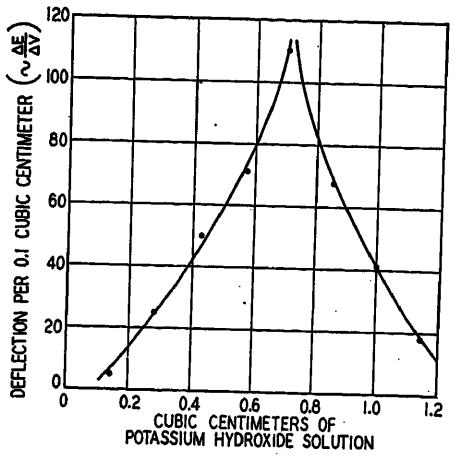



**Fig. 2. Typical titration curve**

The electrical quantities measured are: (*a*) power factor and a-c conductivity; (*b*) dielectric constant; (*c*) short-time d-c conductivity; (*d*) long-time d-c conductivity; (*e*) breakdown strength. Measurements of the electrical quantities were made for various values of acid number and through these related to the other chemical quantities referred to.

When an oil is oxidized acids are formed which dissociate and form new ions. An acidity determination defines the state of the oil in this respect without reference to its earlier history. We have found an excellent correlation between the acidity of an oil, the oxygen absorbed chemically, and certain of its electrical properties.

The saponification number gives an index of the acids combined in the oil which are capable of reacting with metals to form metallic soaps with consequent increases of conductivity and loss.

It has been shown[4] that of the gaseous products of oxidation of an oil, nearly 45 per cent is carbon dioxide. In this work measurements of the amount of carbon dioxide given off at various stages of oxidation show an interesting correlation with both acid number and electrical properties.

So far the studies here described have been made on only one oil. This was furnished by a well-known manufacturer and its properties are as follows:

| | |
|---|---|
| Base | refined light oil |
| Specific gravity at 45 degrees centigrade | 0.877 |
| Flash point, degrees centigrade | 149 |
| Pour point, degrees centigrade | −29 |
| Surface tension at 45 degrees centigrade | 27 |
| Viscosity, poises, at 45 degrees centigrade | 0.133 |
| Viscosity, poises, at 40 degrees centigrade | 0.160 |
| Breakdown volts | 27,500 |

## III. Experimental Method

### Oxygen Chemically Absorbed

Twenty cubic centimeters of the oil were placed in a 50-cubic-centimeter bulb and degasified at less than 1 millimeter mercury pressure. The oil was then saturated with oxygen by shaking for 5 minutes in an atmosphere of oxygen at atmospheric pressure. The bulb was then connected to a mercury burette filled with oxygen and then placed in a thermostat which maintained a constant temperature to within 0.1 degree Centigrade. The oxygen above the oil was maintained at atmospheric pressure. The bulb was then mechanically connected to a shaking machine and shaken at a constant speed of approximately 300 cycles per minute. Burette readings were then recorded as function of the time. This process was repeated for the 3 different temperatures 120, 135, and 150 degrees Centigrade. The oxygen absorption-versus-time curve thus obtained, is a straight line over a long period. The slope of this line, expressed in terms of cubic centimeters of oxygen chemically absorbed per 100 grams of oil per hour, is the reaction constant, *k*. This constant permits the determination of the activation energy of the oil as described below.

### Determination of the Acid Number

The acid number was determined with the method described by Clarke, Wooten, and Kompton.[5] The apparatus consists essentially of a titration cell and a reservoir for the storage of alkali, an electrode system, and a differential vacuum tube voltmeter. A schematic diagram is shown in figure 1. A second tube voltmeter was used to determine the total voltage of the electrode system at any stage of titration. The base electrode is a saturated calomel half-cell which made contact with the solution to be titrated through an agar agar bridge. The chemicals used in the calomel half-cell were specially prepared, and its voltage was 0.558 volt. The indicator electrode consisted of a bright platinum wire dipping into the solution to be examined. This solution consisted of approximately 8 grams of degasified and dehydrated oil dissolved

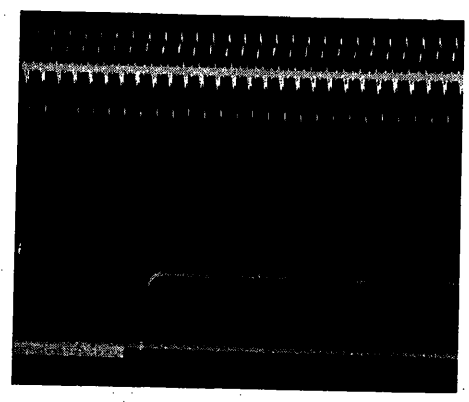


**Fig. 3. Charging current characteristics of undeteriorated oil**

1,000 cycles per second
Series resistance—400,000 ohms
Sensitivity—0.0211 volt per centimeter
*E*—1,500 volts
Power factor—0.000634

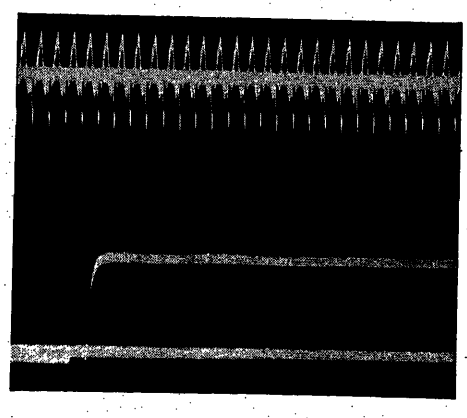


**Fig. 4. Charging current characteristic of most deteriorated oil**

1,000 cycles per second
Series resistance—25,000 ohms
Sensitivity—0.0228 volt per centimeter
*E*—1,500 volts
Power factor—0.01360

in 100 cubic centimeters of *n*-butyl alcohol to which 0.05 grams of quinhydrone had been added. All titrations were carried out in an atmosphere of nitrogen which served both to stir the solution and to exclude carbon dioxide which would lower the neutralizing value of the alkali. The technique of operation is as follows:

The differential voltmeter was first adjusted to read zero by varying a compensating resistor $R_2$. Known increments of alkali from the burette were added and corresponding deflections observed on a milliammeter. After every increment the differential voltmeter was compensated to zero milliammeter reading by adjusting $R_2$. These known equal increments of alkali were added up to, and after a maximum deflection was recorded. For accurate determinations the results are plotted as shown in figure 2, with deflection per 0.1 cubic centimeter as ordinates and total cubic centimeters of alkali added as abscissae. The maximum in this curve corresponds to the end point, that is the point where the slope of the voltage versus titer curve is a maximum. The apparatus as used here had a sensitivity for acid number better than 0.001.

Some observers report a double maximum in the curve of figure 2. This has been studied by Wooten and Reuhle[6] who show that it may appear when the alcoholic potassium hydroxide solution (titer) becomes deteriorated. Clear nonturbid solutions were used in this investigation and there was no occurrence of a second maximum. For the curve of figure 2, 0.715 cubic centimeter of 0.0387 *N* alcohol potassium hydroxide solution was necessary for neutralization of an 8.39-gram oil sample. Titration of the blank solvent had shown that less than 0.01 cubic centimeter of 0.0387 *N* alcohol potassium hydroxide was

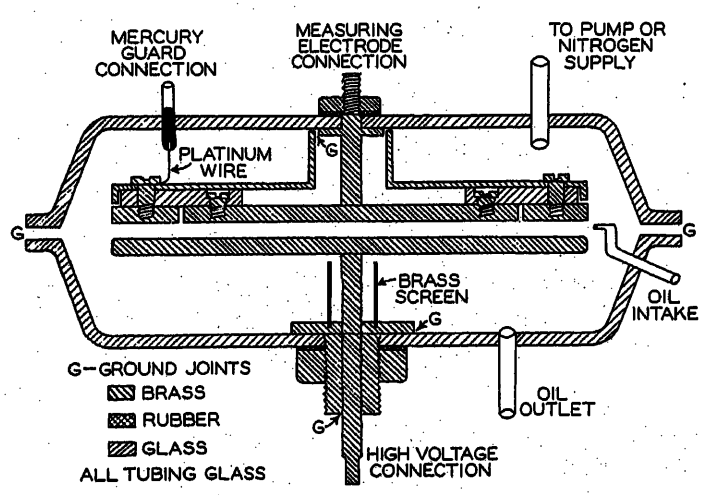


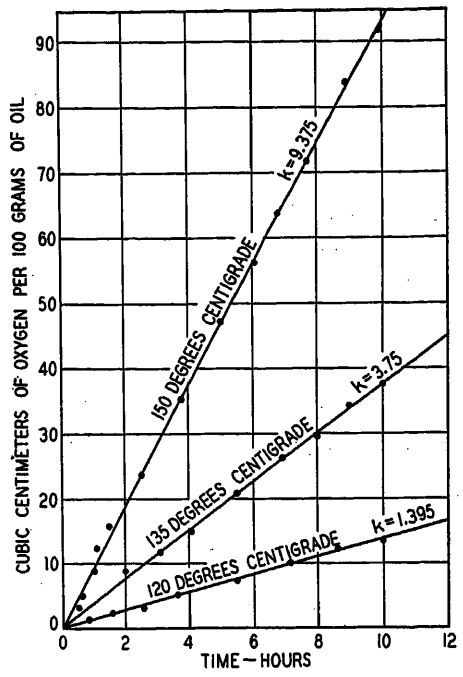

**Fig. 5. Oil cell for electrical measurements**

necessary for neutralization. The molecular weight of potassium hydroxide is 56.11. The acid number is then computed as follows:

$$\text{Acid number} = \frac{(0.715 - 0) \times 0.0387 \times 56.11}{8.39}$$

$$= 0.185 \text{ milligrams potassium hydroxide per gram of oil}$$

**Fig. 6. Oxygen absorption versus time**




### Saponification Number

When an oil is oxidized it may react with metals with which it is in contact to form metallic soaps of high conductivity which are usually soluble in the oil itself. A soap is defined as a metallic salt of a fatty acid. The saponification number is a measure of the amount of acids present capable of forming these soaps. Its determination consists essentially in the boiling of a known quantity of oil with a known quantity of potassium hydroxide. The excess potassium hydroxide not spent in neutralizing acids is then titrated with hydrochloric acid and serves as an index of the soaping value of the oil. The saponification number is expressed in terms of milligrams of potassium hydroxide per gram of oil. Determinations of saponification number in this work were made substantially in accordance with the specifications recommended by the American Society for Testing Materials.[7] Numbers observed were in the range 0 to 3.0 and duplicate determinations agreed within 0.1.

### Carbon Dioxide Given Off

The amount of carbon dioxide formed during the oxidation process was measured at different stages of the measurement of oxygen absorption by bringing the gas above the oil in contact with a potassium hydroxide solution. The difference of burette readings before and after this operation gives the amount of carbon dioxide formed.

### Electrical Measurements

The a-c quantities, power factor, a-c conductivity, dielectric constant, were measured on a shielded high sensitivity Schering bridge as described by Kouwenhoven and Baños.[8] The power factor sensitivity is 0.000006. Measurements were made at 60 cycles supplied from a generator having a pure sine wave. In all these measurements 2 determinations with exchange of the positions of the standard and the oil cells were made.

The a-c conductivity was computed from the dielectric loss and found to be in close agreement with direct measurements of the short time or initial conductivity as measured with the amplifier oscillograph.[9,10] Whitehead[11] has shown that the initial d-c conductivity and the

a-c conductivity of an oil are identical when no polar element is present. Figures 3 and 4 give the oscillograms of the charging currents of the oil in its initial and in its most highly oxidized condition respectively. These curves and the agreement between measured and computed losses indicate the absence of heavy polar aggregates both before and after oxidation.

The long-time d-c conductivity which is approximately constant after 20 minutes of application of voltage was measured with a high sensitivity d'Arsonval galvanometer.

Breakdown measurements were made in accordance with ASTM specifications[12] using a commercial breakdown cup. In all cases the oil was degasified and dehydrated before being placed in the cup. The spread of breakdown values was well within those called for by ASTM specifications.

### Oil Test Cell

The test cell for the electrical measurements consisted essentially of a circular parallel plate capacitor equipped with guard rings as indicated in figure 5. The electrodes were of polished brass. The measuring electrode had a diameter of 13.0 centimeters surrounded by a guard ring 2.54 centimeters wide, with an air gap of 0.16 centimeters. Glass insulation and screening is indicated in figure 5. The capacitance of the cell when empty was 77 micromicrofarads and when full approximately 177 micromicrofarads. The measurements were made at 60 cycles and a stress of 25 volts per mil with electrode separation of 0.152 centimeter.

The electrodes were supported one each in 2 similar glass containers, one of which was inverted, placed on the other with ground surfaces of contact as indicated. The lower container supported the high voltage electrode with a cylindrical screw guard rigidly attached. The top member was coated with tin foil and maintained at guard potential to prevent leakage currents entering the measuring circuit. The test cell held approximately 1,000 cubic centimeters of oil and was so connected as to permit vacuum intake during measurements. The whole cell was enclosed in a thermally insulated box with temperature controlled by thermostat to within 0.2 degrees centigrade and with provision for constant air circulation within the box.

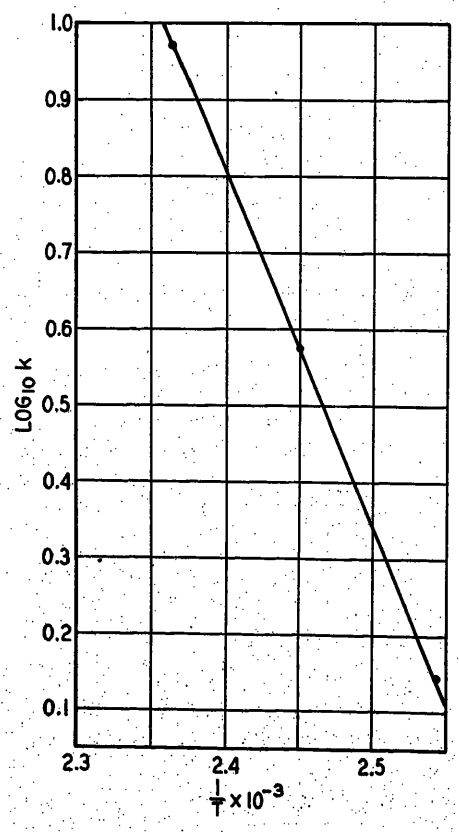



**Fig. 7. $\text{Log}_{10}$ k versus 1/T**

Q = 20,700 calories per mol

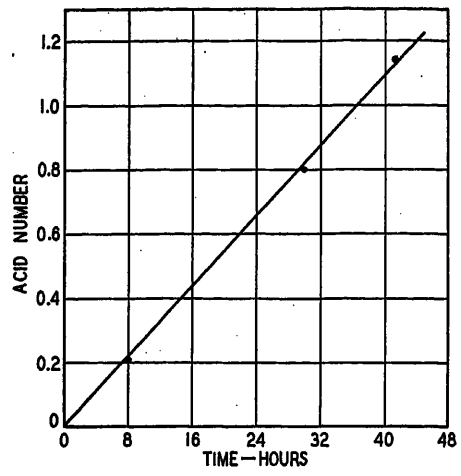



**Fig. 8. Acid number versus time**

Oxidizing temperature—150 degrees centigrade

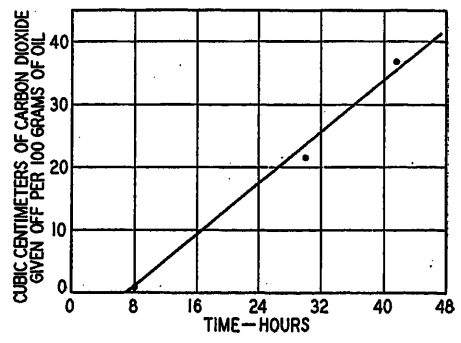



**Fig. 9. Carbon dioxide given off versus time**

Oxidizing temperature—150 degrees centigrade

The oils used in the electrical measurements were oxidized by heating in air at 125 degrees centigrade to various selected values of acidity. Before admission to the test cell each oil sample was given standard evacuation treatment for the purpose of degasifying and dehydrating. This was accomplished by heating the oil to 80 degrees centigrade and admitting slowly into a vacuum of less than 1 millimeter mercury pressure. Thus any water formed during the oxidation process was eliminated before the electrical measurements. The oil was then drawn into the measuring cell without contact with air. Dry nitrogen was then admitted over the oil and maintained at a small positive pressure.

## IV. Experimental Results

The principal experimental results are shown in figures 3 and 4, and figures 6 to 23.

### Chemical Properties

Figure 6 shows the relation between oxygen chemically absorbed and time at each of the 3 temperatures 120, 135, and 150 degrees Centigrade. The ordinates are cubic centimeters of oxygen per 100 grams of oil, and the abscissae, the time in hours. The slope of each of these straight lines is the reaction constant $k$ and is expressed arbi-

trarily in terms of cubic centimeters of oxygen per 100 grams of oil per hour. It will be noted that there is a strictly linear relationship with definite value of $k$ at each temperature. Beginning at zero on the time scale, there is thus no induction period or lagging time of the oxygen reaction. Such lag is often noted at lower temperatures. Thus in the present case lags of 12, 27, and 49 hours were

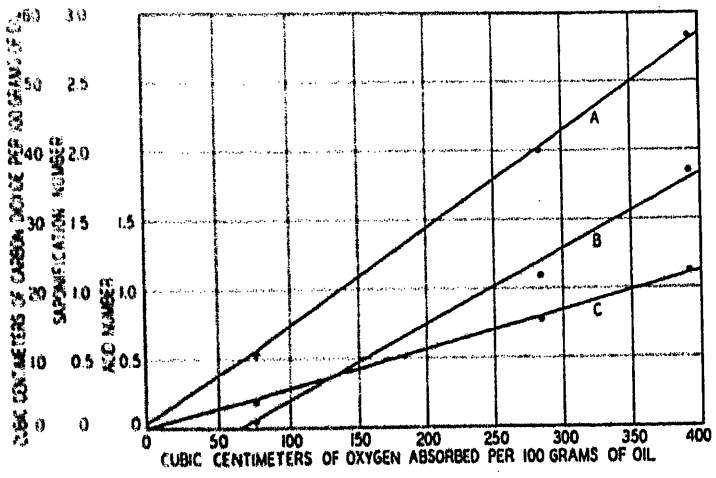



**Fig. 10. Acid number, saponification number, and carbon dioxide given off versus oxygen absorption**

Oxidizing temperature—150 degrees centigrade
*A*—Saponification number
*B*—Carbon dioxide
*C*—Acid number

noted at the temperatures 100, 90, and 80 degrees, respectively.

It is necessary for a molecule to be activated before chemical reaction can begin. For this a minimum quantity of energy is necessary. In the present case this energy, in the form of heat, was found to be constant over the range studied. Thus a determination of the amount of this heat appears to be a good criterion as to the susceptibility of the oil to the oxygen reaction. The activation energy $Q$ may be determined from the data of figure 6 by the use of the Arrhenius equation:

$$\frac{d \log k}{dT} = \frac{Q}{RT^2}$$

in which $T$ is the absolute temperature, $Q$ the activation energy in calories per mol, $R$ the gas constant, and $k$, the reaction constant. On integration of the equation we have:

$$\log_{10} k = c_1 - \frac{Q}{4.58} \times \frac{1}{T}$$

whence $Q$ may be determined graphically by plotting $\log_{10} k$ as function of $1/T$, as shown in figure 7. While only 3 points are available for this curve, corresponding to the 3 temperatures studied, it is seen that they lie accurately on a straight line indicating a constant value of 20,700 calories per mol for $Q$ within this range, with no evidence of a change in slope such as might be caused by molecular disruption or cracking as sometimes proposed.[13] There is clear suggestion here that the activation energy of this oil is constant, at least up to the temperature of 150 degrees.

Figure 8 shows a linear relationship between acid number and time in hours of heating at 150 degrees centigrade, and figure 9 shows a linear relation between the carbon dioxide given off and time of oxidizing at 150 degrees centigrade. In figure 10 the observations of acid number, carbon dioxide, and saponification number are shown together as related to the amount of oxygen absorbed per 100 grams of oil. In obtaining these data 3 samples were drawn for acidity determinations at 8, 30 and 41.8 hours respectively of the continuous oxidation run. The saponification data were taken on a separate run with simultaneous observation of acid number.

In figure 11 the ratio of saponification number to acid number is plotted as function of acid number. It is seen that in the initial stages of oxidation, there are relatively few free acid ions as compared with the acids combined in the oil. On further oxidation the ratio of these 2 concentrations approaches a constant value.

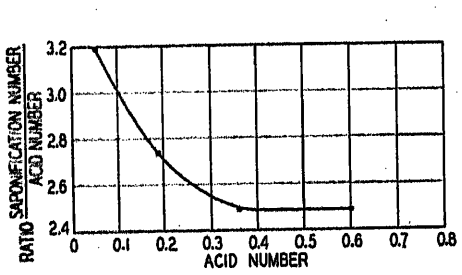
## Electrical Properties

The correlation between chemical and electrical properties is shown in table I, from which the following curves have been plotted.

Figure 12 indicates a definitely linear relationship between power factor as measured at 40 degrees Centigrade and the acid number. Figure 13 shows a similar relation between power factor and saponification number.

Figures 14 and 15 show the variation of dielectric constant with acid number and saponification number, respectively. As seen, these curves are slightly concave upward and indicate an over-all increase of nearly 5 per cent in

**Fig. 11. Ratio (saponification number / acid number) versus acid number**



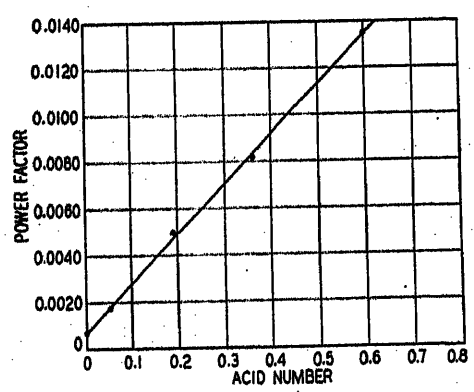




**Fig. 12. Power factor versus acid number at 40 degrees centigrade**

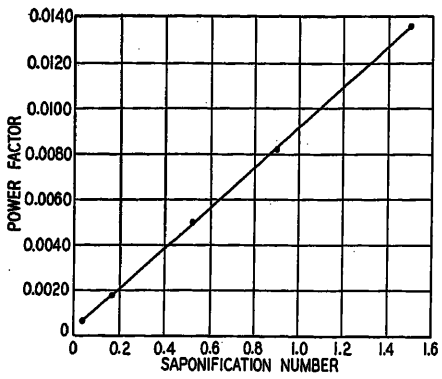



**Fig. 13. Power factor versus saponification number at 40 degree centigrade**

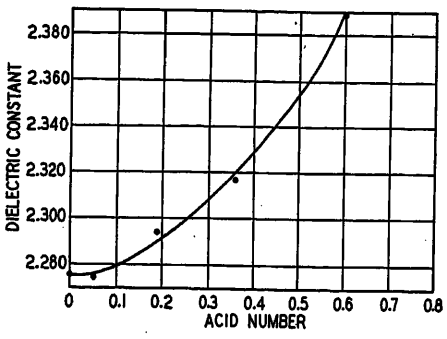



**Fig. 14. Dielectric constant versus acid number at 40 degrees centigrade**

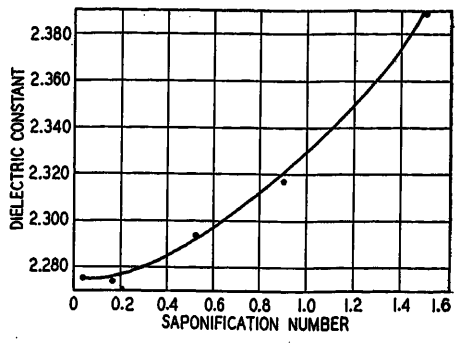



**Fig. 15. Dielectric constant versus saponification number at 40 degrees centigrade**

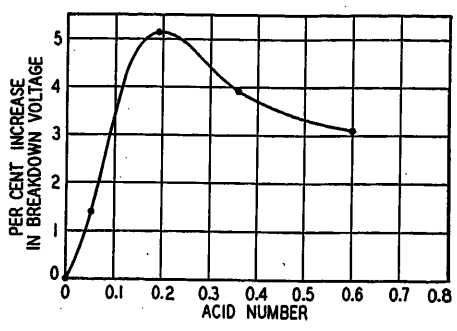



**Fig. 16. Per cent increase in breakdown voltage versus acid number**

Initial breakdown voltage 27,500 volts

dielectric constant over the range 0.0 to 0.6 for acid number.

Figures 16 and 17 show the relationship between breakdown voltage and acid number and saponification number, respectively. It is interesting to note that on initial oxidation, the breakdown strength of the oil increased approximately 5 per cent, and upon further oxidation only a moderate decrease toward the initial value is indicated over a considerable range of oxidation.

Figures 18 and 19 show the variation of final or long-time d-c conductivity with acid number and saponification number, respectively. Final conductivity is seen to vary from $0.2 \times 10^{-15}$ to $154 \times 10^{-15}$ mhos per centimeter over the range studied, an increase of some 750 times.

Figure 18 also shows a curve of computed final conductivity due to free acids. For the purpose of computation, the oil is assumed to have one representative acid having a molecular weight of 150 (Herzfeld[14]) and 2 replaceable hydrogen atoms per molecule. The neutralizing process with potassium hydroxide provides a relation between acid number and concentration of acids in grams per liter of oil. Then using the dissociation constant given by Gemant[15] and the method of the latter, taking due account of viscosity, the value of the final conductivity may be computed. As shown in figure 18 the value so found is of the order of $^1/_{12}$ of the measured conductivity which would seem to suggest some other cause of conductivity than the presence of acid ions. While the figure of 150 for the molecular weight proposed by Herzfeld is quite high the conductivity varies only inversely as the square root of the molecular weight and a substantial reduction in the figure used would still leave a large part of the conductivity unaccounted for.

Figures 20 and 21 show the ratio of the a-c or initial conductivity to the final conductivity as function of acid number and saponification number, respectively. These curves are especially interesting as showing the influence of the oxidation products on the conductivity. For the oil in its initial state, with the acid and saponification numbers practically zero, the ratio of a-c to final conduc-

**Table I—Electrical Results**

| Acid Number* | Saponification Number* | A-C Power Factor | Dielectric Constant | $\lambda_{ac}$— Mhos per Centimeter $\times 10^{-14}$ | $\lambda_i$— Mhos per Centimeter $\times 10^{-14}$ | $\lambda_f$— Mhos per Centimeter $\times 10^{-14}$ | Ratio $\frac{\lambda_{ac}}{\lambda_f}$ | Dielectric Loss— Watts per Centimeter $\times 10^{-8}$ | Breakdown Voltage at Room Temperature |
|---|---|---|---|---|---|---|---|---|---|
| ≦0 | <0.05 | 0.00065 | 2.2755 | 4.93 | 4.81 | 0.02 | 247 | 11.1 | 27,500 |
| 0.052 | 0.166 | 0.00175 | 2.2745 | 13.3 | 12.9 | 1.05 | 12.65 | 29.9 | 27,875 |
| 0.19 | 0.52 | 0.00500 | 2.2940 | 38.3 | 38.0 | 4.54 | 8.45 | 86.2 | 28,900 |
| 0.36 | 0.90 | 0.00820 | 2.3170 | 63.4 | 62.9 | 8.8 | 7.20 | 142.4 | 28,575 |
| 0.60 | 1.50 | 0.01360 | 2.3890 | 108.5 | 108.7 | 15.4 | 7.05 | 244.5 | 28,350 |

Dielectric loss computed at 1,500 volts.
* Expressed in milligrams of potassium hydroxide per gram of oil.

tivity is approximately 247. This ratio decreases rapidly with oxidation and seems to approach a final value. At an acid number of 0.605, the ratio is 7.05. This is in accord with the observations of Whitehead and coworkers[16] that increasing final conductivity is accompanied by a reduction in the value of this ratio.

In figures 22 and 23 the dielectric loss, as computed from the bridge measurement is plotted as function of acid number and saponification number, respectively. The losses were measured at 40 degrees centigrade, 60 cycles and a stress of 25 volts per mil. Values of a-c conductivity computed from the dielectric loss measurements and the initial or short time conductivity, as measured by the amplifier oscillograph were in close agreement, as shown in table 1. The dielectric loss at constant stress varies in linear relation with the acid number following the corresponding variation of the power factor. The variation of dielectric constant with acid number, shown in figure 14 is too small in over-all value to cause an appreciable variation of the dielectric loss from that of its linear relation with acid number.

## V. Discussion

### The Oxidation Process

The linear relation between oxygen chemically absorbed and time, shown in figure 6 indicates that the products of oxidation in the range studied do not act as catalysts for further oxidation. Dornte[17] and Egerton[18] report a "self acceleration" for certain oils, i.e., the products of initial reaction augment further reaction. There is no evidence of such action here.

At low oxidation temperatures there is an initial period at which there is negligible and unstable absorption of

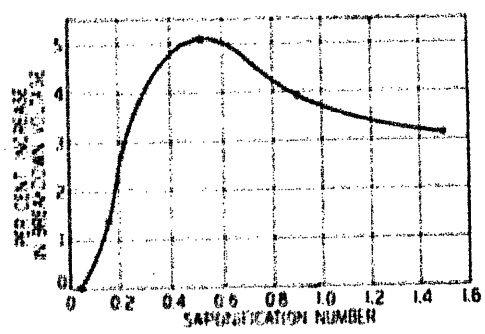



**Fig. 17. Per cent increase in breakdown voltage versus saponification number**

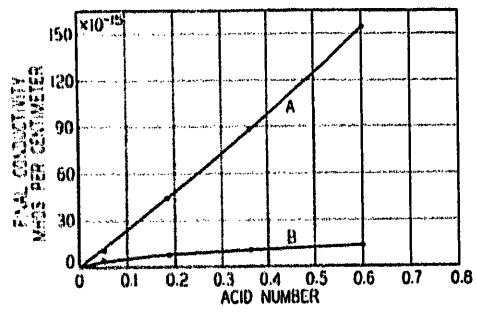
Initial breakdown voltage 27,500 volts

oxygen by the oil. The oil will absorb and then give off oxygen of varying quantities. The duration of this condition is called the "induction period" and its length decreases rapidly with temperature elevation. There is difference of opinion as to the cause of the induction period. Some hold that it is a property of oxidizability of the molecules, others that it is due to impurities in the oil which may act positively or negatively in retarding oxidation. The so-called antioxidants serve to prolong the induction period, whereas a catalyst such as copper shortens it. However, once the reaction begins, the oxygen absorption versus time curves appear to obey the same law, as shown here, and also by Egerton[18] in studies of the same oil (*a*) alone, (*b*) in the presence of copper, and (*c*) when containing an antioxidant. Similar conclusions are to be had from the work of Dornte.[17,19]

The linear relations shown in figure 10 indicate that at 150 degrees for the oil studied there is no induction period in the uniform rise of the values of acid number and saponification number with oxygen absorbed. There is, however, a lag or induction period for carbon dioxide evolved of about 6½ hours. Uniform rises of both acid number and saponification number within this period indicate that the processes leading to the appearance of carbon dioxide also begin uniformly, so continue through the induction period, and on into the actual evolution of

**Fig. 18. Final conductivity versus acid number at 40 degrees centigrade**

*A*—Measured
*B*—Computed conductivity due to free acids




carbon dioxide. In other words, the process is continuous although it may not be immediately evident.

The activation energy is constant over the range 120 to 150 degrees. A part of this energy is obviously expended in the hidden processes of the induction period of carbon dioxide. The 6½ hours of this period measured at 150 degrees is presumably longer at 120 degrees, yet the activation energy is constant over this range. Thus it seems reasonable to conclude that the straight line relation of figure 7 (constant $Q$) may be extended to lower temperatures and that the activation energy is constant in the lower temperature range and at the value determined in the upper temperature range. The activation energy so determined thus appears as a definite measure of the rate of chemical absorption of oxygen or of oxidizability. A sharp change in the slope of the curve of figure 7 would indicate a critical temperature, marking a change in oxidation process. The existence of such a critical temperature at about 120 degrees is proposed by Gemant[13] and others. Karapetoff[20] finds no evidence of such critical temperatures in the work from American laboratories. Dornte[19] in experiments up to 185 degrees Centigrade finds no evidence of a "cracking temperature." Oxidation in insulating oils has long been recognized as a chain process. Dornte [17,19] studying 2 groups of oils found different laws for the 2 groups, but noted that the amounts of each product of oxidation formed over a period of time obeyed the same law as that which applied to the oxygen absorption indicating oxidation as a chain or step-by-step process.

Unfortunately a determination of the value of $Q$ requires much time and is subject to considerable error. The values of $k$, from which those of $Q$ are obtained, may vary in different samples as much as 10 per cent. Thus the

final value of $Q$ found in the present instance is 20,700 calories per mol, with a possible error of about 1,000 calories per mol. The value itself is apparently somewhat low, values as high as 45,000 for oils having been reported by other workers.

Using the value of $Q$ as given above and its relation with $k$ simple computation shows that at 45 degrees Centigrade, the value of $k$ would be 0.0028 and that for saturation

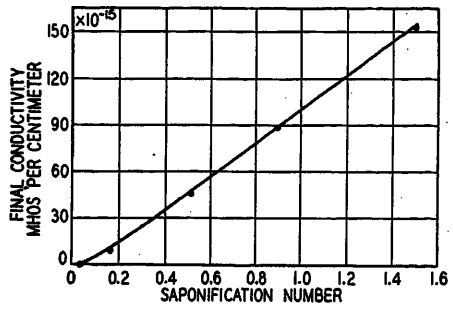



**Fig. 19. Final conductivity versus saponification number at 40 degrees centigrade**

with oxygen this oil would require an induction period of 4 3/4 days. Thirty days after expiration of the induction period, the oil would have absorbed chemically 0.141 cubic centimeters of oxygen per gram of oil. This would cause a change in acid number of 0.0402 or a change in power factor of 0.00086. From these figures, it will be evident that for studies of this character an accelerated program at higher temperatures is imperative.

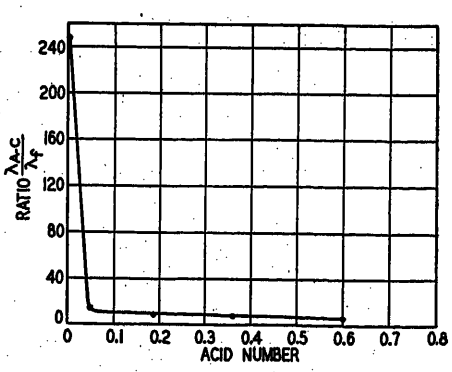
As regards the saponification number and the curve of figure 11 it is apparent that in the initial stages of oxidation there are proportionally more acids combined in the oil capable of forming metallic soaps than there are free acids. This curve as well as the quiescent period for carbon dioxide suggests that the initial oxidation of the oil up to acid number of about 0.2, while increasing acid content uniformly, also has a transient element serving to convert the oil from one oxidation state to another.

## Electrical Properties

Of outstanding interest is the linear relation between acid number and power factor or dielectric loss. The initial or a-c conductivity of an oil is very much larger than the d-c conductivity measured after a long period of application of voltage. There is some evidence[21] that the ions involved in the 2 cases have different origins and perhaps different character. The difference between the 2 types is found only in purer and more highly refined liquids. With increasing impurities or deterioration such as oxidation in an oil, the difference between the 2 conductivities disappears and the ratio of initial to final conductivity approaches unity and the number of ions involved in the initial conductivity is submerged ultimately in those due to the oxidation or other cause. The transfer from the initial pure to a more deteriorated condition is clearly shown in figure 20. It is of interest to note, however, that the range of acid number for which the ions of the initial conductivity play an important part is relatively low. Their contribution to conductivity and power factor, is appreciable in the region of zero acid number, and causes the initial power factor of the oil. However they soon become relatively unimportant with increasing oxidation, nor do they at any point partake of an acid character. Various causes have been suggested for the origin of the ions causing the initial conductivity; as for example, ionic impurities of nonacid character, the liberation of electrons from the electrodes, internal liquid ionization by radio active or cosmic influence. The rate of generation of ions by the latter causes is quite low but over a period of time they accumulate in numbers up to an equilibrium condition, as related to the rates of recombination and diffusion to the walls of the container. They may be swept out temporarily by high continuous voltage, but on open circuit increase again slowly to their original number.[21] From the results of the present work, it is apparent that in the case of a highly refined oil, study of the correlation between the change in electrical properties and oxidation should take due account of the ions already present as shown in the short time conductivity, and of those due to oxidation, especially in the early stages. For later stages of oxidation, however, the initial conductivity plays no appreciable part.

The increase of dielectric constant with acid number as shown in figure 14 is apparently due to the presence of polar molecules, the polar property being well known for the oxidation products of hydrocarbons. The presence of polar aggregates much larger than molecules has been noted by Whitehead, but these larger aggregates are apparently absent in the present case for they are not evident in the short time d-c conductivity oscillograms, nor is there any measurable increase in the dielectric loss due to this cause. The variation in density over the most extended range of oxidation was less than 0.5 per cent indicating that the increase in dielectric constant is not

**Fig. 20. Ratio (a-c conductivity/final conductivity) versus acid number at 40 degrees centigrade**




due in any appreciable measure to increase of atomic polarization.

In the matter of breakdown the transitory period in the oxidation process, involving as it does the molecular structure of the oil, seems to play a part. The breakdown strength increases, due perhaps to the oxidation or clean-up of residual impurities or the break-up of large unstable molecules with loosely connected valence bonds into smaller and more stable molecules. The subsequent de-

crease is apparently due to increased conductivity (Nikuradse[22]).

Considering then oxidation in its influence on the insulating properties of oils, we note 2 notoriously dangerous results, namely, increasing power factor and the evolution of gas. Increasing power factor means increasing dielectric loss and reduction of carrying capacity, and if the increase continues unabated, it leads definitely in the direction of failure. The evolution of gas means gaseous ionization with its well-known rapid destructive influence on fibrous impregnated insulation.

In the oil here studied we have shown a definite linear relation between the oxygen absorbed and the increase in power factor on the one hand, and the amount of gas evolved on the other. Consequently, for oil of this type it is clear that measurements of power factor and gas evolution, as related to oxygen absorbed, should constitute a reliable basis for the comparison of the oxidation stability of different oils. Moreover both measurements are important. At a recent meeting of the committee on electrical insulation, division of engineering and industrial research, National Research Council, R. W. Dornte divides oils into 3 classes as regards the rate with which they absorb oxygen in chemical combination. The oil studied in this paper falls in class (2), showing a rate of absorption directly proportional to the time. Several

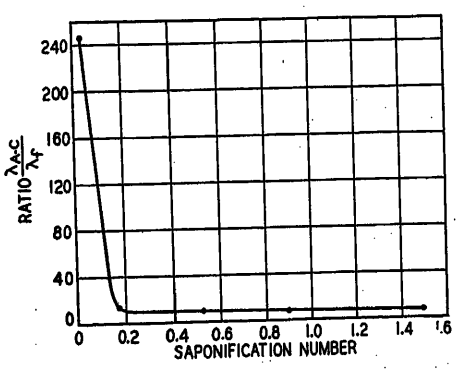



**Fig. 21. Ratio (a-c conductivity/final conductivity) versus saponification number at 40 degrees centigrade**

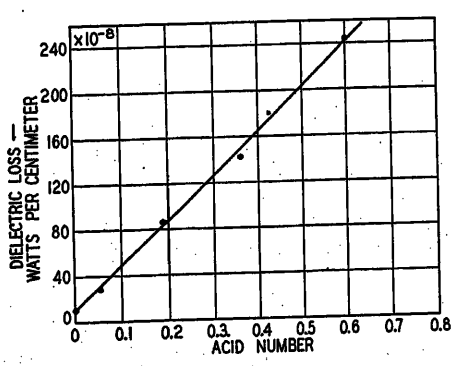



**Fig. 22. Dielectric loss versus acid number at 40 degrees centigrade**

$E$ = 1,500 volts

other papers presented at the same meeting indicated, however, that the oxidation products of various types of oil are proportional to the amount of oxygen and not to the reaction constant $k$ which is a measure of the rate of oxygen absorption. Consequently it appears probable that the above correlations found in the single oil here studied will also be found in other oils.

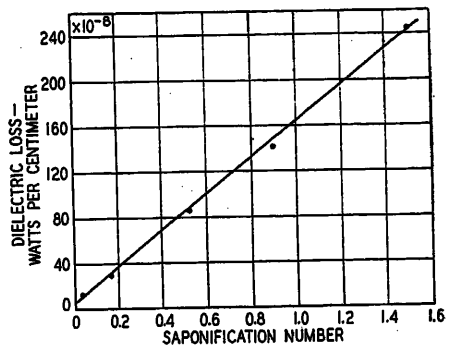
## VI. Conclusions

1. Accelerated oxidation studies have been made on a typical high-grade insulating oil. Linear relations are found over a wide range between the amount of oxygen chemically absorbed and time, acid number, saponification number, and carbon dioxide evolved.

2. Two periods of oxidation are indicated for the oil studied: (*a*) an initial transient period in which intermediate products are formed, (*b*) a subsequent period in which further oxidation does not materially add to the intermediate products, but increases the amount of the end products.

**Fig. 23. Dielectric loss versus saponification number at 40 degrees centigrade**

$E$ = 1,500 volts




3. Similar linear relations have been found between the oxygen absorbed and power factor, dielectric loss, and long time d-c conductivities as measured at 40 degrees centigrade. The ratio of initial or a-c conductivity to final conductivity rapidly decreases with increasing oxidation in its early stages, thereafter much more slowly, indicating different natures for the a-c conductivities of refined and oxidized oils.

4. A relatively small, but apparently characteristic change in dielectric constant with increasing oxidation is due to the polar properties of the oxidation products.

5. With increasing oxidation the breakdown strength at first increases by about 5 per cent, passes through a maximum at about 0.2 acid number, and decreases again. These changes occur in the transient range of the oxidation processes.

6. The linear relation between oxygen absorbed and time leads to definite values of the reaction constant $k$, and to a constant value of the activation energy $Q$. Evidence is presented that the values of these quantities, obtained at higher temperatures, are reliable as good indices of the electrical behavior of the oil as related to oxygen absorption, at lower temperatures.

7. Evidence is presented indicating that the linear correlations found between oxygen absorption, gas evolved, and power factor increase in accelerated oxidation studies provide a reliable basis for estimating the relative oxidation stabilities of insulating oils.

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## Voltage Drop and Load Balance in Open-Y Circuit

(*Continued from page 437*)

feet will be about 1.2 volts and for the lagging phase about 3.2 volts. For a 500,000-circular-mil conductor, assuming the same conditions as for number 8, the voltage drop for the leading phase will be about 2 volts, and for the lagging phase about 1.25 volts.

As indicated by these curves the dashed lines are obtained by the difference in the voltage drop between the leading and lagging phases. At the point where each dashed line crosses the abscissa the difference in voltage drop between the leading and lagging phases is zero, hence the voltage drop is the same on both phases for the indicated amount of unbalancing and the indicated power factor. As shown by the curves for a number 8 conductor and a power factor of 0.9, the leading phase should carry about 60 per cent and the lagging phase about 40 per cent of the load. For a 500,000-circular-mil conductor and a power factor of 0.9, conditions are reversed and the dashed line crosses the abscissa at the point where the leading phase should carry about 40 per cent and the lagging phase about 60 per cent of the load.

Figure 4*A* condenses information about the proper load division between phases at various power factors in order to obtain balanced voltage conditions at the load.

These curves are very useful in determining the correct load balance between the leading and lagging phases in a building where the old d-c wiring is to be used. In such a case, the total load to be carried, the power factor, and the size of the conductors are fixed and the only variable will be the load balance between the 2 phases. The correct load balance can be determined specifically from the curves of figure 4*A*.

It will be noted that these curves have been derived for conditions where the power factors are the same on both phases. An infinite number of other conditions may arise in which the power factors will be different on the 2 phases. If a sufficiently large number of cases occur where certain definite power factors exist, curves of voltage drops for these conditions can, of course, be drawn.

## Power System Faults to Ground

(*Continued from page 433*)

voltage per foot of arc length is practically independent of current magnitude and ranges between about 200 and 400 root-mean-square volts per foot of arc. The results offer a method of estimating, during the first few cycles of an arc, that portion of the fault resistance in the arc. For longer durations of fault, such estimates are likely to be inaccurate unless some idea of the length of extension of the arc can be secured.

(*d*) For steel tower lines carrying ground wires, tower footing resistance will have little effect on fault current magnitude if $l$, the length in miles of the section of line involved, is greater than

$$5\left(\frac{\sqrt{\text{average tower footing resistance}}}{\text{number of towers per mile}}\right)$$

In the case of steel tower lines with high-conductivity ground wires, it seems apparent that arc resistance and tower footing resistance alone will not account for apparent fault resistances of the magnitudes given earlier, indicating that factors other than these are involved.

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## End-Winding Inductance of a Synchronous Machine

(*Continued from page 461*)

$F$ = constant as defined by equations 16 and 17
$h$ = radial dimension in centimeters of the conductors
$K_p$ = reduction factor due to variable pitch
$K_d$ = reduction factor due to distribution of conductors over a phase belt
$K_c$ = reduction factor due to the peripheral distribution of the conductors

$k = \dfrac{bP}{dD}$

$L$ = end-winding self-inductance in henries

$L_{ld}$ = end-winding leakage inductance in henries with the field pole and phase axes coinciding

$l = \sqrt{b^2 + d^2}$

$M_o$ = maximum mutual inductance in henries between field and end winding

$m$ = order of space harmonic

$n$ = number of series connected conductors per pole per phase

$n_f$ = number of turns of the field per pole

$P$ = number of poles

$K_h$ = reduction factor due to the radial distribution of the conductor

$p$ = coil pitch

$q$ = number of phases

$\psi$ = linkage in abampere-henries per pole per phase due to the self-inductance of the end winding

$\Psi$ = end-winding linkage in abampere-henries per pole per phase due to the mutual of the field

$x, y, z$ = rectangular co-ordinates measured in centimeters as shown in figures 3 and 4

$z_1, z_2, x_1, \lambda$ = field coil dimensions in centimeters as shown in figures 6 and 7

$\theta$ = slot pitch in electrical radians

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## A New Magnetic Flux Meter

(*Continued from page 445*)

by means of calibration curves. Another slight disadvantage is that for all readings the current supplied to the bridge must be maintained constant.

The question naturally arises as to whether the bridge can be used for alternating or rapidly varying magnetic fields. Tests made during this research prove that readings are obtained as readily in alternating fields as in stationary fields, but no calibrations have been attempted as yet because of lack of apparatus and time. The reports of previous research [10,11,12] appear to indicate a lag in the change of resistance of the bismuth, though it may not be serious enough appreciably to effect the accuracy of the bridge at low frequencies, perhaps even up to 60 cycles. Further research in the use of the bridge for the alternating flux field appears to be highly desirable.

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## Voltage Regulator Utilizing Nonlinear Circuit

(*Continued from page 464*)

tively. Inspection indicates that operation is completed in 15 to 20 cycles after the disturbance, and that this delay is largely due to the time constants of the machines used rather than the control circuit, which effects the maximum possible change in the rectifier plate current in less than 5 cycles after the disturbance. By its nature, the arrangement is well damped, and no auxiliary circuit was necessary to prevent or reduce hunting.

The regulator arrangement just described would be quite flexible in application since the counter-electromotive-force machine could be designed to control a generator of any size without increasing the tube rating required. In some cases, however, the complication of an extra machine might be undesirable, and therefore the modification shown in figure 6 was developed. The excitation of the alternator is supplied by a standard shunt machine. The shunt field is also connected in the plate circuit of the rectifiers so that the rectifier plate current opposes the exciter field current produced by the exciter terminal voltage. Hence an increase in alternator terminal voltage will produce an increase in rectifier plate current just as before, and this will decrease the total field excitation of the exciter with a corresponding decrease in the exciter terminal voltage thus bringing the alternator voltage back to normal. There will also be the second order effect of the decreased exciter terminal voltage on the exciter field excitation produced by the ordinary action of a shunt machine, and this will be in the proper direction for assisting regulator action. The circuit of figure 6 was even more effective than that of figure 4 utilizing the same machines as before. When properly adjusted, there was no readable change in voltage from full load to no load. The oscillograms shown in figures 7*a* and 7*b* illustrate the speed of operation of the regulator which is again largely a function of the machine time constants.

This method could be applied to large machines by increasing the rating of the tubes used, or by providing an exciter with 2 field windings. One of these windings would be used as the regular shunt field, and the other would be separately excited by the rectifier tubes. By properly proportioning the separately excited winding, small tubes could be used to control the larger machines. The addition of a low-rating single-phase voltage-adjusting transformer between the source and the nonlinear control circuit would permit operation at any desired voltage above or below nominal rating.

## Conclusion

Because of the wide variation possible in machine constants no definite comparisons between this and other types of regulators can be made. Even under the conditions which this circuit was tested, however, it produced sensitivity and operating speed comparable with any of the existing electronic types with the decided advantage of simplicity of design. It has no moving parts, and the only attendance required would be the periodic inspection and testing of the rectifier tubes. Even if both tubes should fail simultaneously in service, a very unusual occurrence, the worst possible result would be the operation of the alternator at light load with a field excitation corresponding to normal voltage at full load. In case of short circuits on the system, the field excitation can only exceed that required to maintain normal voltage at full load by a predetermined amount, and hence the severity of short circuits will be lessened. If the frequency drops, the regulator will still exercise considerable regulatory action at subnormal voltage. If the frequency rises the control circuit will be sensitive at a higher value of voltage, and would regulate for this voltage if the field excitation for maintaining this voltage were available. Usually, however, the field excitation would be only slightly greater than normal full-load value, and the regulator would be inoperative except at light loads.

Thus we see that the regulator herein described has a number of advantages over other types without any apparent disadvantages.

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## Special Uses for the Automatic Oscillograph

(*Continued from page 440*)

110-kv system. Applying the 6 volts direct current to this element gives an offset to the a-c wave during the interval that the tripping circuit is open. This is shown in figure 4. A similar arrangement of connections is made to the carrier receiver relay on the second 132-kv circuit and the d-c offset is obtained on another a-c voltage element of the oscillograph. The oscillograph battery is used for the offset on one circuit, and in order to eliminate the possibility of short-circuiting the secondaries of 2 potential transformers, a separate battery is used for the offset on the other circuit.

With this arrangement it is possible to check the over-all time required for the relays on each circuit to operate and open the trip circuit, and also the time required for them to reset and stop carrier after the fault is cleared. Comparing the times required by the relays on each circuit with the times obtained on the previous calibration and test, will indicate any change in total time which has taken place. A change in the total time may be due to any one of a number of relays, but by checking this total time it is possible to determine when a special calibration and test should be made on the individual relays.

## Conclusions

The operating records shown indicate that the use of the automatic oscillograph in locating faults, affords a means of reducing the cost of patrolling circuits after trip-outs. The annual saving, especially on systems composed of long circuits and whose terrain is subjected to a large number of electrical storms, makes the installation of several automatic oscillographs a profitable investment.

Temporarily connecting the automatic oscillograph to obtain a complete over-all check of the carrier-current-controlled relays is a new aid in insuring the correct operation of the relay protection for all types of trouble.

By using the oscillograph to indicate the performance of the carrier-current-controlled relays for faults both inside and beyond the protected section, complete over-all checks can be made less frequently with a subsequent saving in maintenance costs.

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# Discussions

## Of AIEE Papers—as Recommended for Publication by Technical Committees

ON THIS and the following 4 pages appears a part of the discussion presented at the electrophysics session of the AIEE winter convention, New York, N. Y., January 28, 1937. Other discussion of winter convention papers will be published in later issues. Authors' closures, where they have been submitted, will be found at the end of their respective papers.

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## A-C Characteristics of Dielectrics—II

**Discussion and author's closure of a paper by Alfredo Banos, Jr., published in the December 1936 issue, pages 1329–37, and presented for oral discussion at the electrophysics session of the winter convention, New York, N. Y., January 28, 1937.**

J. B. Whitehead (The Johns Hopkins University, Baltimore, Md.): Only a few years ago our knowledge of the nature of dielectric loss was extremely vague. With increasing importance of dielectric loss and phase difference in high-voltage insulation, however, it was soon realized that the d-c phenomenon of residual charge or dielectric absorption must be related to dielectric loss. Theories as to the cause of dielectric absorption were not then, nor are they now, in quantitative accord with experiment. Consequently Von Schweidler, leaving aside the question of theory, substituted the relaxation function $\varphi(t)$, expressed as current in the normal a-c power expressions, and derived the values of both in-phase or power, and quadrature or capacitance components of the periodic current of a capacitor. These values both involve $\varphi(t)$ which consequently had to be determined for their evaluation. Now $\varphi(t)$ can be determined from d-c experiments. It so happens, however, that $\varphi(t)$ so determined, is rarely such a form that it can be expressed in a single term. All such decaying functions, however, can be expressed as a sum of negative exponential terms, and these are readily handled in the Von Schweidler formulas. If, however, the number of such terms necessary to represent $\varphi(t)$ is large, the computation becomes rather burdensome.

The method of 3 exponentials has been developed because it has been found that in the range of power frequencies, 3 terms are amply sufficient: first, for accurate computation of the a-c loss from the d-c characteristics of the material, second, the division of that loss into its 2 components due to dielectric absorption and anomalous conduction, respectively, and, third, because this analysis provides information upon which studies looking to the improvement of any particular insulation may be based.

The present paper shows that for agreement between computed and measured values of the capacitance component of current, the curve of $\alpha(t)$ must be extended further in the direction of $t = 0$, than is the case for the power component. Bañios has given a very clear analytical explanation of why this is so.

**M. G. Malti** (Cornell University, Ithaca, N. Y.): I have been interested in theories of dielectrics for some time. To me a physical theory consists of linking physical facts with mathematical relations in a one-to-one correspondence so that every mathematical relation corresponds to a certain physical fact and vice versa.

The "method of 3 exponentials" described in this and the previous paper does not state explicitly what the 3 exponentials represent physically. Unless there is a physical basis for the 3 exponentials, I feel inclined to state that the method is purely a curve-fitting process and has nothing to do with the "A-C Characteristics of Dielectrics." Indeed while these exponentials were used by the authors to "fit" the relaxation curve, I see no reason why that same curve could not be just as well (perhaps much better) "fitted" by a polynominal or any other of the myriads of mathematical functions known to mathematicians and engineers.

The point I should like to make is this: Many of the so-called theories of dielectrics have been nothing but curve fitting processes. Unfortunately physicists are too busy splitting atoms and otherwise probing into the constitution of matter to help us with our immediate practical problems of dielectrics and magnetics. Those of us who are concentrating our efforts on such studies would do well to emulate the physicists and devote more attention to the fundamental *physical* phenomena underlying observed facts.

**W. A. Del Mar** (Habirshaw Cable and Wire Corporation, Yonkers, N. Y.): It may seem like quibbling to take exception to the use, by Bañios, of the expression "predetermination of a-c characteristics" but I think that a very incorrect impression of the paper is given thereby. The author's accomplishment is not one of prediction but of correlation between the residual relaxation curve obtained by d-c measurements and the power factor obtained by tests at 60 cycles. This is done by the resolution of the residual relaxation curve into the sum of a series of exponential curves. The same thing would be done by using some other empirical formula for this curve. When one writes a theoretical paper on the predetermination of performance of a dynamo, one implies the ability to predict the performance of the dynamo from the design, before the dynamo is built. In the Bañios paper the dielectric must be in existence and can be tested with alternating current as easily as with direct current.

A means of really predicting power factor of impregnated paper from d-c measurements of oil and paper before impregnation was given by Del Mar and Hanson in June 1922 and the curve given by Hanson for petrolatum impregnated cables (AIEE TRANSACTIONS, volume 41, 1922, page 624) is very striking in its close co-ordination between the prediction and the measured value. This method of predicting power factor is based on the conventional one-minute resistivity of the cable oil. If the residual relaxation function were always the same, a single point, such as corresponding to one minute, would suffice to establish a connection between the one-minute $\frac{dE}{dI}$ or conventional resistivity, such as shown by Hanson's curve. If, however, the residual relaxation function is variable and must be represented by the sum of, say, 3 exponential fuctions, the factors representing the magnitude of these components are likely to vary with different oils and papers and true prediction of power factor (that is, prediction from the properties of the oil and paper, before they are united), will be impossible unless these factors are known for the oils and papers concerned. It would be a worth-while research to develop a simple means of predetermining these factors.

I have a classification for researches which is as follows:

1. Those which are headed somewhere and get there.
2. Those which are headed somewhere and get somewhere else.
3. Those which are headed somewhere and get nowhere.
4. Those which are headed nowhere and get somewhere.
5. Those which are headed nowhere and get nowhere.

When I first read Bañios' paper and my eye was caught by the word "predetermination," I thought that his research belonged in class 2, but I now see that it really belongs in class 1.

**E. W. Greenfield** (Anaconda Wire and Cable Company, Hastings-on-Hudson, N. Y.): As Bañios has pointed out, the frequency function of the quadrature component of absorption permits contributions from the unobserved so called residual relaxation function which must be taken into account in order to accurately predict the a-c dielectric constant from the d-c absorption curves. The initial residual relaxation function is the difference between the relaxation function of the exponential of shortest time constant, and the relaxation function of that part of the initial curve not recorded by the oscillograph and expressed also in exponential series. When this residual relaxation function is large, its contribution is large and the "3 exponential" computed absorption component of capacity will be appreciably smaller than observed by frequency measurements. Another way of expressing the above is to say that the effective time constant of the d-c characteristic as computed from the experimentally taken oscillograms is too large when no account is taken of the initial unrecorded characteristic which has generally smaller time constants. The smaller the time constants, or the steeper the slope, of this unrecorded portion, the greater the deviation between computed and observed values.

If the frequency-capacity variation for the dielectric be available, a check of the range of frequency over which the absorption component of dielectric constant falls before reaching constant value will immediately indicate the range of time necessary for the oscillograph to accurately record the d-c characteristic. Where the dielectric has an extended frequency range of capacity decrease, the time constants or, for simplification, the effective time constant of the exponential function series representing the whole initial d-c characteristic, will be small and considerable contribution can be expected from the higher frequency terms. Where the frequency range of capacity is small, not over 500 cycles per second, oscillograph records starting at one millisecond may yield quite accurate prediction of the absorption component of capacity at 60 cycles.

In the experimental work on dry paper referred to by Bañios, AIEE TRANSACTIONS, volume 53, 1934, page 1389, Whitehead and I have shown in figure 4, curves of capacity plotted against frequency for a cable paper specimen of varying degrees of dryness. Inspection of these curves indicates that the range of frequency over which the capacity is seen to decrease is different for each moisture condition, being smaller in the drier state. For example, when dried at 765 millimeters of mercury, the capacity decreased continuously from its 60-cycle value to become constant at 3,000 cycles per second. On the other hand, for the paper in its driest state, the range of capacity decrease was only over 500 cycles. From this it is evident that the form of the relaxation function of the dielectric has been altered by its change in residual moisture content. This is also evident on figure 5, where the short-time d-c discharge curves of the dielectric are shown. Increase of moisture content is apparently responsible for addition to the relaxation function of components of small time constant, and thus causes an increase of the so-called residual relaxation function. Based on the frequency-capacity curves of figure 4, it may then be predicted that the correlation of absorption component of capacitance between a-c and d-c measurements should be better for the driest condition and poorest for the most moist condition. That this is so is evident from table I, which gives the power factor and capacity analysis of the d-c oscillograph curves. In columns 8 and 9 the agreement between observed and computed values of absorption capacity is generally better as we proceed from moist conditions to dry conditions of the dielectric.

**Alfredo Bañios, Jr.:** I feel grateful to Whitehead for his pertinent remarks which ably summarize both the purpose of our earlier researches and the goal actually attained in these studies. It is clear from our publications that, in this aspect of the work, we have at no time professed to give a theory of dielectrics, but that we have simply brought Von Schweidler's method of a-c computation to the domain of experimental quantitative verification and that, in so doing, we have developed a method of separating dielectric loss into its 2 fundamental components: reversible absorption

and anomalous conduction. The importance of this achievement, not only from the theoretical point of view, but also from the standpoint of high voltage insulation design, is now generally well recognized and need not be further stressed.

In connection with Malti's discussion I must again reiterate that we offer no theory of dielectrics; hence our "3 exponentials," which are only a means to an end, have no physical significance. In fact, casual study of our method of "curve fitting," as explained in our first publication, should leave no doubt that, on account of its inherent indeterminateness, the 3 exponentials lose all hope of ever attaining a definite physical meaning. I do insist, however, that from among the myriads of junctions known to mathematicians and engineers, the exponential function is the best suited for our purpose. Indeed, a clear understanding of Von Schweidler's method of a-c computation depending, as it does, on the determination of 2 infinite definite integrals whose convergence requirements must be carefully inspected, should make it plain why the exponential function is admirably suited for the purpose at hand and why any other function, a polynomial, for example, while fitting the relaxation function accurately for a limited range of time, could not yield at all reasonable values for the $A$ and $B$ integrals in Von Schweidler's method.

Referring to Del Mar's discussion I agree that the title "correlation of a-c and d-c characteristics of dielectrics" would undoubtedly give a better idea of the subject matter treated. I do take exception, however, to the statement that correlation between the d-c characteristics and the a-c power factor could be attained by the use of any empirical equation representing the relaxation function, for, as explained in the preceding paragraph, the exponential is the simplest function which complies with the convergence requirements of the method.

To E. W. Greenfield I wish to express my appreciation for his excellent and thorough discussion of my paper, bringing out clearly the correct interpretation of our results together with an enlightening set of remarks based on his own experimental results which, in themselves, constitute a valuable supplement to our conclusions.

## Dielectric Strength of Transformer Insulation

**Discussion and authors' closure of a paper by P. L. Bellaschi and W. L. Teague published in the January 1937 issue, pages 164–71 and 137, and presented for oral discussion at the electrophysics session of the winter convention, New York, N. Y., January 28, 1937.**

**J. B. Whitehead** (The Johns Hopkins University, Baltimore, Md.): The fundamental dielectric properties of an insulating material can rarely be conserved and maintained through the processes of manufacture, transportation, installation, and operation of assembled equipment. It is for this reason that the results and values obtained in laboratory research may not be immediately applied in manufacture. The paper of the present authors and that of Montsinger, a few months ago, describe results of breakdown tests on oil and laminated materials with almost identical types of test sample. These test samples, however, in all cases employ an electrode with square edges and without guards which is recognized by long experience as being a very unsuitable set-up for a study of the inherent characteristics either of a liquid or a solid. Obviously, therefore, these and similar tests cannot be considered as tests of the properties of the insulating materials, but are tests of these materials in relation to special types of electrodes. Moreover, these electrodes are known to give highly irregular fields, brush discharge, corona, etc., long recognized as disturbing influences in breakdown tests.

These things may be said without in any way questioning the practical importance of such tests. They are evidently designed to cover the actual conditions under which the insulation must be assembled in manufacture. This is obviously a sufficient justification for any design of test sample. I judge that the use of a sharp edge is intentional so as to produce the worst conditions, but if the tests are in accord with measurements on assembled power transformers, as is indicated, the question arises as to whether the breakdown strength of these might not be improved by looking for all sharp edges and rounding them off.

It seems to me idle in view of the conditions of the tests, involving as they do the continued presence of brush discharge and corona, to write formulae for the voltage-time curves, or to speculate as to an explanation of their unusual shape. In view of the results of many careful experiments on the inherent properties of the materials themselves, I strongly suspect that the sharp rise of the curve of measured breakdown voltages for short impulses does not give the actual voltage on the sample, but that within this region the rise of voltage above the horizontal portion of the curve is due to a loss in voltage within the brush discharges, corona, and local capacitances within the sample itself. Support of this view is found in a number of cases in which the solid insulation broke down at points outside the electrode.

**J. R. Meador** (General Electric Company, Pittsfield, Mass.): The authors, under the heading of "Combined Solid and Liquid Insulation," give impulse and 60-cycle breakdown voltages for an insulation barrier consisting of 2 0.056-inch thick fullerboard sheets and 3 1/8-inch oil ducts arranged alternately. The impulse tests were made with waves having durations of from 0.35 microsecond to a full 40 microseconds. Over this range the impulse ratio on repeated applications of voltage is shown to be practically constant at 2.2. In a previous paper ("Insulation Coördination of Transformers—II," by Bellaschi and Vogel, June 1934 issue of ELECTRICAL ENGINEERING) similar tests are made on 2 larger barriers. These tests showed an impulse ratio on repeated applications of voltage of 1.79 and 1.78. Three possible explanations for this difference of impulse ratio are as follows:

1. A change of technique giving different results.
2. A change in the shape or size of the electrodes.
3. A change in the insulation arrangement.

Assuming that the difference is not due to cause 1, it appears that different insulation arrangements and electrode sizes and shapes have an effect on the repeated shot impulse ratio. Consequently, it does not appear logical to use the maximum impulse ratio of 2.2 for determining the impulse test for transformers of all voltage classes.

The tests on the assembled transformers presumably were made without damage to the transformers. If no damage occurred, then the "turn up" of the voltage at short "times" on figure 10 has significance only if the relation between the applied voltage and the breakdown voltage is constant in each region.

With regard to the switching surge tests shown on figure 10, what was the frequency of the switching surges as compared with the lowest natural frequency of the transformer winding?

It has been shown ("Effect of Transient Voltages on Power Transformer Design," K. K. Paluev, AIEE TRANSACTIONS, volume 48, July 1929, page 681) that oscillatory waves caused by switching or arcing grounds may have frequencies comparable with the natural frequencies of transformer windings. This is of importance since an oscillatory wave applied to an unshielded transformer will cause high concentrations of voltage in the winding if the frequency of the wave is within plus or minus 40 per cent of one of the natural frequencies of the winding. If the frequencies of the switching surges represented by the points on figure 10 were considerably less than the lowest natural frequency of the transformer winding, the effect of these tests on the winding was not comparable with the stresses that may occur in service.

**V. M. Montsinger** (General Electric Company, Pittsfield, Mass.): This paper gives very complete data on the volt-time curves on various oil gaps and on single sheets of pressboard. The statement made by the authors that more data were required to establish adequately the volt-time characteristics of insulation needs to be qualified. If they are referring only to the characteristics of oil alone and to solid insulation alone, I more or less agree with them, but if they refer to insulation as used in transformers, particularly major insulation, I must take exception to the statement in so far as it relates to the increase in the breakdown strength for short waves of the order of approximately one microsecond and less.

My experience shows that the volt-time curve of solid insulation and oil in series starts bending up in the neighborhood of 2 to 3 microseconds and bends up considerably more than shown in either figure 6 or figure 7 of the paper. In fact, considering that the volt-time curve of oil alone as shown in figures 3, 4, and 5 starts bending up around 10 microsecond—and the breakdown strength increases in the order of 100 per cent for 1/2 microsecond time—it is to be expected that the volt-time curve of transformer major insulation, where oil is used in series with solid, should not only

start bending up earlier but also should bend up more than shown by the authors' curves for pressboard alone. Figure 4 shown in the closure of my paper "Breakdown Curve for Insulation," given (in the April issue of ELECTRICAL ENGINEERING) at last winter's convention, shows the bend-up in the curve as indicated by tests made by both Vogel and myself on various thicknesses of barriers. This curve shows that the breakdown strength at one microsecond is 25 per cent greater than the full wave breakdown strength and at $1/2$ microsecond is approximately 50 per cent greater than the full wave strength.

Since the presentation of my paper last winter, our Laboratory has made many hundreds of tests to determine the shape of the volt-time curve from approximately 3 microseconds back to $1/2$ to $1/4$ microsecond on barriers of different thicknesses and based not only on single shot breakdown, but on repeated applications of voltage. A still better gauge than repeated voltage breakdown is the point at which corona starts to damage the insulation. This also has been investigated. While the tests are not yet completed, results up to the present time indicate that for full waves the injurious corona point will range anywhere from approximately 70 to 90 per cent of the single shot breakdown depending on the kinds of electrodes used. For bare electrodes with sharp edges injurious corona may start around 65 to 70 per cent while for well insulated electrodes injurious corona may not start until about 90 per cent of the breakdown strength is reached. For average conditions I think we can assume that injurious corona (or breakdown if subjected to sufficient number of shots) occurs at 80 per cent of the single shot breakdown value. This applies to either solid or solid and oil in series.

The shape of the curve is somewhat similar to but does not bend up quite as much as the single shot breakdown curve as shown in figure 1. The purpose of these tests is, of course, to obtain basic data for protecting transformers in service against both long waves and short waves. As it is planned to give the results of these tests in a paper for a later convention, no attempt will be made to present the data in this discussion. It can be seen therefore, that before rules can be drawn up for testing transformers on the front of waves, we must have considerably more data than has been published up to the present.

Last winter when my paper on "Breakdown Curve for Insulation" was presented, the question was raised as to whether major insulation of transformers, consisting of solid insulation and oil in series, had the flat characteristics; that is, the constant breakdown strength over the region in time from approximately 3 microseconds to 1, 2, or 3 cycles of 60-cycle voltage. Since that time tests have been made on a barrier consisting of 2 $1/32$-inch pressboard sheets separated by $1/16$-inch oil duct. The results of these tests are shown in figure 2. It will be noted that where 50 per cent of the space is occupied by oil, the other 50 per cent by solid, the shape of the curve is essentially the same as the curve for a single sheet of pressboard.

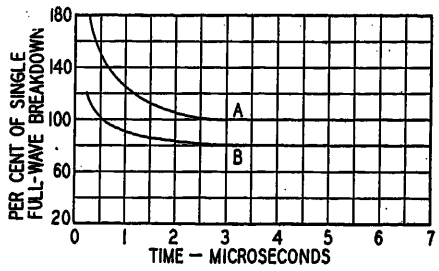



**Fig. 1. Volt-time curves of insulation consisting of solid and oil in series, simulating major insulation in a transformer**

*A*—Breakdown by single application of voltage
*B*—Breakdown by repeated application of voltage (approximate) 1.5 x 40 impulse wave (positive or negative)

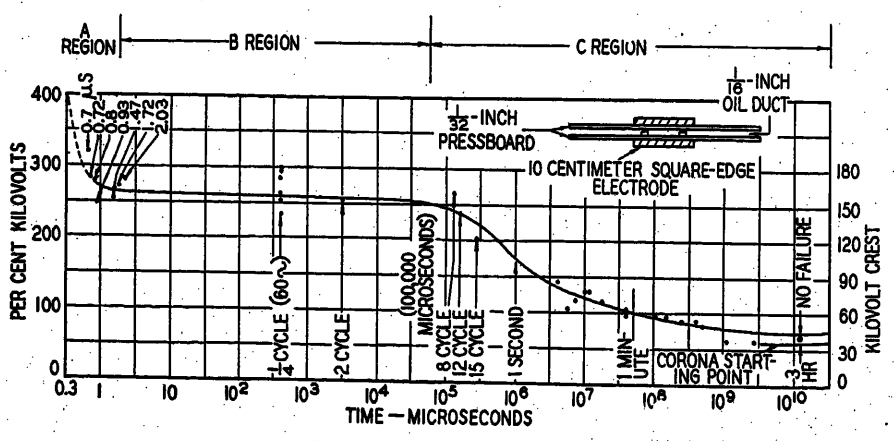



**Fig. 2. Volt-time curve of single shot breakdown of 2 $1/32$-inch pressboard and $1/16$-inch oil duct in series in oil at 25 degrees centigrade**

In view of the results which our laboratory has obtained on the breakdown strength of many barriers on front of wave tests, as compared with breakdown for full waves, I am at a loss to understand why the authors' tests show the same breakdown strength of 300 kv for 0.35 microsecond as for $2\frac{1}{2}$ microseconds on the insulation barrier consisting of 2 0.056-inch thick pressboard sheets and 3 $1/8$-inch oil ducts arranged alternately, as given on page 170.

I believe it can readily be appreciated that the main difference between my views and the authors' views is that the authors feel that when short or front of wave tests are made on transformers, the kilovolt values should not be allowed to exceed the kilovolt values used for the full wave tests, whereas my views, as based on laboratory tests, indicate that a somewhat greater increase in kilovolt values can be used when testing transformers on the front of the wave.

As to the claim that the impulse test kilovolt should be 2.2 times the 60-cycle crest test, many tests made on actual transformer windings have shown impulse ratios varying from about 2.2 to 3, the general average being approximately 2.6. This applies only to single wave impulse strengths of major insulation.

Under repeated voltage conditions the impulse strength of the major insulation is obviously lower than 2.2 to 3 times the 60-cycle one-minute strength, the reduction depending upon the difference between the impulse single voltage application and impulse repeated voltage application strengths of the insulations involved. The repeated impulse strength of transformer windings is in the order of 80 per cent of the single shot strength. That is, it will range from about 1.75 to 2.4 with a general safe average value of approximately 2.0 times the 60-cycle one-minute strength. Therefore for a 138-kv transformer the impulse kilovolt should not exceed $2\sqrt{2} \times 277 = 782$ kv which is quite close to the present AIEE recommended value of 745 kv which is 105 per cent of the bushing flashover.

I. W. Gross (American Gas and Electric Company, New York, N. Y.): This paper is a worthy contribution to the rather meager published data on the electrical strength of insulation typical of that used in transformers. I particularly wish to compliment the authors on the completeness with which they have substantiated their test curves by showing test points in all of their curve data.

In regard to the switching surge tests, it is not clear from the paper if one impulse only was applied or whether the surge consisted of several high frequency cycles similar to actual switching surges recorded in the field by the cathode ray oscillograph. If only one impulse was used it seems possible that the values of insulation breakdown might be somewhat lower than given by the authors.

The tests shown graphically in figure 10 throughout a wide range of voltage conditions on full size commercial transformers are particularly interesting, but the logic behind some of the conclusions drawn from that data is difficult to follow.

First, it is stated the test in region *E* (these being front of wave tests where the wave rose to crest in from $1/2$ to 1 microsecond) encroach on the margin of the

insulation impulse strength. Yet it will be noted one transformer withstood 15 tests in this region, and the other 4 tests. It is hard to understand why they believe the test in this case was excessive, and there appears to be nothing in the paper to bear out this statement.

They further state that "these tests on the transformer are amply indicative that the voltage time characteristics of this and other apparatus of the kind is similar in shape to that for oil and fullerboard." While I do not question the latter part of this conclusion, the fact must not be lost sight of that the transformers *withstood* the tests, but the samples of oil and fullerboard *failed* all under similar voltage test conditions. It seems quite possible, therefore, that the transformers may have a safe impulse strength, at some points on the volt-time curve given considerably greater than the values at which they were tested.

The authors further state that the large number of tests made on the 2 transformers with impulse and 60-cycle voltages "are sufficient to establish the adequacy of a transformer design for practically all conditions of service." This statement assumes a great deal as to service which often may not be reasonably attainable in practice.

I certainly hope their statement is correct; for if so, most of us would cease to worry about many of the refinements in supplying transformers with protection which have recently been advocated.

It is true the large number of tests on these 2 transformers do tend to give us some assurance that transformers can be built to adequately meet a given set of insulation specifications; but I believe we still have with us the practical problem of protecting these transformers under the varying conditions of service encountered in the field.

**P. L. Bellaschi and W. L. Teague:** In his discussion, V. M. Montsinger calls attention to the relation between the impulse strength of insulation for a single voltage application and for repeated applications. His conclusion is that the impulse voltage on transformers should not be more than 2.0 times the 60-cycle one-minute strength, thus for a 138-kv transformer the impulse kilovolts should not exceed $2.0\sqrt{2} \times 277 = 782$ kv. This is an important conclusion to consider as it essentially comprehends the various points considered throughout the discussion. In this connection reference to figure 10 of the author's paper clearly shows that impulse tests up to $2.2\sqrt{2} \times 277 = 860$ kv could be applied repeatedly on the 132-kv transformers, both shell and core types. Similarly, in a previous paper where the fundamental relations on possible insulation deterioration on repeated impulses of long, medium, and very short duration were first set forth ("Factors Influencing the Insulation Coördination of Transformers—II," P. L. Bellaschi and F. J. Vogel, ELECTRICAL ENGINEERING, June 1934), attention was called to repeated tests on 230-kv transformer design at $461\sqrt{2} \times 2.2 = 1430$ kv.

In Montsinger's discussion, he refers to tests made by both Vogel and himself on various thicknesses of barriers, and that they showed an increase in breakdown strength at very short times. I would like to call attention to the fact that Vogel has not published data showing this to be the case for repeated tests, as his data are shown in the paper just referred to. It should also be noted that the data previously reported referred to a particular type of barrier and electrode arrangement, representative of the higher voltage transformers, and not including other arrangements used on lower voltage transformers.

Curve *A* of figure 1 for the breakdown of insulation by single application of voltage is well known. It appears, for example, in figure 1 of the paper cited in a previous paragraph. The curve *B* of figure 1 for repeated applications is interesting, but it is not clear from the discussion whether the author considers this as a specific or a general curve. For example, tests have been made where the corresponding curve *B* rises much higher on very short impulses than indicated in figure 1 ("Direct-Stroke Protection of Distribution Transformers," H. V. Putman, *Electric Journal*, February 1937, page 60). The converse is possible for other apparatus. Curves such as *B* of figure 1 need be clearly specified with reference to the apparatus or test specimen, number of voltage applications, and similar essential information.

Montsinger has presented additional data of interest on the characteristic of insulation over the "region *B*," that is, from some 2 to approximately 100,000 microseconds. His figure 2 further confirms that the voltage characteristic of transformer insulation is practically flat over the entire range of medium and long impulses and switching surges.

The point raised by Meador that change in shape or size of electrodes or in the insulation arrangement may result in different levels of possible damage is quite true as has been discussed in the previous paragraphs. Thus distribution apparatus has a relatively higher strength and endurance to repeated impulses than the higher-voltage class insulation. Again, the ratio of 2.2 indicated in figure 10 has been established by repeated tests.

The question of switching surges in relation to so-called possible resonance effects has always been intriguing. Available data (see, for example, *C.I.G.R.E.*, 1935, paper 353, and similar data published here) indicate that true oscillatory voltages superimposed on the 60-cycle wave are relatively of low value. The higher values that may be encountered are impulsive in character. For these reasons the tests applied to one of the transformers are amply severe both from the standpoint of oscillations and amplitude. Repeated tests running into the hundreds were applied at values $3\frac{1}{2}$ the operating voltage and in addition, as indicated in figure 10 the voltage was raised to 5 times and more the operating voltage. The character of these switching voltages is abruptly steep and enduring for hundreds of microseconds, fully developing all internal oscillations. These would produce stresses more severe than could be accounted for even had the wave been in resonance and of such amplitude as has been encountered in practice. Our own experience has not yet shown failure due to switching causes even on under-insulated transformers.

We well agree with Whitehead that the tests and data in the paper are primarily of an engineering character and are directed chiefly toward engineering progress in insulation co-ordination. Though the results also bear out interesting findings of a theoretical nature. It is amply apparent from this discussion that in the design of apparatus all possible causes of corona should be completely or practically suppressed. The rise in the voltage time-lag characteristics, to which Whitehead refers, has also been found by other investigators both in this country and abroad (on oil, for example, see *C.I.G.R.E.*, 1935).

I. W. Gross rightly raises the point whether the limited tests applied to the 2 transformers in the region *E* (figure 10) do encroach on the insulation, since they withstood the tests. A considerably greater number of repeated tests indicate that damage would result. It is apparent from this cumulative effect that a smaller number of tests would also encroach, in a certain measure on the margin factor of the insulation.

The voltage values in region *D*, *C*, and *B* were limited by the rod gap. Were no gap employed the bushing would naturally set a limit of the same relative order. These hold values should be considered in relation to the major insulation strength and the strength throughout the entire winding for the corresponding stresses set up. To continue these tests to breakdown would require an increase in rod gap spacing or what amounts to the same thing, a higher voltage bushing. Between the ultimate strength and the hold strength naturally a margin exists.

Even after fulfilling by proper design and adequate test the requirements in a transformer, the problem of protection remains. It was not the intention a all to convey such idea that this problem would be dispensed with. One purpose of this paper, supported by the tests, is to call attention to the full significance of the 60-cycle and impulse tests as an index to an expectancy of good service in the transformer. The preceding paper to this one ("Factors Influencing the Insulation Coördination of Transformers—II," P. L. Bellaschi and F. J. Vogel, ELECTRICAL ENGINEERING, June 1934) presents fundamental considerations underlying the problem of protection in relation to the characteristics of substation apparatus. We wish to recall the attention to these principles, even though each case of application may in addition present problems inherent in the particular service conditions.

The switching surge applied in the insulation tests appears in oscillogram *D* (figure 8). The surge is oscillatory; besides 60-cycle voltages of equally great amplitude were applied the insulation for several oscillations, indicating with adequate assurance that the voltage-time characteristic for the various possible conditions of switching can hardly be other than a flat curve. The transformer was subjected (figure 1) to a large number of repeated surges at $3\frac{1}{2}$ times the operating voltage, then in addition at 5 times and more as indicated on figure 10. These switching voltages are abruptly steep and enduring for hundreds of microseconds, comprising a severe test.

# News

## Of Institute and Related Activities

# Elihu Thomson—

## March 29, 1853—March 13, 1937

CONCLUDING one of the longest, most varied, and most fruitful careers in electrical engineering, Elihu Thomson died at his home in Swampscott, Mass., on March 13, 1937, just a few days before his eighty-fourth birthday. Indisputably the dean of American electrical engineers, he was regarded as being second to none among the small group of his contemporaries upon whose inventive genius the electrical industry of the world was founded and through whose perseverance and keen foresight it grew.

Recognized for his character and ability, and honored by his contemporaries throughout his lifetime, few men, if any, have contributed more to the progress of the world than did Elihu Thomson, and fewer still have lived to see such full fruition of their ideas. He was one of the last of the original group of great electrical pioneers.

His signature was on the "call" for the May 1884 organization meeting of the AIEE, and Doctor Thomson became a charter member of the Institute. He maintained an active affiliation for the remainder of his life. He is survived by only 3 other charter members whose names still appear on the active list. Although not caring for administrative work, preferring to remain "in the ranks" and closer to his work, Elihu Thomson was elected a vice-president of the Institute in 1887 and immediately upon completion of his term in that office became in 1889 the fifth in the line of great leaders who have guided the Institute's destiny.

Doctor Thomson was particularly active in local Institute affairs, and a perusal of the AIEE PROCEEDINGS prior to 1910 will show that he presented papers and discussions at many Section meetings. He served as a member of the Institute's committees on co-operative research and standardization from 1898 to 1900, and as chairman of the Edison Medal committee from 1911 to 1915. Thomson was not a prolific scientific writer, but the character of his writings is attested by the following papers published in the AIEE TRANSACTIONS:

1. NOVEL PHENOMENA OF ALTERNATING CURRENTS, volume 4, May 1887, page 160.

2. MAGNETISM IN ITS RELATION TO INDUCED ELECTROMOTIVE FORCE AND CURRENT, volume 6, May 1889, page 269.

3. PHENOMENA OF ALTERNATING-CURRENT INDUCTION, volume 7, April 1890, page 132.

4. COMPOUNDING DYNAMOS FOR ARMATURE REACTION, volume 12, June 1896, page 288.

5. A NEW FORM OF INDUCTION COIL, volume 14, July 1897, page 225.

6. CONDITIONS AFFECTING STABILITY IN ELECTRIC LIGHTING CIRCUITS, volume 28, January 1909, page 1.

In 1904 the Institute, in response to an invitation by an organization of associates and friends of Charter Member Thomas A. Edison, undertook the responsibility of making the awards of a gold medal now known as the Edison Medal. Elihu Thomson, in 1909, was the first to receive the award "for meritorious achievement in electrical science engineering, and arts, as exemplified in his contributions thereto. . . ."

In June 1928 the Institute was priviliged to give further recognition to Thomson's services and achievements. The constitution provides that Honorary Members may be chosen, upon the *unanimous* vote of the board of directors, "from among those who have rendered acknowledged eminent service to electrical engineering or its allied sciences." Prior to June 1928 the few distinguished persons thus elected all were from foreign countries, but at that time Thomson's name was included in a list of 5 outstanding American engineers unanimously endorsed by the directors.

### THOMSON'S EARLY LIFE

Elihu Thomson was born March 29, 1853, at Manchester, England, to an English mother and a Scotch father. The family came to the United States in 1858, settling in Philadelphia, Pa., where Doctor Thomson attended the public schools. Completing his preparatory education at the age of 11, he had to wait 2 years to meet the minimum age of 13 years required of high school entrants. During this 2-year period, with the encouragement of his parents, he devoted himself to his experiments and his hobbies. He constructed a friction type of electric generator from a wine bottle, and built Leyden jars to be charged by his generator; these and the other similar electrical apparatus of the time were followed by such things as batteries, and electromagnets and telegraph instruments in which the bare wire used for the windings was insulated by the laborious task of winding thread around it by hand. While still a child his interest in astronomy led him to construct his own telescope with the help of a friendly lens maker. In later life he continued the pursuit of this hobby, building powerful telescopes himself and grinding his own lenses.

After he graduated from Central High School early in 1870, he entered a laboratory as an analyst, but was appointed assistant professor of chemistry in the high school later in the same year. In 1876, at the age of 23, he was appointed professor of chemistry in the same school, but he had become deeply interested in the applications of electricity, and in 1880 resigned to devote his entire time to electrical research and development. He always had been fascinated by physical and chemical studies, and especially by electricity.

Possessed of a natural knack for construction and the use of tools, he gave what time he could spare from other duties to making such apparatus as he needed. In this way, before the age of 20, he had built induction coils, electromagnets, cameras, chemical balances, and many other devices. In his early twenties he constructed numerous pieces of scientific apparatus for demonstration and laboratory use, including a compound microscope; also numerous electrical machines and a pipe organ with electrical action for which he made the pipes, windchest, bellows, keyboard, and all other parts.

### INDUSTRIAL DEVELOPMENT

When Doctor Thomson resigned his professorship at Central High School in 1880, he took charge of the commercial development of an arc-lighting system for the American Electric Company, a small firm that had been started in Philadelphia in 1879. At the same time E. J. Houston, his colleague at the high school and later a president of the Institute, resigned his teaching position and joined him in the business. Later in the same year the company moved to New Britain, Conn. E. W. Rice, Jr., subsequently a president of the Institute and president of the General Electric Company, accompanied Thomson as an assistant. In 1883 the modest establishment at New Britain was moved to Lynn, Mass., a "Lynn Syndicate," as it was called by Thomson and his associates, having bought control of the American Electric Company. At Lynn the name of the company was changed to the Thomson-Houston Company, and during these pioneer years Doctor Thomson was "electrician" and chief engineer, and many of the fundamentally important inventions upon which the business was established and grew were his. He shunned administrative duties, and the commercial destiny of the company was largely in the hands of Charles A. Coffin.

In 1892, the Thomson-Houston Electric

Company and the Edison General Electric Company were merged to form the General Electric Company. Thomson remained as consulting engineer and director of the Thomson Research Laboratories at Lynn. By his own choice he devoted his time and efforts to research and development rather than to administrative work. Charles A. Coffin became the first president of the new and rapidly expanding company.

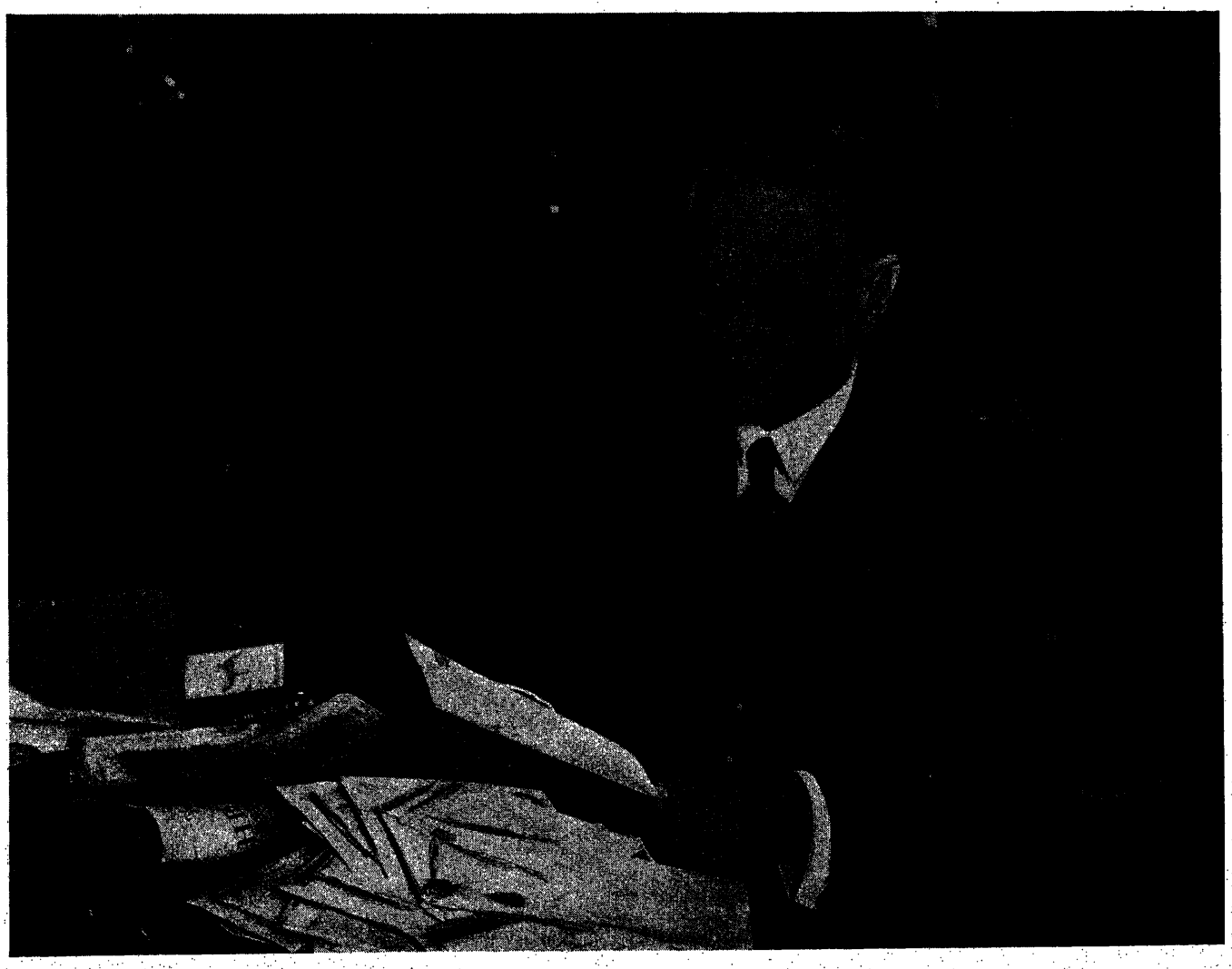
### Honors Conferred on Thomson

Elihu Thomson probably was the most honored scientist in America. He was acclaimed by several colleges and universities, receiving the honorary degrees of master of arts (1890) from Yale University, doctor of philosophy (1894) from Tufts College, doctor of science from Harvard University (1909) and the University of Manchester (England) (1924), and doctor of laws from the University of Pennsylvania (1924). He was awarded many prizes, medals, and decorations, and had the distinction of being the only man to receive all 3 of the most important scientific medals of Great Britain: the Hughes Medal of the Royal Society, the Kelvin Medal, and the Faraday Medal of the Institution of Electrical Engineers. The Royal Institution of Great Britain elected Thomson an honorary member, the highest scientific honor that Englishmen can confer upon a foreigner. The complete list of awards, decorations, and medals received by him is impressive:

1. John Scott Legacy Medal, for electric welding, 1888
2. Grand Prix, Paris Exposition, 1889
3. Appointed officer et chevalier of the Legion D'Honneur, 1889
4. Certificate of award of gold medal, Columbian Exposition, 1893; no medal was received
5. First prize, Trans-Mississippi and International Exposition, Omaha, Nebr., 1898
6. Grand Prix, Paris Exposition, 1900
7. Rumford Medal, for electric welding and lighting, 1901
8. John Scott Legacy Medal, for constant-current transformer, 1901
9. Grand Prize, Louisiana Purchase Exposition, St. Louis, Mo., 1904
10. First Edison Medal of the AIEE, 1909
11. Elliott Cresson Medal of the Franklin Institute, 1912
12. John Fritz Medal, 1916
13. Hughes Medal of the Royal Society, London, England, 1916
14. Kelvin Medal, 1924
15. Franklin Medal, of the Franklin Institute, 1924
16. Faraday Medal, Institution of Electrical Engineers, 1927
17. Medal of the Verein Deutscher Ingenieure, 1935

In 1925 Thomson was designated as "father of protective grounding" by a resolution adopted by the Western Association of Electrical Inspectors. He was one of 6 official United States delegates to the chamber of delegates of the electrical congress in Chicago in 1893; president of the International Electrical Congress in St. Louis in 1904; a member of the World Engineering Congress at Tokyo, Japan, in 1929; and a United States delegate to the International Electrical Congress at Paris, France, in 1932. Many technical and scientific organizations including the Institute, had conferred honorary membership upon Doctor Thomson. These were:

1. Franklin Institute
2. Institution of Civil Engineers (Great Britain)
3. Institution of Electrical Engineers (Great Britain)
4. Royal Institution (Great Britain)



**A photograph showing Doctor Thomson on his eightieth birthday, reading some of the many congratulatory letters that came to him from all parts of the world on that occasion**

# In Memoriam

## ELIHU THOMSON

DR. ELIHU THOMSON, a charter member, the fifth president, and an honorary member of the American Institute of Electrical Engineers, died at his home in Swampscott, Mass., on March 13, 1937, about two weeks before his eighty-fourth birthday.

Beginning his electrical experiments at the age of eleven, when he had completed his preparation for high school but found it necessary to wait two years to meet the minimum age requirement for entrance, he built and operated several types of equipment, and quickly demonstrated his ability in fundamental science and also his remarkable inventive genius. After graduating from the Central High School in Philadelphia and teaching chemistry and mechanics in that school during the next ten years, he resigned in 1880 to devote his entire time to electrical research.

The American Electric Company which he joined soon became the Thomson-Houston Company and the latter merged, in 1892, with the Edison General Electric Company to form the General Electric Company, with which Dr. Thomson was connected until his death.

His more than 700 inventions included many of outstanding importance which added materially to scientific knowledge and laid the foundation for many significant developments in the electrical industry. The combination of marked scientific ability, broad vision, sound judgment and pleasing personality gave him a position of outstanding leadership throughout his long career.

He received the first Edison Medal awarded by the Institute, and received many of the most notable medals in the world, having been the only man to receive all three of England's highest scientific honors, the Hughes, Kelvin, and Faraday medals. He received several high honorary degrees, including Ph.D. ScD., and LLD. He was elected an Honorary Member by the AIEE and several other societies, and received other high honors in the United States and abroad.

Entering the Institute as a charter member, he immediately became active in its affairs, and was a vice-president 1887–89, and president 1889–90. He also rendered valuable services to the Institute as member of various important committees and as its representative in joint activities. He was transferred to the grade of Member in 1891 and to the grade of Fellow in 1913. He was elected an Honorary Member in 1928.

RESOLVED: That the Executive Committee of the American Institute of Electrical Engineers, upon behalf of the Board of Directors and the membership, hereby expresses its keen regret at the death of Doctor Thomson, and its deepest appreciation of his many outstanding contributions to electrical engineering progress, and be it further

RESOLVED: That these resolutions be entered in the minutes and transmitted to his family.

—AIEE Executive Committee, March 25, 1937.

5. Alumni Association of Massachusetts Institute of Technology
6. American Electrotherapeutic Association
7. American Welding Society
8. American Society of Mechanical Engineers
9. Illuminating Engineering Society
10. New York Electrical Society
11. Engineers' Club, New York, N. Y.
12. Western Association of Electrical Inspectors
13. New England Roentgen Ray Society
14. American Institute of Electrical Engineers

### Outstanding Accomplishments

Perhaps the first great contribution to electrical engineering made by Elihu Thomson was his invention, in about 1879, of the 3-coil dynamo with its automatic regulator and other novel features, which formed the basis of the first commercially successful lighting system. This was manufactured by the Thomson-Houston Company in the early 1880's and quickly found its place not only in the United States, but also in several European countries. The machine was entirely automatic in its operation, and was so adjusted that it could maintain constant regulation of a system of many electric arcs, regardless of the number of arcs that might be turned on or off. The need for such a regulator and its general nature were suggested to him by his earliest serious electrical studies, which concerned the relations between the voltage and current in an electric arc, and which led him to the discovery that as the current increases the voltage decreases. This relation accounted for the instability of the arc and indicated what characteristics the dynamo should have. This 3-coil dynamo was a d-c machine, for at that time direct current was more easily handled than was alternating current, and had certain advantages for arc-lighting purposes. The same machine, however, with different connections, constitutes the 3-phase generator that is so important in present electric power installations, and was so represented by Thomson in his original patent application.

While he was working on his arc-lighting system, Thomson heard that Edison was tinkering with an incandescent lamp. Accordingly he went to Menlo Park to discuss the matter with Edison, who gave him a model of the lamp. This model subsequently was dissected by Thomson and Houston, with the decision that it never would amount to anything.

### Lightning Protection—Magnetic Blowout

About 2 years later, in 1881, he invented another important electrical device: the magnetically operated lightning arrester. Although this arrester was created for the particular purpose of protecting his arc-light systems from lightning, it was the invention of a fundamental method of breaking electrical circuits that has found numerous applications, one of the most important of which was by Doctor Thomson himself in control contactors for electric cars and trains. The device consisted of an insulator so placed between the poles of a magnet, and the whole so arranged with respect to the contacts or electrodes, that any arc forming was forced by the magnetic field to elongate itself to the breaking point, thus quickly and effectively interrupting the circuit. This principle is of as much importance today as it was then, for it is the foundation of several modern systems of switching large currents.

### Power Transmission

In those very early days of electrical engineering, long before the importance of electric power transmission and distribution was realized generally, Thomson devised the now commonly used method of transmitting electrical energy, stepping it down from high voltage with the aid of a local transformer for local consumption. This was set up as a working model for demonstration at the Franklin Institute in Philadelphia in 1879. A patent was applied for in 1885, and after a strenuous period in the patent office a fundamental patent for multiple-arc distribution systems with transformers was granted in 1902. During this same time Thomson developed and patented the procedure of grounding the secondary of the transformer as an additional safety measure for high-voltage operation. A notable characteristic of Doctor Thomson is indicated by his advice to the General Electric Company that this patent should be dedi-

## Future AIEE Meetings

**North Eastern District Meeting**
Buffalo, N. Y., May 5–7, 1937

**Summer Convention**
Milwaukee, Wis., June 21–25, 1937

**Pacific Coast Convention**
Spokane, Wash., Aug. 30–Sept. 3, 1937

**Middle Eastern District Meeting**
Akron, Ohio, Fall 1937

cated to the public, because no patent or invention dealing with public safety should be restricted or made unavailable for general use.

### Developments on the Transformer

In the further development of a-c machinery, he invented the constant-current transformer and the induction regulator, in which a movable secondary or primary coil could be adjusted automatically to give constant-current output. For the purpose of increasing the power capacity of transformers, he proposed in 1887–89 the use of oil for cooling and for insulation purposes, and further called attention to the deleterious effect of moisture in the oil.

### Resistance Welding—Repulsion Motor

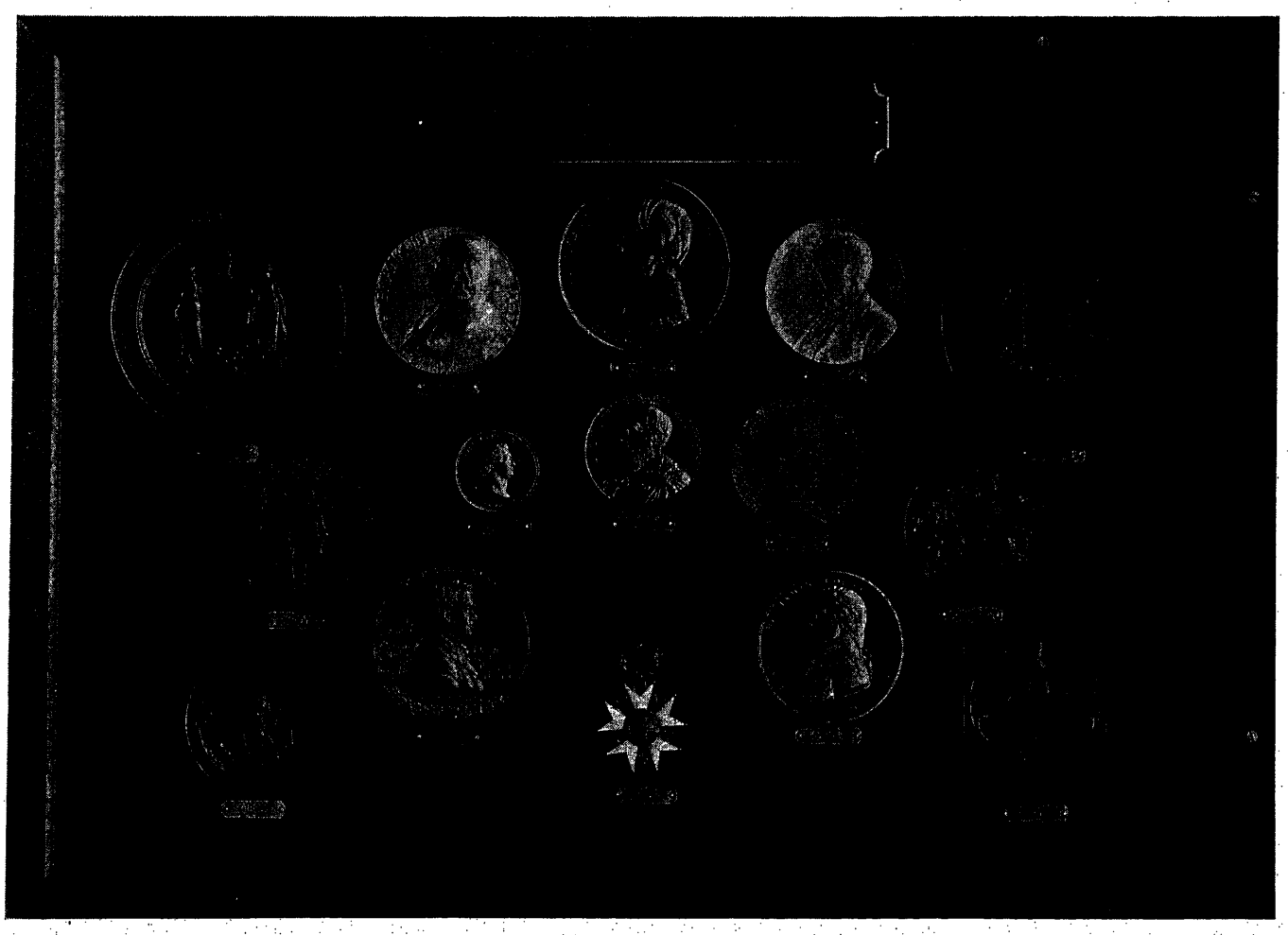
One of the most important of Thomson's contributions to industry was his discovery of the principles and development of the resistance process of electric welding, whereby the welded surfaces were fused and united by the heat produced by the resistance in the contact between them. Although Elihu Thomson was not the first to utilize the electric arc in welding, the fundamental Demeritens patent was bought by the Thomson Electric Welding Company on Thomson's advice and, had arc welding developed within the life of the patent, that company would have controlled the arc- as well as the resistance-welding art.

Another of Thomson's most fundamental discoveries was the principle of dynamic repulsion between a primary and a secondary coil, which he demonstrated by simple experiments. A vertical iron core was wound with a coil through which an alternating current could be passed. The core projected above the coil into a jar of water. Fitting loosely around the core was a second small coil, free to slip up and down the core in the water, and supporting by its terminals an incandescent lamp. When an alternating current was sent through the primary coil, a current was induced in the movable secondary coil, which lighted the lamp and at the same time raised the coil against the force of gravity high up in the jar of water. This scientific observation subsequently was developed by Thomson into an a-c repulsion motor.

### Meters—High-Frequency Apparatus

During the years 1885–95 Doctor Thomson was busily engaged in the development of electric meters, especially recording wattmeters. For his wattmeter he was awarded the Grand Prix of the Paris Exposition at a competition held after the exposition in 1889.

As early as 1890, and continuing intensively for several years thereafter, he conducted a series of experiments on high-



**A collection of the medals and decorations conferred upon Elihu Thomson**

Top row (left to right): John Scott Legacy Medal, for constant-current transformer, 1901; Franklin Medal, of the Franklin Institute, 1924; Faraday Medal, Institution of Electrical Engineers, 1927; John Fritz Medal, 1916; and John Scott Legacy Medal, for electric welding, 1888

Middle row (left to right): Grand Prix, Paris Exposition, 1900; Elliott Cresson Medal of the Franklin Institute, 1912; Kelvin Medal, 1924; Hughes Medal of the Royal Society, London, England, 1916; and Grand Prix, Paris Exposition, 1889

Bottom row (left to right): First Prize, Trans-Mississippi Exposition, Omaha, Nebr. 1898; Edison Medal, 1909; Legion D'Honneur, officier et chevalier, 1889; Rumford Medal, for electric welding and lighting, 1901; and Grand Prize, Louisiana Purchase Exposition, 1904

A gold medal was awarded to Doctor Thomson at the Columbian Exposition, in 1893, by certificate of award, but no medal was received; he also received in 1935 the medal of the Verein Deutscher Ingenieure, which is not shown here

frequency alternating currents, building the foundation for many of the developments in radio and other high-frequency applications in use today. He constructed one of the first high-frequency dynamos, if not the first; a machine operating at frequencies of from 30 to 40 times as great as any previously built. In conjunction, he designed some of the earliest high-frequency transformers. While Thomson was working in this field he discovered a method of producing alternating currents of still higher frequencies from a d-c arc by shunting the arc with inductance and capacitance. This interesting method of producing alternating currents later was applied to radiotelegraphy by Poulsen, and therefore is generally known as the Poulsen arc. Thomson also discovered that the insulating power of oils at these high frequencies is much greater than at ordinary commercial frequencies, if the insulating power is measured in terms of the path through which the arc passes.

Incidentally, Thomson is credited with having discovered the principle of the tuned electric circuit, and with having been the first to use the method in electrical communication. This was done very early in his career, while he was still a professor at Central High School, in performing some experiments in wireless signaling that preceded the famous experiments of Hertz by about 12 years.

Immediately following the announcement of the discovery of Roentgen rays, Doctor Thomson began a series of experiments and developments in connection with X rays. The foundation for this work had been laid by his previous experiments on electrical discharges through gases at low pressures, and led to the first application of stereoscopic methods in X-ray technology only one year after Roentgen rays themselves had been announced. This work led to various practical improvements in the design of X-ray tubes. Thomson also took an interest in the physiological effects of X rays.

Elihu Thomson also was active outside the domains of electrical research. Working with Houston, while they were at Central High School, he perfected his centrifugal machine for the separation of liquids of different densities, the forerunner of the widely used cream separator and the laboratory and commercial centrifuge. He also devised the fluid-pressure engine and the fused-quartz mirror for astronomical telescopes. In his own name he held more than 700 American patents.

### Thomson the Man

In his private life as a citizen, as well as an inventor, Elihu Thomson endeared himself to his neighbors and his fellow workmen and always was considered to be a wise counselor in civic affairs. Even outside his laboratories he was always engaged in some research project as a hobby. A lifetime hobby was astronomy, in which he was active as an amateur from an early age. He also was interested in microscopes, color photography, and in building and playing pipe organs. He had a host of friends, not only in the United States, but also in Europe.

His aspect of life is characterized by his own words "No greater joy has come to me than the joy of accomplishment. Then too, I have had the satisfaction of aiding in giving employment to large numbers of intelligent men and women."

Doctor Thomson was a member of many organizations in addition to those that had awarded him honorary memberships, including:

1. American Academy of Arts and Sciences (fellow and member of the Rumford committee)
2. American Association for the Advancement of Science (fellow)
3. American Astronomical Society (member)
4. American Chemical Society (life member)
5. American Electrochemical Society (member)
6. American Mathematical Society (member)
7. American Optical Society (member)
8. American Philosophical Society (fellow and past-president; also a past member of the council)
9. American Physical Society (fellow and life member)
10. Pi Gamma Mu, national science honorary society (life member)
11. British Association for the Advancement of Science (life member)
12. Engineers' Club of London, England
13. Société Française des Electriciens (member)
14. Commercial and Merchants Club of Boston, Mass. (member and past-president)
15. Engineers' Club of Boston (life member)
16. Boston Press Club (life member)

and 22 other societies and clubs of local, national, and international character.

Doctor Thomson was particularly interested in educational work. His vast store of experience and knowledge always was at the disposal of his younger, less experienced associates, among whom he was noted for his ability to explain the most abstruse subjects in simple, understandable language. He was affectionately known to them as "the Professor," a simple "friendly" title that he strongly preferred in spite of his many degrees. He was a life member of the Corporation of Massachusetts Institute of Technology, a member of the executive committee of the corporation, and twice served as its acting president.

For many of its most fundamental contributions—technical, ethical, and humanistic—the profession of electrical engineering is indebted to Elihu Thomson.

### Thomson as Seen By Some Institute Leaders

**Arthur E. Kennelly,** president 1898–1900—I had the privilege of knowing the late Professor Thomson for many years. He was endowed with great abilities as an engineer, inventor, researcher, and teacher. His special fields of work were in applied physics, chemistry, and mechanics. He was a pioneer in electric power transmission and distribution, as well as in electric welding, an art which he founded and highly developed. He was an excellent designer and constructor of electric machinery and apparatus. Many of the machines and instruments used in the early days of the electric power industry were constructed under his design and superintendence. At one time he constructed a 25-centimeter telescope, lenses and all, with his own hands. He introduced and developed the existing prevalent types of electric motor-driven energy meters, registering in kilowatt-hours.

He was a tireless scientific worker from early boyhood. At 17 years of age he was assistant professor of chemistry and at 22 was professor of chemistry in the Central High School of Philadelphia, where, in his leisure time, he made important inventions in electric power transmission.

He never allowed any of his time to be wasted. His was a kindly, engaging, and stimulating, personality. As a leader in electrical engineering he was admired and esteemed by thousands.

**Charles F. Scott,** president 1902–03—As I recall Professor Thomson, several specific incidents come to mind, trivial perhaps, but characteristic.

One afternoon some 12 or 13 years ago we had been in conference in Boston on some committee matter and found ourselves with a couple of hours to spare. We strolled about the city as he led the way to some particular photographic shops, in his search for films for color photography in which he took great interest. I was never more impressed with the great simplicity and ease of his manner and conversation.

To me, Professor Thomson always was a great electrical pioneer. Later I had met him, principally in AIEE activities. But, in strolling with him through the streets of Boston, I realized that my once mystical hero was very human; in simple companionship, he even insisted on accompanying me to my place of departure.

On the occasion of the celebration of his eightieth anniversary held in 1933 at Massachusetts Institute of Technology, I asked him what it was at the centennial exposition in Philadelphia in 1876 that aroused his interest in electricity. Immediately a smile came over his face and with a twinkle in his eye he said, "I will tell you. There was a Gramme dynamo there from France which operated one arc lamp, and there was another dynamo for electroplating, and another which lighted the lamp on the top of the building." This memory meant a great deal to him as it later on shaped his whole career.

He told me also an interesting incident "The Rhumkorff coil uses a low-voltage current for producing a very high voltage. I wondered if the process could be reversed and the high voltage current in the fine winding would produce a current in the heavy winding. I was fearful of the results and put off the experiments until I had a coil of my own. I placed the ends of the heavy terminals close together and observed carefully when the Leyden jars were discharged through the fine wire coil. There was a flash and when I attempted to separate the terminals I found them solidly welded together. That was the beginning of my work in electric welding."

His curiosity, his readiness to experiment, his observation, and his practical deductions from his experiments were the beginning of a new art.

And it seems to me that these qualities of simplicity and modesty, and his following along the lines prompted by his curiosity and interest, indicate qualities which were inherent in the man and have influenced his whole career.

**Dugald C. Jackson,** president 1910–11—Elihu Thomson was great as an engineer, as a scientist, and as a citizen; and in each

category he has received deservedly high recognition. I first met him when he was 35 years old and I was 21, and the impression of his fascinating enthusiasm for the development of electrical engineering and his fertile approach to difficult problems of experimental science has never left me. It has seemed to me that those qualities in Thomson have equally stirred others and led to the wish to honor him that has been displayed internationally.

Being, by intellectual nature, a great inventor, Thomson directed his qualities into human service, and the world is indebted extraordinarily to him for his productions. At least one of his original inventions, electric welding, has become a great industry of itself as well as contributing advantages to many industries. Numerous others of his productions have widely influenced industry and contributed to human comfort. The death of Thomson takes a great man from electrical engineering and a great citizen from the nation.

**Gano Dunn,** president 1911–12—Elihu Thomson's magnificent scientific and engineering accomplishments have made history. To me his personal influences was as great as his intellectual influence. He always had in mind the inventor, the engineer, the student, as well as the invention, the design and the study. This will forever cause him to be rated as one of our greatest teachers as well as one of our greatest engineers and scientists.

It was to him I early owed recognition that all engineering, notwithstanding its tremendous economic involvements, rests inseparably upon science. His lectures and papers were marvels of exposition. A talk with Elihu Thomson invariably stimulated thought and fired ambition.

His methods of work and qualities of character formed the careers and won the undying affection of large numbers of the generation of engineers who now mourn his loss.

**Frank B. Jewett,** president 1922–23—Appraisal of Elihu Thomson and his contributions to the advancement of electrical engineering in the light and power field can best be made by those who were his close associates in the many sectors of it which were enriched by his scholarly mind.

Outside the field of our common interest in the welfare of the American Institute of Electrical Engineers, in which our association commenced, my long and close friendship with Dr. Thomson has hardly been involved with things electrical. It has been concerned mainly with matters of general scientific interest and in the problems which came to us as fellow members of the Corporation of Massachusetts Institute of Technology.

Above all other things, however, it has been as an esteemed friend that I have known, admired, and loved Doctor Thomson. His versatile and cultured mind, his simplicity, and his joy in the simple worth-while things of life, which did not diminish with the years, made him a friend to be cherished.

Quite outside the boundaries of his professional life, his death will deprive the world of one of its choice spirits.

**H. P. Charlesworth,** president 1932–33—Doctor Thomson's investigations and inventions contributed enormously to the advance of all the engineering arts. However, his contributions went further than these individual activities. In addition to publishing his results and methods, his enthusiasm and technique were passed on to hundreds of engineers, first as a professor, later as a director of the laboratories which bear his name, and finally as a great leader in his profession. His fruitfulness was shared with others whom he had trained and inspired. His whole life was indeed in accord with and greatly contributed to the highest ideals of the engineering profession. It is not surprising, therefore, that his name is among the illustrious group who were the charter members of the American Institute of Electrical Engineers which ever is endeavoring to perpetuate these high ideals.

**A. M. MacCutcheon,** president 1936–37—One of my greatest regrets is that I did not have the privilege of a close personal acquaintance with Doctor Elihu Thomson, but I am fortunate in having met him. His writings have been an inspiration to me even as far back as my student days.

His deductions, his inventions, and his achievements form a cornerstone in the theoretical structure which represents the engineering knowledge of our time.

His modesty, his cheerful optimism, his breadth of vision, his clear thinking, and his indomitable spirit formed a pattern which all engineers may well emulate.

He was a charter member of the American Institute of Electrical Engineers and its fifth president. We who have followed in his footsteps, looked upon him as an inspiration, a valued counselor, a guiding light.



Elihu Thomson in his laboratory, studying the heavens through his telescope. Astronomy was his life-long hobby

### Elihu Thomson as Seen By Some Industrial Associates

**Owen D. Young,** chairman, General Electric Company—Mr. Thomson was one of the few great pioneers in the electrical field who had the rare good fortune to see his vision become a reality and to receive the appreciation of a justly grateful world for his contribution to the health and happiness of people everywhere. The General Electric Company was always proud of his intimate association with it.

**Willis R. Whitney,** vice-president, General Electric Company—Professor Thomson was one of the leaders who helped in the estab-

lishment of the Northeastern Section of the American Chemical Society back in '97 or '98. We New England chemists knew him as an expert in our field, just as the electrical engineers recognized him as pre-eminent in their field, and the mechanical engineers as a leader in theirs. Astronomers also knew that he was of their group. He was an all-round scientist.

When the General Electric Company offered me the research work at Schenectady, I was in doubt as to my fitness and as to the quality of the opportunity until I hurriedly consulted "the Professor." He was very kind, as always, and was quite clear that the opportunity offered me was a great one. So I owe a large part of the satisfactions I have enjoyed during the past 36 years to Professor Thomson's kindly interest. Through those years my admiration and affection for him steadily increased, and in his death I feel a great personal loss.

**Gerard Swope,** president, General Electric Company—Since the very beginning, Professor Thomson was associated with the General Electric Company and its predecessor bearing his name, the Thomson-Houston Company. His accomplishments for these companies and many others throughout the world bearing his name and for the entire electrical industry were many and conspicuous.

His interest in research, his enthusiasm for new ideas, and the advancement of young engineers continued almost to the day of his passing. His memory will long be cherished by those who knew him, and he leaves a fine tradition and inspiration for those who follow him.

**William D. Coolidge,** director, General Electric Research Laboratory—In the death of Professor Thomson, the General Electric Company has suffered a great loss. Its earliest products were for the most part the offspring of his brain. Great in engineering and invention, he played a most important rôle in the early development of the electrical art. He was a pioneer in arc lighting, was the father of electric welding, devised the first commercial recording wattmeter, and produced by the score the various devices needed for making electric generation and distribution reliable and safe.

He was a true scientist, and by example and precept established the tradition of scientific research in the General Electric Company. When the research laboratory of the company was founded, he served on its advisory council, and, by his experience, wisdom, and fertility in ideas, was of great help to the laboratory in its early years.

His breadth of knowledge, mental alertness, and originality made association with him delightful and stimulating, while his kindliness and simple sincerity won the affection of all who knew him. I was privileged to know him well, and I feel the loss of a great and good friend.

**Karl T. Compton,** president, Massachusetts Institute of Technology—In his own character and in his great achievements he was one of the truly great men of his century. In all the years of his interest in the Institute [MIT], he displayed a loyal and active faith in the social values of technological education.

Professor Thomson's loss to this institution and all others would be irreparable were it not for the fact that his nobility of character will remain as a lasting inspiration, and his scientific achievements will continue permanently to confer immeasurable benefits to the world.

## Lightning Reference Book To Be Issued Soon

Culminating more than 2 years of work carried on by the lightning and insulator subcommittee of the AIEE power transmission and distribution committee, the AIEE Lightning Reference Book is scheduled to be issued in July.

Lightning and its effect upon electric power systems and apparatus have been under investigation for more than 20 years during which many articles of interest and value have been published in the technical literature. Heretofore this extensive literature has been available principally only through library research. Now, recognizing the value of a conveniently bound volume containing the full reproductions of texts, illustrations, and tabulations of all important material that has been published on the subject of lightning, the subcommittee has completed the selection of just such material for just such a handy reference volume.

The Lightning Reference Book will be about the size of the current annual volumes of AIEE TRANSACTIONS and similarly bound in durable green cloth. It will contain some 1,550 pages, 8½ by 11 inches in size, in which will be reproduced in full some 230 technical papers and articles selected by the subcommittee from the technical press of the past 18 years for their important and practical utility to all those in any way interested in the study of, or the protection against, lightning

A comprehensive subject and author index will facilitate the ready reference use of the volume and, for those who may wish to carry their pursuit further, 200 additional technical papers and articles of a supplemental nature not included in the volume will be fully covered in the indexes.

The announced price of the Lightning Reference Book is $6.00 to members and $7.50 to nonmembers, plus postage in either case (10 pounds shipping weight).

### ADVANCE ORDERS REQUIRED

A limited edition only will be issued. The actual number of volumes to be published will be governed by the number of advance orders on file at AIEE headquarters, 33 West 39th Street, New York, N. Y. by May 15, 1937 (with reasonable allowance for overseas mail).

The several hundred advance orders that have been on file the past year have made possible the prosecution of this project to successful conclusion with publication now imminent. All persons wishing to increase standing orders, or to place orders, must do so immediately to be assured of receiving the volume.

Further details and a convenient order coupon are given on page 4 of the advertising section of this issue.

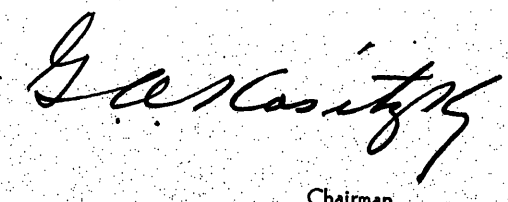
## Membership—

Mr. Institute Member:

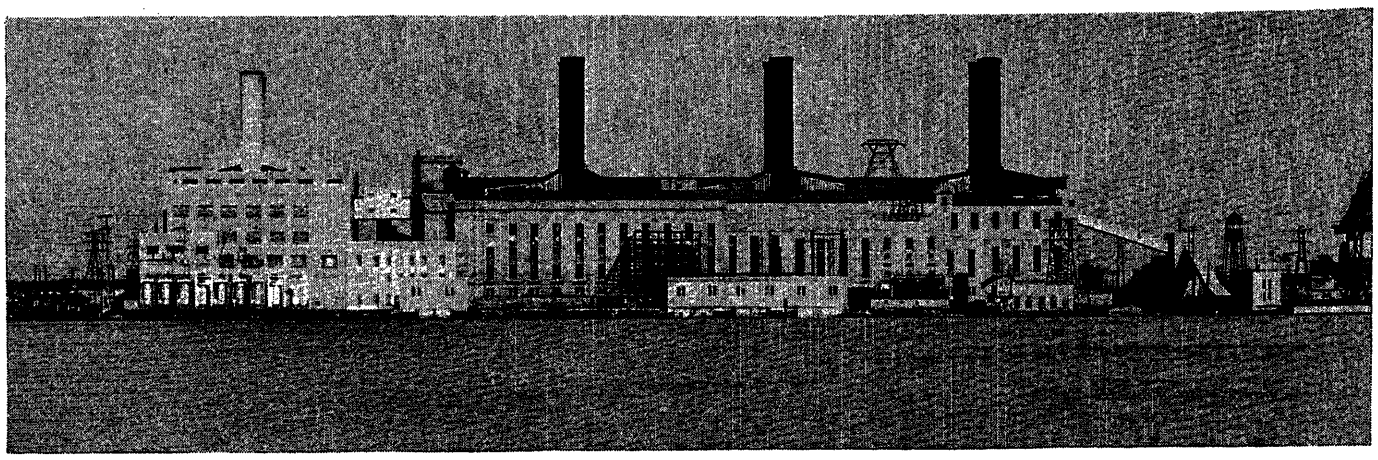
Have you finished reading that recently distributed pamphlet entitled "Membership in the American Institute of Electrical Engineers"? It does a fine job of sketching the activities of the Institute—don't you agree?

Please do not forget to pass it along to some non-member who is eligible for membership. Also, if you can interest him in becoming a member, recommend him by using the stamped and addressed card furnished with the pamphlet. He will receive application blanks and necessary information promptly.

Your Membership Committee thanks you sincerely for the very good co-operation you have given it throughout the year. With your continuous service, we shall surely reach our goal of twenty-five per cent more applications than last year.



Chairman
National Membership Committee



Huntley stations of the Buffalo General Electric Company

# North Eastern District Meeting and Student Branch Convention

THE annual meeting of the North Eastern District of the AIEE and student Branch convention will be held in Buffalo, N. Y., from Wednesday to Friday, May 5–7, 1937. The meeting headquarters will be in the Hotel Statler. Buffalo "the gateway to the west" with its many diversified industries makes an ideal convention city and the local committee has taken full advantage of the situation and arranged a very attractive program. Thus there is a trip to the new $22,000,000 hot and cold strip mill of the Bethlehem Steel Company, Huntley stations 1 and 2, some of the hydroelectric stations at Niagara Falls, the Ford Motor Company's plant, and several of the other industries, not to mention a very attractive trip for the ladies, including the marvelous spectacle of Niagara and its color illumination. Entertainment has been arranged for the evenings and men prominent in Institute affairs are on the program. Registration will take place in the Hotel Statler from 9:00 a.m., Wednesday, May 5.

### Technical Sessions

The opening session will consist of an address of welcome by A. C. Stevens, Institute vice-president for the North Eastern District, which will be followed by a series of papers of outstanding interest to all who are connected with the central station industry. These papers include the latest information in the field of lightning investigations on transmission lines, the application of automatic oscillography, operating performance, research, and testing.

On Thursday, May 6, a general session will be held at 9:30 a.m. which will be opened with a greeting by President MacCutcheon. This session will feature conductor vibration studies illustrated by motion pictures, surveying telephone service requirements, and design trends in steel mill electrification. In the afternoon the electrical features of the new Bethlehem 72-inch strip mill will be described by F. D. Egan and his talk will be followed by a trip to the plant. On Thursday morning a student technical session will be held at which papers will be presented by the students.

**Table I—Hotel Rates**

| Hotel and Location | Room Capacity | Single | | Double | | Twin |
|---|---|---|---|---|---|---|
| | | Without Bath | With Bath | Without Bath | With Bath | |
| Arlington, 136 Exchange | 150 | $1.50 | $2.00 up | $2.50 up | $3.50 up | $4.00 up |
| Buffalo, Swan and Washington | 450 | | 2.00 up | | 4.00 up | 4.50 up |
| Fairfax, 715 Delaware | 400 | | 2.50 up | | 4.50 up | 5.50 up |
| Fillmore, 207 Delaware | 60 | | 1.75 up | | 3.00 up | 3.50 up |
| Ford, Delaware and Cary | 750 | 1.50 up | 1.50 up | 2.50 up | 3.00 to 4.00 | 3.25 to 4.00 |
| Graystone, Johnson Park | 150 | 1.50 up | 2.00 up | 2.50 up | 3.00 up | 3.00 up |
| Lafayette, Lafayette Square | 420 | | 2.50 up | | 4.50 up | 4.50 up |
| Lenox, 140 North St. | 200 | | 2.00 up | | 3.50 up | 4.00 up |
| Men's, Genesee and Pearl | 283 | 0.75 to 1.25 | | 1.50 & 2.00 | (Master bathroom on each floor) | |
| Statler, Niagara Square | 1,100 | | 3.00 up | | 5.00 up | 6.00 up |
| Stuyvesant, 245 Elmwood | 450 | | 2.00 up | | 3.00 up | 4.00 up |
| Touraine, Delaware | 300 | 1.75 | 2.00 up | 3.00 up sharing bath | 3.50 up | 4.50 up |
| Westbrook | 312 | | 2.50 up | | 4.00 up | 6.00 up twin 3-room suite |

On Wednesday evening a talk and demonstration on "Fiber Glass" will be given by L. W. W. Morrow, general manager of the fiber glass department of the Corning Glass Works. All who know Mr. Morrow and his ability to give an interesting talk will look forward to a very enjoyable evening. On Thursday evening directly following the informal dinner another very instructive, interesting talk and demonstration will be given. The subject will be "Kodachrome Colored Film" by L. D. Mannes, co-inventor, of the Eastman Kodak Company. After the lectures dancing also may be enjoyed in the hotel.

### Women's Entertainment

In addition to the foregoing entertainment the following has been specially arranged for the women guests of the Institute. Buffalo is a large, smartly metropolitan city, possessing beautiful parks and suburban areas.

**Wednesday, May 5**

A trip to the incomparable Niagara Falls. Leaving at 11:00 a.m., the party will cross the Peace Bridge and drive down the beautiful Canadian Boulevard. After luncheon, there will be an inspection trip of the Falls and the Niagara Rapids, followed by dinner in the modern General Brock Hotel, from the roof garden of which can be seen another interesting view of the cataract. At 8:00 p.m. the illumination takes place and to see the mighty waterfall in the play of clear and colored lights is a sight never to be forgotten.

**Thursday, May 6**

A luncheon at the Hotel Statler, followed by a fashion show presented by one of Buffalo's smartest shops.

### Inspection Trips

Buffalo and its environs have over 500 diversified industries. The committee has

## Program

Daylight Saving Time

For the papers that have been published in ELECTRICAL ENGINEERING reference to the issue and page is given.

### Wednesday, May 5

**9:00 a.m.—Registration**

**10:00 a.m.—Opening Session**

Address of Welcome, A. C. Stevens, vice-president, North Eastern District, AIEE.

LIGHTNING CURRENTS IN 132-KV LINES, Philip Sporn and I. W. Gross, American Gas & Electric Company. February, pages 245–52, 259–60

PROBABLE OUTAGES OF SHIELDED TRANSMISSION LINES, S. K. Waldorf, Pennsylvania Water & Power Company. Scheduled for May issue

SPECIAL USES FOR THE AUTOMATIC OSCILLOGRAPH, G. A. Powell and R. E. Walsh, New York Power & Light Corporation. April, pages 438–40, 476–7

**2:00 p.m.—General Session**

*THE OPERATING PERFORMANCE OF VARIOUS RELAY APPLICATIONS, George Steeb and L. J. Audlin, Buffalo, Niagara, and Eastern Power Corporation.

*THE OPERATING PERFORMANCE OF HUNTLEY STEAM STATION, J. M. Geiger (electrical) and Donald Scranton (mechanical), Buffalo General Electric Company.

*RESEARCH AND TESTING IN A LARGE ELECTRIC UTILITY, (*A*) by W. F. Davidson, Brooklyn Edison Company, Inc., and (*B*) by W. P. Dobson, Hydro Electric Power Commission of Ontario.

**8:00 p.m.—Talk and Demonstration**

FIBER GLASS, L. W. W. Morrow, Corning Glass Works.

### Thursday, May 6

**9:30 a.m.—General Session**

Greeting, A. M. MacCutcheon, president AIEE.

*EXPERIMENTAL STUDY OF DANCING CABLES, D. C. Stewart, Buffalo, Niagara and Eastern Power Corporation. Illustrated by motion pictures of dancing when the cable was coated with water to simulate an ice formation.

*SURVEYING TELEPHONE SERVICE REQUIREMENTS FOR LARGE USERS, R. E. Corey, New York Telephone Company.

*DESIGN TRENDS IN STEEL MILL ELECTRIFICATION, L. A. Umansky, General Electric Company.

**2:00 p.m.—Special Address**

ELECTRICAL APPLICATION—BETHLEHEM 72-INCH STRIP MILL, F. D. Egan, Bethlehem Steel Company.

**3:00 p.m.—Inspection Trip**

Bethlehem Steel Company's 72-inch new strip mill. Note: Number limited and women are excluded. Everyone must arrive by bus in the party and cameras are prohibited. Nominal charge for busses to and from the hotel.

**7:00 p.m.—Informal Dinner**

**8:30 p.m.—Talk and Demonstration**

KODACHROME COLORED FILM, L. D. Mannes, co-inventor, Eastman Kodak Company.

### Friday, May 7

**9:30 a.m.—Student Technical Session**

**2:00 p.m.—Inspection Trip**

Huntley stations No. 1 and No. 2 of the Buffalo General Electric Company; number will be limited and a nominal charge will be made for busses to and from the hotel.

* These papers are scheduled for presentation, but they have not been accepted for publication at the time of going to press.

judiciously selected the following trips, some of which are optional in the short time available.

**1. Bethlehem Steel Company's New $22,000,000 Hot and Cold Strip Mill**

The number to be accommodated is of necessity limited and all people must arrive by bus with the party, which will not include any ladies. Anyone arriving by private car will not be admitted. The carrying of cameras or taking pictures is not permitted. Nominal charge for busses to and from the hotel.

**2. Huntley Stations No. 1 and No. 2 of the Buffalo General Electric Company**

The number is of necessity limited. Nominal charge for busses to and from the hotel.

**3. Other Trips of Interest.**

The number which can be accommodated on some of them is of necessity limited.

*A.* Niagara Falls Power Company—(1) Adams and Schoellkopf stations; (2) Harper and Gibson substations.

*B.* Distribution system of Buffalo General Electric Company (Network and Automatics).

*C.* Local plants of New York Telephone Company.

*D.* Variable-ratio frequency changer at Lockport, N. Y.

*E.* Spaulding Fiber plant, Military Road.

*F.* Remington Rand plants.

*G.* Albright Art Gallery.

*H.* Ford Motor Company's plant.

*I.* Modern broadcasting.

*J.* Museum of Science.

Industrial plants near Buffalo include:

Lapp Insulator Company at LeRoy, N. Y.—50 miles

Porcelain Insulator Company at Lima, N. Y.—65 miles

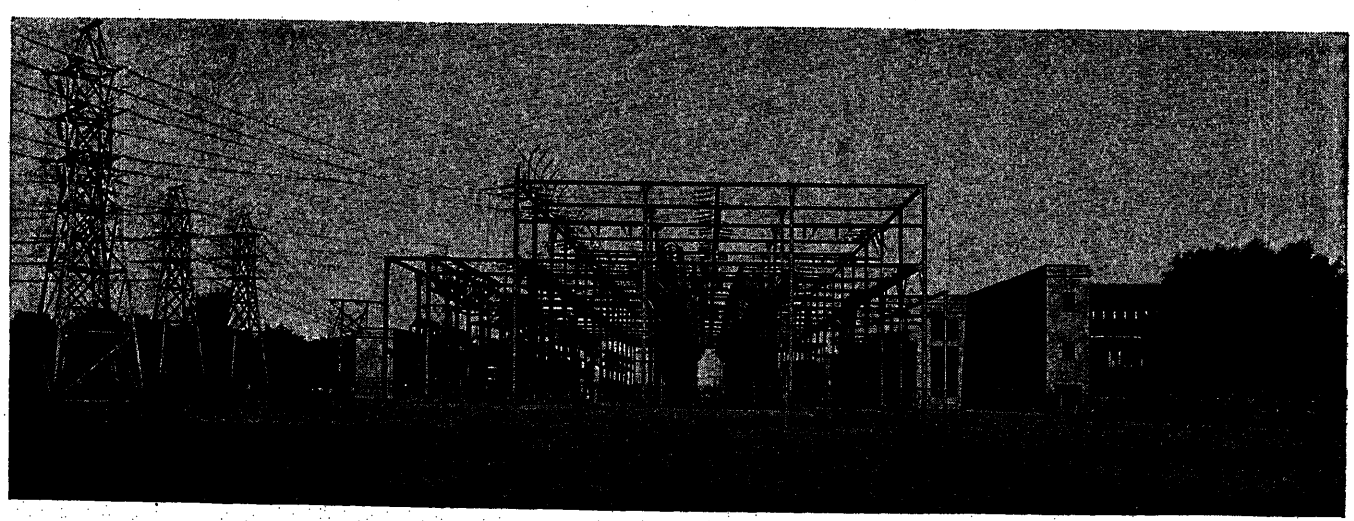
Corning Glass Company at Corning, N. Y.—125 miles

SPORTS

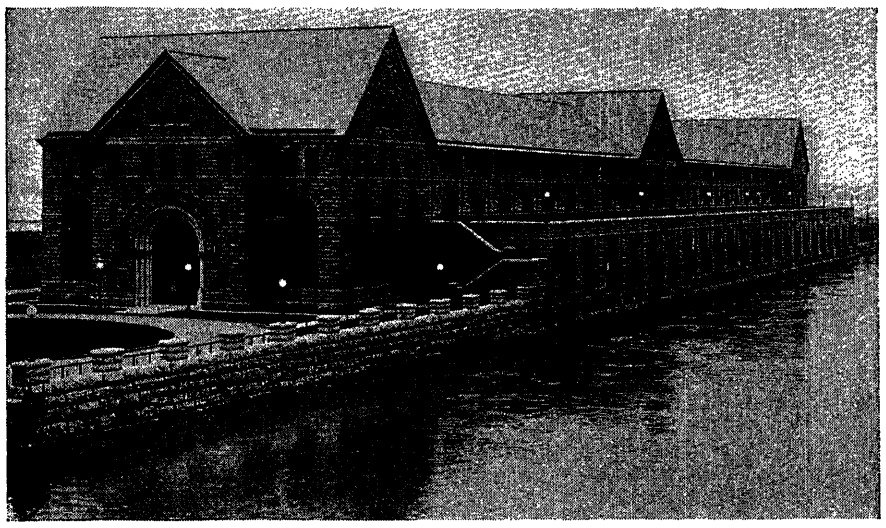
Golfing in this region is not usually much of a sport until along about Decoration Day. However, weather permitting, the committee will be very glad to furnish the necessary cards so that anyone wishing to play can do so at any course in western New York State.

REGISTRATION

Members who plan to attend the meeting should register in advance by mail. Advance registrations should be sent to George M. Pollard, chairman, registration com-



Harper substation of the Niagara Falls Power Company



Adams station of the Niagara Falls Power Company at Niagara Falls, N. Y.

mittee, Buffalo General Electric Company, 39 East Genesee St., Buffalo, N. Y. Registrations should be completed on arrival at headquarters in the Hotel Statler. A registration fee of $2 will be charged all nonmembers except Enrolled Students and the immediate families of members.

### Hotels

Members should make room reservations by writing directly to the hotel of their preference. For convenience the rates of the headquarters hotel, the Statler, as well as the rates of a number of the other hotels are listed in table I.

### Rules on Presenting and Discussing Papers

At the technical sessions, papers may be presented in abstract, 10 minutes being allowed for each paper unless otherwise arranged or the presiding officer meets with the authors preceding the session to arrange the order of presentation and allotment of time for papers and discussion.

Any member is free to discuss any paper when the meeting is thrown open for general discussion. Usually 5 minutes is allowed to each discusser for the discussion of a single paper or of several papers on the same general subject. When a member signifies his desire to discuss several papers not dealing with the same general subject, he may be permitted to have a somewhat longer time.

It is preferable that a member who wishes to discuss a paper give his name in advance to the presiding officer of the session at which the paper is to be presented. Each discusser is to step to the front of the room and announce, so that all may hear, his name and professional affiliations. Three typewritten copies of discussion prepared in advance should be left with the presiding officer.

Other discussions to be considered for publication should be typewritten (double spaced) and submitted in triplicate to C. S. Rich, secretary of the technical program committee, AIEE headquarters, 33 West 39th St., New York, N. Y., on or before May 21, 1937. Discussion of addresses and papers which is not for publication need not be submitted for consideration.

### Committees

**District Meeting Committee:** A. C. Stevens, vice-president, North Eastern District, *chairman;* R. G. Lorraine, secretary-treasurer, North Eastern District, *secretary;* F. N. Tompkins, *chairman,* committee on student activities, North Eastern District; N. E. Brown, R. F. Chamberlain, C. L. Dawes, E. D. Lynch, K. B. McEachron, and J. L. Scanlon.

**General Committee:** E. S. Bundy, *chairman;* T. J. Brosnan, R. T. Henry, Cromwell McIntosh, and H. M. Sharp.

**Program Committee:** R. W. Graham, *chairman;* J. F. Oehler and T. O. Zittel.

**Registration Committee:** G. M. Pollard, *chairman;* J. N. Ewart and J. M. Pfohl.

**Ladies Committee:** Miss Laura Rischman, *chairman;* Miss Muryle Baker, Miss Nora Haun, and Miss Maryon Ingham.

**Dinner Committee:** D. C. West, *chairman;* E. A. Brown, H. L. Randall, and T. J. Woth.

**Inspection Committee:** George Eighmy, *chairman;* C. H. Lockwood and H. L. Townend.

**Publicity Committee:** N. A. Brown, *chairman;* A. D. Gibson and W. J. Thompson.

**Transportation:** Clair Gaylord, *chairman;* E. J. Rahill and W. J. Schnautz.

**Printing:** Melvin Brown, *chairman;* F. L. West and G. A. Zehr.

## Canadian Engineers to Celebrate Semicentennial

The Engineering Institute of Canada is planning to celebrate its fiftieth anniversary at a semicentennial meeting to be opened in Montreal on June 15, 1937. The organization, which was formed in 1889 as the Canadian Society of Civil Engineers, now embraces the professional interests of engineers of all branches. There are some 4,500 members, including over 400 outside of Canada.

It is desired that the anniversary meeting may be the means of bringing about closer acquaintances between engineers in the United States and Canada. The principal functions of the meeting are to be in the Windsor Hotel, June 15 to 17 inclusive. Further information may be obtained from the headquarters of the organization at 2050 Mansfield Street, Montreal.

## AIEE Summer Convention Features of General Interest

Internationally known industrial plants in the Milwaukee metropolitan area will open their gates to convention visitors during the AIEE summer convention, to be held in Milwaukee, Wis., June 21–25, 1937, with headquarters in the Schroeder Hotel. Trips through a number of such plants are being arranged by the inspection trips committee, of which S. H. Mortensen of Milwaukee is chairman.

Present plans call for the holding of technical sessions of the convention in the mornings, leaving the afternoons free for special inspection tours, sightseeing trips, and sports. The inspection trips are being planned with the view of providing interesting diversion as well as technical and scientific information.

### Convention Sessions

Tentative arrangements are being made to hold 10 technical sessions and 1 general session designed to interest a great many members. This session will be in 2 parts, which will not be in parallel with any of the other sessions, to permit general attendance. The first part will consist of an address by a prominent speaker, which will have to do with engineering and economics. The second part of the session will consist of a discussion of the topic "how can institute programs be made of greatest value to the membership." The subject will be introduced by men invited to prepare brief statements by the special committee on Institute activities. The 10 technical sessions are as follows: electrical machinery, power transmission, vibration and balance, education, instruments and measurements, protective devices, general power applications (control), selected subjects, research, and production and application of light. The program will be further broadened by technical conferences on other subjects which will be arranged later.

### Inspection Trips

Among the large industrial firms with whom inspection visits have tentatively been arranged are the following:

**Allis-Chalmers Manufacturing Company; power, electrical, industrial, and agricultural equipment.**

**A. O. Smith Corporation; automobile frames and parts, welded pipe, pressure vessels, glass-lined storage tanks, and steel barrels.**

**Harnischfeger Corporation; large cranes, hoists, and excavators, and electric welders.**

**Globe Union, Inc.; storage batteries, radios, and roller skates.**

**Joseph Schlitz Brewing Company; beer.**

**Milwaukee Electric Railway and Light Company; as announced in the February issue of Electrical Engineering, opportunity will also be provided for a trip through the new Port Washington power plant. This station holds the world record for economy of operation in steam generating stations, having generated 382,868,218 net kilowatt-hours in 1936, with an average coal consumption of 10,954 Btu per kilowatt-hour.**

# National and District Prizes Available for Technical Papers

ALL members and Enrolled Students who have presented papers at Institute meetings, as stipulated and otherwise in accordance with the following "Conditions of Awards," are eligible under rules adopted by the board of directors for one or more of the established national and District prizes.

These rules have recently been revised by actions of the board of directors. A new prize in each of the geographical Districts, to be known as "the District prize for graduate paper" has been established. In the future the award of this prize as well as the national and District prizes for Branch paper will be on the basis of presentation during the academic (college) year, July 1 to June 30, inclusive, rather than on the basis of presentations during the calendar year.

Excerpts of the rules as revised fully describing each prize and stating the conditions of awards, when and where the papers should be submitted for consideration, are given in the following paragraphs. However, the changes in these rules explained in the preceding paragraph are not to be applied retroactively and they do not pertain to the 1936 papers now under consideration. The winners of every prize will each receive a certificate of award but by action of the board of directors the only cash award for 1936 papers will be $25 for the "District prize for Branch paper" in each geographical District. When papers are written jointly the cash awards shall be divided and a certificate shall be issued to each author.

## National Prizes

### Conditions of Awards

1. The national best paper prize in each of the 3 classes namely, engineering practice, theory and research, and public relations and education, may be awarded for the best original paper presented at any national, District, or Section meeting of the Institute, provided the author, or at least one of coauthors, is a member of the Institute.

2. The national prize for initial paper may be awarded for the most worthy paper presented at any national, District, Section, or Branch meeting of the Institute, provided the author or authors have never previously presented a paper which has been accepted by the technical program committee, and the author, or at least one of coauthors, is a member of the Institute or is a graduate student enrolled as a Student of the Institute.

3. The national prize for Branch paper may be awarded for the best paper based upon undergraduate work presented at a Branch or other Student meeting of the Institute, provided the author or authors are Enrolled Students of the Institute.

For the national best paper prize and the national prize for initial paper, only papers presented during the calendar year shall be considered except those for the best paper prize in the class of public relations and education. In this class all papers presented subsequent to those considered at the time of the last previous award in this field and prior to the end of the last calendar year will receive consideration. For the national prize for Branch papers only papers presented during the preceding academic (college) year, July 1 to June 30, inclusive, shall be considered.

### Papers Must Be Submitted

All papers approved by the technical program committee which were presented at the national conventions or District meetings will be considered for the best paper prizes and initial paper prize without being formally offered for competition. All other papers which were presented at Section, Branch, or Student meetings must be submitted in triplicate with written communications to the national secretary on or before February 15 of the following year, stating when and where the papers were presented. This may be done by authors, by officers of the Institute, or by the executive committees of Sections or geographical Districts.

### Basis of Grading Papers

The valuations which shall govern the grading of papers for purposes of making awards shall be as follows:

**Analysis of Subject**.....10 per cent
The paper shall present a clear outline of the situation out of which arises the need for the preparation of a paper on the particular subject, explaining the point of view assumed in the presentation.

**Logical Presentation**.....10 per cent
The presentation should include an analysis of the difficulties encountered, the methods of attack, and the solution of the problem.

**Originality**.....10 per cent
Credit should be given to the paper which brings to its subject matter a fresh point of view, a healthy openmindedness, or a discarding of some outworn traditions.

**Unity**.....10 per cent
While brevity and conciseness are important they should not be attained at the sacrifice of unity and completeness of presentation.

**Value in Its Field**.....30 per cent
The value of the paper as a contribution to the literature in its own field should receive particular consideration.

**Value to Electrical Engineering**.....30 per cent
The paper should be considered from the standpoint of the quality of its contribution to the advancement of electrical engineering and its value to civilization.

### Publication

Papers awarded prizes shall be published in full or in abstract, in Electrical Engineering, in the Transactions, or in pamphlet form.

## District Prizes

### Conditions of Awards

1. The District prize for best paper may be awarded for the best paper presented at a national, District, or Section meeting, provided the author, or at least one of coauthors, is a member of the Institute.

2. The District prize for initial paper may be awarded for the most worthy paper presented at a national, District, Section, or Branch meeting, provided the author or authors have never previously presented a paper before a national, District, Section, or Branch meeting of the Institute, and the author, or at least one of coauthors, is a member of the Institute or is a graduate student enrolled as a Student of the Institute.

3. The District prize for Branch paper may be awarded for the best paper based upon undergraduate work presented at a Branch or other Student meeting of the Institute, provided the author or authors are Enrolled Students of the Institute.

4. The District prize for graduate paper may be awarded for the best paper based upon graduate work and presented at a national, District, Section, or Branch meeting of the Institute. At the time of presentation, the author must be a graduate student and either a member or an Enrolled Student of the Institute. In the case of coauthors, the graduate requirement applies to all and the membership requirement applies to at least one of the coauthors.

Each District prize may be awarded only to an author who, or to coauthors of whom at least one, is located within the District, and for a paper presented at a meeting held within, or under the auspices of the District.

### Papers Must Be Submitted

Only papers presented during the calendar year shall be considered for the prize for best paper and for initial paper. Only papers presented during the preceding academic (college) year, July 1 to June 30, inclusive, shall be considered for the prize for Branch paper and for graduate student paper. They must be submitted in duplicate by authors, or by officers of the Section, Branch, or District concerned to the District secretary on or before the following dates: best paper and initial paper, February 15; Branch paper and graduate student paper, July 15.

### Committees on Awards

All the District prizes for a given calendar year shall be awarded prior to May 1 of the succeeding year by the District executive committee or by a committee appointed by the District executive committee and authorized to make such awards.

### Basis of Grading Papers

The valuations which shall govern the grading of papers for purposes of making awards shall be the same as those for the national prizes but the papers will not be graded by the technical committees.

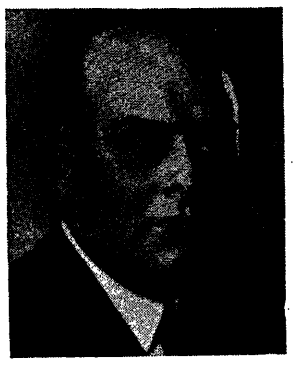
**Four New Groups Join ASA.** Sixty national organizations are now affiliated with the American Standards Association according to an announcement of Dana D. Barnum, president. The 4 new groups affiliated since January 1, 1937, are Automobile Manufacturers Association, Brick Manufacturers Association of America, American Society of Heating and Ventilating Engineers, and Structural Clay Products, Inc.

## In Memoriam

ON THE thirtieth day of January 1937, the Institute suffered a serious loss in the death of Edward Barnard Meyer, who had, only 6 months previously, completed his term as its forty-eighth president, and who had long been one of its most loyal and active members.

Doctor Meyer was graduated from the Newark Technical School in 1901 and from Pratt Institute in 1903. He was immediately employed by the Public Service Electric and Gas Company of New Jersey as an engineering assistant, and remained with it and its subsidiaries until 1922, rising steadily to higher positions, and being assistant chief engineer during the last 3 years. In 1922, he was appointed chief engineer of the Public Service Production Company, which was formed at that time, and, in 1929, was promoted to vice-president. Upon the merger of that company, in 1930, with the United Engineers and Constructors, Inc., he was made vice-president of the latter and executive and engineering head of its Newark office. In 1935, he returned to the Public Service Electric and Gas Company as chief engineer of the electric engineering department.

Doctor Meyer joined the Institute in 1905, and was transferred to the grade of Member in 1913 and to the grade of Fellow in 1927. He was a director 1927–31, a vice-president 1932–34, and president 1935–36. He served as chairman of many of the Institute's most important committees, as a member of others, and as an Institute representative upon numerous joint organizations. He was chairman of the New York Section 1926–27.



E. B. MEYER

The Newark College of Engineering awarded him the honorary degree of doctor of engineering in 1936.

Doctor Meyer's ability as an engineer, his constant adherence to the highest ideals, his patient and persistent efforts to encourage co-operation, and the breadth and thoroughness of his consideration of all matters connected with his duties gave him an outstanding position of leadership in his chosen profession.

RESOLVED: That the executive committee of the American Institute of Electrical Engineers hereby expresses, upon behalf of the membership, its deepest regret at the death of Doctor Meyer, and its most sincere appreciation of his unusually large number of important contributions to the conduct and development of Institute activities, and be it further

RESOLVED: That these resolutions be entered in the minutes and transmitted to his family. —AIEE Executive Committee March 25, 1937

## To Institute Members Planning Trips Abroad

Members of the Institute who contemplate visiting foreign countries are reminded that since 1912 the Institute has had reciprocal arrangements with a number of foreign engineering societies for the exchange of visiting member privileges, which entitle members of the Institute while abroad to membership privileges in these societies for a period of 3 months and members of foreign societies visiting the United States to the privileges of Institute membership for a like period of time, upon presentation of proper credentials. A form of certificate which serves as credentials from the Institute to the foreign societies for the use of Institute members desiring to avail themselves of these exchange privileges may be obtained upon application to Institute headquarters, New York. The members should specify which country or countries they expect to visit, so that the proper number of certificates may be provided, one certificate being addressed to only one society.

The societies with which these reciprocal arrangements have been established and are still in effect are: Institution of Electrical Engineers (Great Britain), Société Française des Electriciens (France), Association Suisse des Electriciens (Switzerland), Associazione Elettrotecnica Italiana (Italy) Koninklijk Instituut van Ingeniurs (Holland), Verband Deutscher Elektrotechniker E. V. (Germany), Norsk Elektroteknisk Forening (Norway), Svenska Teknologforeningen(Sweden), Stowarzyszenie Elektrykow Polskich (Poland), Elektrotechnicky Svaz Ceskoslovensky (Czechoslovakia), The Institition of Engineers, Australia (Australia), Denki Gakkwai (Japan), and South African Institute of Electrical Engineers (South Africa).

## Middle Eastern District Executive Committee Meets

A meeting of the executive committee of the Institute's Middle Eastern District was held in Pittsburgh, Pa., October 27, 1936. Circumstances have prevented reporting this meeting in an earlier issue. The meeting was attended by the following:

W. H. Harrison, vice-president, AIEE
H. A. Dambly, secretary, Middle Eastern District
H. H. Schroeder, chairman, Akron Section
H. L. Brouse, secretary, Akron Section,
A. O. Austin, Akron Section
J. H. Lampe, secretary, Baltimore Section
O. C. Schlemmer, secretary, Cincinnati Section
W. E. Wickenden, chairman, Cleveland Section
E. E. Kimberly, chairman, Columbus Section
W. D. Bearce, secretary, Erie Section
G. E. Northup, chairman, Lehigh Valley Section
O. C. Traver, chairman, Philadelphia Section
Paul Frederick, secretary, Pittsburgh Section
R. L. Dunlap, director, Pittsburgh Section
T. H. Frankenberry, Sharon Section
W. A. VanWie, Toledo Section
G. G. Coleman, Washington Section
E. O. Lange, chairman, District committee on student activities, Drexel Institute, Philadelphia

Vice-President Harrison, who presided, first discussed briefly the objectives and status of the efforts of the Institute's membership committee. A general discussion of membership activities of the Sections

**Electronics Program.** A special lecture and conference program in electronics will be held in Ann Arbor, Mich., as a part of the 1937 summer session of the University of Michigan, with the co-operation of members of the technical staffs of the General Electric Company, Westinghouse Electric and Manufacturing Company, Radio Corporation of America, and Bell Telephone Laboratories, Inc. The primary objective will be to provide an opportunity for teachers and prospective teachers of electronics, engineers and physicists engaged in electronic development work in industry, and graduate students interested in electronics to broaden and unify their grasp of fundamental electronic principles. Lectures will be given by Doctors Saul Dushman (A'13) and Lewi Tonks of General Electric, Doctors H. E. Mendenhall and F. B. Llewellyn of Bell Telephone Laboratories, Doctors Joseph Slepian (A'17, F'27) and R. C. Mason (A'26) of Westinghouse, Doctor V. K. Zworykin (M'22) and B. J. Thompson of RCA, and Professors L. B Loeb of the University of California and W. G. Dow (A'19, M'32) of the University of Michigan. A special bulletin describing the details of the program will be mailed to anyone interested upon request to Professor W. G. Dow, electrical engineering department, University of Michigan, Ann Arbor.

**Medal for Papers on Welding.** The board of directors of The American Welding Society has accepted a gold medal to be known as the Lincoln Gold Medal, to be presented to the author of the best paper on any phase of welding published in the *Journal* of The American Welding Society during the year October 1936 to October 1937. The medal was offered by J. F. Lincoln (A'08, M'20) president of the Lincoln Electric Company, Cleveland, Ohio. Papers to be considered must be received by the editor of the *Journal* before September 15, 1937.

throughout the District followed. At the conclusion of this discussion, the report of the District prize paper committee was presented; appointment of a prize paper committee for 1936–37 was deferred.

Student conferences and conventions was the next subject discussed. The various delegates outlined briefly what is being done by their respective Sections and Branches. Vice-President Harrison urged the Sections to do all possible to assist and stimulate interest in technical schools. He called attention to the probable shortage of technically trained men in the years ahead. There was also an exchange of ideas pertaining to Section programs and activities.

To serve as the District co-ordinating committee for the year ending July 31, 1937, the following were selected: O. C. Schlemmer, W. C. Kalb (Cleveland Section), E. E. Kimberly, Paul Frederick, and E. O. Lange. The vice-president and District secretary are *ex-officio* members of this committee.

Vice-President Harrison reported that the proposed Akron (Ohio) District meeting had been approved by the Institute's board of directors on May 25, 1936. Although no definite date for the meeting was selected, early October was suggested. A. O. Austin and H. L. Brouse were designated as representatives of the Akron Section to serve on the committee for this meeting. These 2 members together with the District co-ordinating committee constitute the complete committee for this meeting.

A proposal to request that the Institute's 1938 summer convention be held at Pennsylvania State College was discussed in detail. Although the college is not within Institute Section territory, delegates of neighboring Sections indicated their willingness to assist. After lengthy discussion it was voted unanimously that the executive committee of the Middle Eastern District recommend that consideration be given to Pennsylvania State College for a summer convention or District meeting in 1938. (After considering this and other invitations for the 1938 summer convention the Institute's board of directors voted at its meeting of January 25, 1937, to hold the 1938 summer convention at Washington, D. C.)

**French Congress on Lighting.** A congress on lighting is being arranged by a French committee to be held from June 24, 1937, to a date to be set early in July during the international exposition. American lighting men have been invited to attend and to participate in discussions on lighting matters. According to Preston S. Millar, president of the United States National Committee of the International Commission on Illumination, "This congress is not to be confused with the next meeting of the ICI scheduled for next year in Holland. The French lighting congress is to be held in connection with the international exposition. The United States National Committee of the ICI, however, is lending its support and will be glad to serve as a 'clearing house' for American lighting men desiring to present papers at the forthcoming congress on lighting in Paris." Inquiries relating to the subject should be addressed to Mr. Millar, in care of Electrical Testing Laboratories, 80th Street and East End Avenue, New York, N. Y.

## Springfield Section Offers Prizes for New Ideas

In an effort to develop "ways and means to advance and improve the Springfield Section of the AIEE," that Section announced at its March 12 meeting that for the best papers on that subject submitted within the ensuing 6 months, cash prizes of $25 for the best and $10 for the next best paper would be awarded at the Section's October or November meeting. All members of the Springfield Section (national, local, and student) except present Section officers, present chairmen and vice-chairmen of Section standing committees, and members of the Section's prize paper contest committee, are eligible to enter the contest.

Papers submitted are specified to be between 500 and 2,500 words in length, and subject to grading on the following basis:

*Clarity of Presentation.* The paper shall give a clear presentation of the merits of proposed changes and/or any defects in present practices..20 per cent

*Originality.* The paper should include new ideas for the management and activities of the Section, that will make it more interesting and of greater benefit to the largest number of members. It should bring to its subject matter a fresh point of view, a healthy open-mindedness, and/or a discarding of any outworn traditions.....30 per cent

*Value to the Section.* The improvements and benefits, estimated to result from adopting the ideas presented in the paper will receive particular consideration.....50 per cent

## Great Lakes District Executive Committee Meets

The annual meeting of the executive committee of the Institute's Great Lakes District was held at Chicago, Ill., on November 16, 1936. Circumstances have prevented reporting this meeting in an earlier issue. The following members of the committee were present:

C. F. Harding, vice-president, AIEE
A. G. Dewars, secretary, Great Lakes District
F. L. Stanley, chairman, Central Indiana Section
Burke Smith, chairman, Chicago Section
J. A. Fitts, secretary, Chicago Section
S. S. Attwood, chairman, Detroit-Ann Arbor Section
D. H. Hanson, chairman, Fort Wayne Section
C. S. Allen, secretary, Fort Wayne Section
F. H. McClain, chairman, Iowa Section
R. R. Benedict, chairman, Madison Section
W. A. Kuehlthau, secretary, Madison Section
J. A. Potts, chairman, Milwaukee Section
J. H. Kuhlmann, chairman, Minnesota Section
C. H. Nelson, secretary, Minnesota Section
H. J. Reich, chairman, Urbana Section
K. A. Auty, treasurer, District executive committee

K. L. Hansen of Milwaukee, chairman of the 1937 summer convention committee, was present by invitation.

Vice-President Harding presided. Following the presentation of the treasurer's report, Mr. Auty was re-elected treasurer for the ensuing year. The following were chosen to serve on the District co-ordinating committee for the ensuing year: Burke Smith, R. R. Benedict, F. L. Stanley, and J. A. Potts; these, together with Vice-President Harding and District Secretary Dewars, who serve as *ex-officio* members, constitute the complete committee.

Concerning the Institute's 1937 summer convention to be held in Milwaukee, Wis., June 21–25, K. L. Hansen reported that the various committees had been active and were already well along on their way toward completion of their plans. He called attention to the proposal to include on the program a paper, or papers, on economic or social subjects and asked the opinion of the members of the District executive committee on this matter. Vice-President Harding had mentioned at the opening of the meeting that the Institute's board of directors had considered the general question of broadening Institute activities to include discussions on social and economic subjects, at its meeting of October 20, 1936. After considerable discussion, a committee was appointed to prepare a resolution expressing the attitude of the District executive committee on the general subject of including papers of this type on convention programs. At the close of the meeting, this committee, which consisted of F. L. Stanley, D. H. Hanson, and Burke Smith, offered the following resolution:

"Resolved, That the executive committee of the Great Lakes District hereby goes on record as endorsing the action taken by the board of directors of the American Institute of Electrical Engineers at its meeting on October 20, 1936, in which it favored broadening of the scope of papers for national presentation and publication, to include topics of economic and sociological interest to the profession."

The resolution was adopted and the secretary was instructed to forward a copy to the Institute's board of directors.

Reports were presented by the various Section delegates, in which the activities of the respective Sections during the preceding year were described, and plans for the coming year outlined. Practically all of the Sections represented reported an increase in membership during the preceding year.

## Medals Awarded for Public Service

Two awards of the American Institute of the City of New York for 1937—a gold medal to the Bell Telephone Laboratories, New York, N. Y., and a fellowship to Watson Davis, director of Science Service, Washington D. C.—were announced December 28, 1936, by Dr. Gerald Wendt, director of the organization, and presented February 4, 1937.

The gold medal, given annually by the organization in recognition of outstanding accomplishment in research, was awarded to the Bell Telephone Laboratories "for researches in electrical science which, applied to communication, have promoted understanding, security, and commerce among peoples by transmitting human thought instantly throughout the world."

One of the pioneer industrial organizations for scientific research, Dr. Wendt said, the Bell Telephone Laboratories developed and perfected many of the valuable means of modern communication. Its outstanding achievements have been in the development of the instrumentalities on which are based a nation-wide system of communication. The award was received in the name of the more than 4,000

men and women of the Laboratories by its president, Dr. F. B. Jewett (A'03, F'12, past-president).

The fellowship, conferred for "outstanding service in the interpretation of science to laymen," was awarded to Watson Davis "for interpreting to the people of the Nation the rapid progress of science upon which modern civilization depends, and for the organized dissemination of research findings as news."

Mr. Davis is director of Science Service, a pioneer organization in the interpretation and dissemination of the news of science. He is well known as author and editor of books on scientific subjects including "The Story of Copper", "Science Today," and "The Advance of Science." His articles, appearing regularly in newspapers, magazines, and technical journals, bring science to the people in the language of the layman.

The council on awards of the American Institute of the City of New York consists of: M. L. Crossley (chairman) Calco Chemical Co.; Oscar Riddle, Carnegie Institution, Station for Experimental Evolution; W. D. Coolidge (A'10, F'24) General Electric Co.; W. H. Carrier, Carrier Engineering Corp.; Oliver Kamm, Parke Davis & Co.; Ward F. Davison (A'14, F'26) Brooklyn Edison Co.; L. O. Kunkel, Rockefeller Institute for Medical Research; Clinton J. Davisson, Bell Telephone Laboratories; and Harden F. Taylor, Atlantic Coast Fisheries.

The American Institute of the City of New York was incorporated in 1828 for the purpose of "encouraging and promoting domestic industry in this State and in the United States." Its membership includes leading scientists and others interested in promoting this aim. Its work among school children, including its "science congress," "Christmas lectures," and "children's science fair," is notable.

## Production of Electricity in 1936 Breaks All Records

PRELIMINARY figures on the total production of electricity for public use in the United States in 1936, as given by the Federal Power Commission, indicate a total output of 113,473,000,000 kilowatt-hours, which is an increase of 14 per cent over that for 1935, the year of the previous maximum.

The production of electricity by the use of water power was about 40,893,000,000 kilowatt-hours, or 2 per cent more than in 1935, and amounted to 36 per cent of the total, whereas the average for the 16-year period, 1920 to 1935, was 36.9 per cent of the total. The percentage for 1936 indicates that despite the abnormal conditions experienced in the drought-stricken states the production of electricity by the use of water power is maintaining its relative position with respect to other sources of power.

The preliminary data indicate that the fuel rate for 1936 was about 1.45 pounds per kilowatt-hour as compared with 1.46 pounds per kilowatt-hour in 1935. Following the former procedure of the U.S. Geological Survey, the fuel rate was calculated by converting the oil and gas used in the production of electricity into equivalent tons of coal and dividing the total coal used in producing electricity and coal equivalent of the gas and oil used by the corresponding output. This method does not allow for the variation in Btu content of the gas and oil as fired, and includes the output of both steam and internal combustion engines, and is therefore only approximate.

An analysis of all steam plants using coal exclusively for fuel indicates that the coal rate is 1.49 pounds per kilowatt-hour. Since these data include coal used in plants held in reserve and operated intermittently, it is not representative of good practice. Some of the more efficient plants are producing a kilowatt-hour with approximately 0.8 pound of coal at the present time.

The accompanying tables show for the United States and its divisions the annual production of electricity for public use by use of water power and by the use of fuels for the years of 1935 and 1936 and the percentage change from 1935 to 1936 in the production of electricity and in the use of different fuels in generating electricity. The information is preliminary and is based on the figures of production of electricity in the monthly reports during 1936. The output of central stations, both publicly and privately owned, electric railway plants, plants operated by steam railroads generating electricity for traction, and U.S. Bureau of Reclamation plants and that part of the output of manufacturing plants which is sold are included in these data. Accurate data are received each month representing approximately 98 per cent of the total output shown; the remaining 2 per cent of the output is estimated so that the data represent 100 per cent of the generation.

A final report, which will give totals for each state for 1936 and include final revisions of previously published data, will be published in April 1937; copies may be obtained by application to the Federal Power Commission, Washington, D. C.

### Annual Production of Electricity for Public Use in the United States, 1935 and 1936

| | Production of Electricity—Millions of Kilowatt-Hours | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | Total | | | By Use of Water Power | | | By Use of Fuel | | |
| | 1935 | 1936 | Change—Per Cent | 1935 | 1936 | Change—Per Cent | 1935 | 1936 | Change—Per Cent |
| United States | 99,398 | 113,473 | +14 | 39,968 | 40,893 | + 2 | 59,430 | 72,580 | +22 |
| New England | 6,914 | 7,496 | + 8 | 2,950 | 2,852 | − 3 | 3,964 | 4,644 | +17 |
| Middle Atlantic | 25,905 | 29,281 | +13 | 7,836 | 7,348 | − 6 | 18,069 | 21,933 | +21 |
| East North Central | 22,833 | 26,384 | +16 | 2,686 | 2,310 | −14 | 20,147 | 24,074 | +19 |
| West North Central | 6,588 | 7,026 | + 7 | 2,148 | 1,497 | −30 | 4,440 | 5,529 | +25 |
| South Atlantic | 11,430 | 13,746 | +20 | 6,495 | 7,137 | +10 | 4,935 | 6,609 | +34 |
| East South Central | 4,206 | 4,985 | +19 | 3,458 | 3,865 | +12 | 748 | 1,120 | +50 |
| West South Central | 4,879 | 5,634 | +15 | 286 | 168 | −41 | 4,593 | 5,466 | +19 |
| Mountain | 3,518 | 4,309 | +22 | 2,681 | 3,256 | +21 | 837 | 1,053 | +26 |
| Pacific | 13,126 | 14,612 | +11 | 11,428 | 12,460 | + 9 | 1,698 | 2,152 | +27 |

### Annual Consumption of Fuels in Generating Electricity for Public Use, 1935 and 1936

| | Coal—Thousands of Net Tons | | | Oil—Thousands of Barrels | | | Gas—Millions of Cubic Feet | | |
|---|---|---|---|---|---|---|---|---|---|
| | 1935 | 1936 | Change—Per Cent | 1935 | 1936 | Change—Per Cent | 1935 | 1936 | Change—Per Cent |
| United States | 34,807 | 41,973 | +21 | 11,393 | 14,110 | +24 | 125,239 | 155,525 | + 24 |
| New England | 2,025 | 2,380 | +18 | 2,622 | 3,198 | +22 | 0 | 0 | 0 |
| Middle Atlantic | 11,133 | 13,129 | +18 | 3,356 | 4,868 | +45 | 1,602 | 4,773 | +198 |
| East North Central | 13,627 | 16,274 | +19 | 145 | 183 | +26 | 9,476 | 13,359 | + 41 |
| West North Central | 3,041 | 3,627 | +19 | 785 | 927 | +18 | 25,002 | 30,727 | + 23 |
| South Atlantic | 3,033 | 4,076 | +34 | 2,331 | 2,548 | + 9 | 1,432 | 2,682 | + 87 |
| East South Central | 599 | 880 | +47 | 98 | 112 | +14 | 4,488 | 5,465 | + 22 |
| West South Central | 764 | 889 | +16 | 768 | 903 | +18 | 60,895 | 72,594 | + 19 |
| Mountain | 585 | 718 | +23 | 294 | 370 | +26 | 4,304 | 5,085 | + 18 |
| Pacific | 0 | 0 | 0 | 994 | 1,001 | + 1 | 18,041 | 20,840 | + 16 |

## John Scott Awards for 1937 Presented

Doctors W. D. Coolidge (A'10, F'34) and Irving Langmuir, director and associate director respectively of the research laboratory of the General Electric Company in Schenectady, N. Y., and Doctor Evarts A. Graham of the school of medicine of Washington University in St. Louis, Mo., were recipients of the John Scott awards for 1937 granted by the City Trusts of the City of Philadelphia and presented at a recent dinner of the American Philosophical Society. With each award went a certificate, a copper medal, and $1,000 in cash. Doctor Coolidge accepted the award for Doctor Langmuir in the latter's absence.

The award to Doctor Coolidge was based on his application of a new principle in X-ray tubes; to Doctor Langmuir for his physical and chemical discoveries resulting in improved gas-filled incandescent lamps; and to Doctor Graham for his application of the X ray to the study and diagnosis of gall-bladder conditions.

In making the presentations, Ernest I. Trigg, chairman of the Board of City Trusts, explained that history had made but scant recordings of John Scott, the donor of the fund, and his reason for bequeathing to the City of Philadelphia in 1816 the sum of $4,000, the income from which was to be "laid out in premiums to be distributed among ingenious men and women who make useful inventions."

It was originally stipulated that no award was to carry a cash premium of more than $20 and the medal was to be inscribed "To the most deserving."

History reveals that John Scott was a chemist in Edinburgh, Scotland, but just why he chose Philadelphia for his grant is a mystery. It is thought his attention had been drawn to the city either through the American Philosophical Society or his admiration of Benjamin Franklin whom he may have met when Franklin visited Scotland in 1769. When the fund was taken over by the Board of City Trusts, the principal had grown to $21,000 and in 1917, or 100 years after the original grant, it amounted to $100,000. At this time the board appealed to the courts and received permission to increase the amount of the awards to a maximum value of $2,000, but none has been for any amount greater than $1,000.

In the period between 1920 and 1937 inclusive, 73 awards were made to outstanding scientists and inventors in all parts of the world, including Japan, Holland, England, France, Italy, and South America. Recipients have included Madam Curie, Reginald A. Fessenden, Orville Wright, Lee De Forest (A'04, F'18), Thomas A. Edison (A'84, M'84, HM'29, past vice-president, deceased '33), Guglielmo Marconi (HM'17), Samuel M. Vauclain, W. L. R. Emmet (A'93, M'94, HM'33, past vice-president, member for life), Nikola Tesla (A'88, F'17, member for life), Charles F. Kettering (A'04, F'14), and Edward G. Budd.

## $100,000 Edison Memorial Gift of W. S. Barstow

The Edison Pioneers, composed of early associates of Thomas Alva Edison, met February 11, 1937, in New York, N. Y., to observe the ninetieth anniversary of Edison's birth. At that meeting, it was announced that a 135-foot concrete tower surmounted by a huge electric-light bulb would be erected in Edison's memory during the summer of 1937 on the site of his early laboratory at Menlo Park, N. J. The tower, which will cost more than $100,000, will be the gift of W. S. Barstow (A'94, F'12) retiring president of the Edison Pioneers. (Mr. Barstow served the AIEE as a manager in 1900–03, and as a vice-president in 1903–05.) Mr. Barstow specified that the gift was to the Thomas Alva Edison Foundation in the name of the Edison Pioneers.

The Thomas Alva Edison Foundation was conceived jointly by the Edison Pioneers and the AIEE, with the approval of the Edison family, and was incorporated in 1935. Its purpose is to carry out plans to perpetuate recognition of the world's progress emanating from the inventor's efforts. The construction of this memorial tower constitutes one phase of the Foundation's program.

It is planned to build a concrete tower around the skeleton steel tower which was erected in 1929, 2 years before Edison's death. The light which will be at the top is that which is now at the top of the steel structure. It is a bulb-like light composed of more than 900 incandescent lamps, and will be enclosed in prismatic glass. Edison turned it on from Dearborn, Mich., on October 21, 1929, during the national celebration of the fiftieth anniversary of his invention of the incandescent electric light. It has burned every night since and will not be extinguished during the construction of the new tower.

## Electrical Vocabulary Prepared by IEC

The International Electrotechnical Commission plans publication of the first edition of its "International Vocabulary" in 1937. This work, undertaken soon after the St. Louis Electrical Congress in 1904, contains some 2,000 scientific and industrial terms used in the various branches of electrotechnics. It is the result of many years of continuous effort by a committee of experts including delegates from Austria, France, Germany, Great Britain, Italy, the Netherlands, Poland, Spain, and the United States.

Definitions appear in English and French, the 2 official languages of the IEC, and a translation of terms is given in German, Italian, Spanish, and Esperanto. While the committee developing this international vocabulary appreciates that it does not constitute a complete unification of electrotechnical nomenclature, through periodic review and revision based on the constructive criticism of electrical authorities throughout the world it should become increasingly valuable to engineers.

The edition will be limited, and copies at about $2.50 each may be reserved by writing to the United States National Committee of the International Electrotechnical Commission, 29 West 39th Street, New York, N. Y.

**Electrical Treatment of Air.** A new technical subcommittee on the treatment of air with electricity, formed under the committee on research of the American Society of Heating and Ventilating Engineers, recently held its first meeting to plan a research program directed toward discovering, if possible, and duplicating in indoor conditioned air, certain intangible qualities that seem to give outdoor air a particular zest and life. Discussion at the meeting included the problem of ozonization, ionization, and treatment of air with ultraviolet rays, which has shown possibilities in the killing of air-borne disease germs, and the subject of electrical filtering of air by precipitation processes. Members of the subcommittee include L. W. Chubb (A'09, F'21, past director) director of research laboratories of Westinghouse Electric and Manufacturing Company, East Pittsburgh, Pa., and Vannevar Bush (A'15, F'24) vice-president and dean of engineering at Massachusetts Institute of Technology, Cambridge.

# American Engineering Council

## Council Acts on Patent Situation

In all the flurry of patent legislation in recent years, Council's patents committee has kept closely in touch with the situation and has acted in the interest of engineers and the public where opportunity was found to improve patent-court conditions and patent-office procedure. Of most importance are actions taken on the proposed court of patent appeals and legislation affecting pooling and cross-licensing.

The committee has recommended that Council support legislation for a single court of patent appeals, and the AEC assembly has approved the recommendation and has taken the position that it will look with favor upon the idea of having the judges named to such court selected by the President and confirmed by the Senate only after careful review of their special and technical competence with the advice of engineering and scientific societies as well as the advice of the patent bar and the legal profession.

Scientific advisers to the courts have been recommended by a number of agencies, but not all with the same purpose. Most often quoted is the suggestion of a special patents committee of the Science Advisory Board. That committee recommended that scientific advisers be made available to aid *trial* court justices. In this conclusion, the committee agrees with the recommendations of the special patents committee of the Science Advisory Board. The patents committee looks with some favor on such an idea if a suitable method of selecting advisers free from preconceived opinions were fixed and if a sufficiently diversified list of skilled scientific and engineering talent were made available. However, the committee has doubted the wisdom of having such scien-

tific advisers named permanently as a part of a new single court of patent appeals. It feels that the idea of naming 3 such advisers who would serve for all classes of cases would not afford such highly skilled aid in all divisions of science and technology as courts really require.

The committee believes that the public interest has been much more served than harmed by patent pools and by cross-licensing. Such evils as may have been experienced would not have been corrected by any of the proposed forms of legislation. The committee believes that administration of present laws, including proper and reasonable application of antitrust legislation, would suffice to correct those types of evils of pooling that have been disclosed or charged as bad practice.

Council also has approved the patents committee's recommendation to oppose all the various types of proposals which would restrict the freedom of owners of patents to use them constructively under present laws. It regards such offenses as are now charged against the patent system as the result of defects in administration of present laws and not as evidence of the need of more legislation.

The committee believes that every effort should be made by industry as well as by the engineering profession to increase the presumption of validity of patents as issued. It feels that engineers generally should assist patent examiners whenever possible to keep abreast of the arts with respect to which they are examining patent applications. The committee has not found any legislation, proposed to date, sufficiently constructive to feel that it deserves support of AEC. It does, however, hope that some means may be developed for increasing the standards of competence and experience of the staff of examiners in the Patent Office.

The staff is following legislation for the court of patent appeals in *S.*475 introduced by Senator McAdoo of California, and the patents committee is giving further consideration to such matters as technical advisers to the courts, patent pooling and cross-licensing, compulsory working and licensing, automatic validation of patents 5 years after issue, and taxation during nonuse.

## AEC Unites Opinion On Rural Electrification

In its unbiased approach to the subject, Council's rural electrification committee seems to have made a real contribution toward a better understanding of the practical uses of electricity on the farm and toward a meeting of private and public minds on sound practices in rural electrification. The report of this committee's Report for 1936 was referred to by Morris L. Cooke, ex-administrator of REA, in a letter to the editor of the New York *Times* entitled "Rural Electrification" which was published in the February 1, 1937, issue of the *Times*. Mr. Cooke is also reported to have referred publicly to the report as representing an excellent approach to rural electrification.

Utilities and private industry also have sought copies of this report. All criticism received has been constructive and directed toward improving the recommendations for increasing the use of electricity on the farm and making the use pay dividends to the farmer in health, time-saving, and economy. Other suggestions concern ways and means to make rural distribution systems pay their own way, and the construction of rural lines of the lowest cost consistent with quality and service.

The AEC rural electrification committee made 5 recommendations with the ultimate well-being of citizens in rural life as the final objective: (1) every farmer who can use electricity economically should be supplied with it; (2) service should be supplied in the most efficient and dependable manner and at the lowest cost consistent with quality and service; (3) each farm operator should be informed as rapidly as possible regarding the electric-power and equipment needs of his own individual farm; (4) each farmer should be informed as rapidly as possible regarding the best ways of using this power and equipment so that the greatest economy may be effected; and (5) every effort should be made to develop new equipment and processes whereby electric power can be used to bring the farmer closer to his market, whether he is selling food products or the raw materials of industry.

In conclusion, the report advances the opinion that such a program of rural electrification will require the utmost co-operation between all branches of the agricultural and engineering professions, and all agencies, public and private, that are involved in this development. The problem is a tremendous one, but its solution will go so far in helping to solve the economic problems of American agriculture, and indirectly the economic problems of the nation, that it is worth the best efforts of all who have anything to contribute to it.

## Rural Electrification Administration Notes

Rural Electrification Administration news is the resignation of Administrator Morris L. Cooke. Mr. Cooke is reported to have resigned voluntarily to seek a rest from the burden of responsibility that the President drafted him to carry from the creation of the REA. An interesting rumor in connection with Mr. Cooke's resignation is the unofficial report that his friendly consideration of the interests of privately owned utilities added to the burden of his responsibility and engendered trying misunderstandings among his liberal colleagues.

John M. Carmody, an editor and industrial engineer, formerly a member of the National Labor Relations Board, chief engineer of CWA and FERA, with much experience in the railroad, steel, and coal industries and in private practice, succeeded Mr. Cooke. He is being assisted by Colonel George D. Babcock of North Carolina who was associated with Mr. Carmody in the other emergency agencies.

At the conclusion of Mr. Cooke's administration, REA had lent or ear-marked a total of more than $50,000,000 for 257 rural electric projects to serve 165,000 rural customers in 40 states and Alaska. These figures do not include funds involved in contracts providing that the Electric Home and Farm Authority co-operate with both public and private utilities in financing the sale of electric appliances for use by consumers located on public and private utility power lines.

# Engineering Foundation

## Doctor A. D. Flinn, Director of Foundation, Dead

Doctor Alfred Douglas Flinn, director of The Engineering Foundation, died March 14, 1937, at Scarsdale, N. Y., after a prolonged illness. He was born in New Berlin, Pa., August 4, 1869. He was graduated in 1893 from Worcester (Mass.) Polytechnic Institute, with the degree of bachelor of science in civil engineering, following which he took postgraduate work at the Massachusetts Institute of Technology, Cambridge. The University of Louvain, at its 500th anniversary celebration in 1927, conferred on him the degree of doctor of applied science, *honoris causa*. He received the honorary degree of doctor of engineering from Worcester Polytechnic Institute in 1932.

From 1894 to 1895, Doctor Flinn was employed successively by: Rice and Evans, civil engineers, of Boston, Mass.; Associated Factory Mutual Fire Insurance Companies, Boston; Waterworks Division of the Boston City Engineer's Office. From 1895 to 1902, he was engineer for the Massachusetts Metropolitan Waterworks, becoming principal assistant engineer. He served as managing editor of *The Engineering Record* (later combined with *The Engineering News*) 1902–04, following which he became general inspector for the Croton Aqueduct Commissioners, being in charge of their New York engineering office. In August 1905, he became associated with the Board of Water Supply of the City of New York, which he served until January 1918. He was successively division engineer, department engineer of headquarters, deputy chief engineer, and, on several occasions, acting chief engineer.

In January 1918, Doctor Flinn was named secretary of the United Engineering Society, which was succeeded by Engineering Foundation and United Engineering Trustees, joint agencies of the 4 Founder societies. He continued as secretary of United Engineering Trustees until June 23, 1934, and of The Engineering Foundation until his death. He became director of Foundation in 1922.

As secretary, or executive officer, of United Engineering Trustees, he supervised the Engineering Societies Building at 29 West 39th Street, executed and recorded the actions of the board of trustees, including administration of trusts and other funds, and rendered secretarial services to standing and special committees. After his resignation in 1934 he continued some special serv-

ices until the end of that year, when his engagement with the Trustees ended.

In co-operation with National Research Council, Doctor Flinn aided in developing and financing the Fatigue of Metals Research, the Arch Dam Investigation, the Alloys of Iron Research, and the Education Research Committee, including the pamphlet, "Engineering: A Career—A Culture." He also assisted smaller researches and the special research committees of the Founder societies and organizations co-operating with them.

He was instrumental, in conjunction with the National Research Council, in establishing the Personnel Research Federation, the Highway Research Board, and the American Bureau of Welding; and in conducting the Marine Piling Investigation, and the compilation of the Directory of Industrial Research Laboratories in the United States.

Doctor Flinn was assistant secretary of the John Fritz Medal Fund Corporation from 1920 to 1935. In February 1928, he was elected secretary and treasurer of the Daniel Guggenheim Medal Fund; he resigned as treasurer in May 1935, and relinquished his duties as secretary in May 1936.

He was a Fellow of the American Association for the Advancement of Science, and a member of the American Society of Civil Engineers, American Institute of Mining and Metallurgical Engineers, American Mathematical Society, American Iron and Steel Institute, Sigma Xi, Sigma Alpha Epsilon, the Century Association, and the Engineers' Club. He was a past-president of the Municipal Engineers of the city of New York and holder of its gold medal for the best paper of the year. He was honorary foreign member of the section of engineering sciences of the Masaryk Academy of Prague, Austria, and a Knight of the Order of the White Lion, Republic of Czechoslovakia.

With R. S. Weston and C. L. Bogert, he compiled a "Waterworks Handbook," now in its third edition and extensively used in the United States and other countries. He originated and edited for 12 years the "Research Narratives" printed by the Engineering Foundation. He was also the author of many technical papers and chapters in technical books.

# Letters to the Editor

CONTRIBUTIONS to these columns are invited from Institute members and subscribers. They should be concise and may deal with technical papers, articles published in previous issues, or other subjects of some general interest and professional importance. ELECTRICAL ENGINEERING will endeavor to publish as many letters as possible, but of necessity reserves the right to publish them in whole or in part, or reject them entirely.

ALL letters submitted for consideration should be the original typewritten copy, double spaced. Any illustrations submitted should be in duplicate, one copy, to be an inked drawing but without lettering, and other to be lettered. Captions should be furnished for all illustrations.

STATEMENTS in these letters are expressly understood to be made by the writers; publication here in no wise constitutes endorsement or recognition by the American Institute of Electrical Engineers.

## Short-Time Spark-Over of Gaps

*To the Editor:*

The paper "Short-Time Spark-Over of Gaps," by J. H. Hagenguth (ELECTRICAL ENGINEERING, volume 56, pages 67–76, January 1937) gives rise to several questions.

The curves *B* of figure 14 (page 74), showing the relations between breakdown voltage and time to breakdown of a 20-inch, rod gap for both positive and negative surges, cross in 2 places. No experimental points are shown on the curves—but if the author's estimates of from 10 to 20 per cent accuracy in determination of time to breakdown are accepted one might wonder if there is justification for showing 2 distinct curves. If the curves represent the physical picture correctly, the explanation for the negative surge breakdown time being both higher and lower than that for a positive surge, depending upon the magnitude of the overvoltage, might be that given below.

It will be noted that the minimum breakdown potential is always lower for a positive surge. The difference is small for suspension-insulator spark-over, amounts to 30 per cent in some cases for rod gaps. The fields at the 2 electrodes of the suspension insulator are probably nearly alike. However, because of the proximity of the ground plane the field at the grounded electrode of the rod gap is much less than at the ungrounded electrode. From simple sparking theory the sharper gradient at the cathode should give a lower breakdown potential.[1] Since the tests referred to in the paper are at high pressure, the theory of "electron avalanche" [2,3] must be invoked. The increase in gradient caused by the electron avalanche is in some cases only 14 per cent of the existing gradient.[4] The electron avalanche (with a lack of a positive source of electrons by illumination) might begin anywhere between the electrodes and reach its maximum value in the vicinity of the anode. Hence, for minimum breakdown potential the positive surge, with higher gradient at the ungrounded electrode due to both dissymmetry of the field and the electron-avalanche field, would be expected to give a lower breakdown voltage than a negative surge with only the dissymmetry of the field to give a high gradient.

In the case of overvoltage the problem is not quite the same, for we are dealing with the time required for breakdown. The potential gradient with either surge certainly will cause breakdown; it is only a question of how long a time before breakdown. On a statistical basis it might be expected that a negative surge will give a lower time to breakdown, for the electron avalanche certainly would have a considerable magnitude in the vicinity of the cathode, thus increasing the field at this point in a time shorter than that required for motion of the avalanche to the high field of the anode and the time for propagation of the secondary process of ionization to the cathode. These deductions are borne out in the tests involving a large distance between electrodes as shown in curves *A* and *B* figure 10, page 72, for intermediate overvoltages. (Note that the ordinates are per cent over voltage.) For the third case of very great overvoltage the times of breakdown should be about the same regardless of polarity of the surge, within the limits of the experimental error given by Hagenguth, as shown in figures 10 and 14.

The choice of definition of rate of voltage rise applied to surges given on page 71 seems consistent enough from examination of figure 9 and comparing it with figure 14. This brings up the method of measuring rate of rise of voltage for a voltage variation similar to figure 7*b* with an accentuated first rise. Here rate of rise would be smaller factor compared with the effect of 2 sudden voltage impulses. In standardizing a definition, or in expressing the results of tests, some limitation should be made on the magnitudes of a disturbing initial voltage pulse.

REFERENCES


1. CONDUCTION OF ELECTRICITY IN GASES (a book), J. Slepian. Westinghouse Electric & Manufacturing Company, East Pittsburgh, Pa., 1933, page 129.

2. BREAKDOWN OF SPARK GAPS, J. Slepian. *Electrical World*, volume 91, April 14, 1928, pages 761–5.

3. STOSSPANNUNG UND DURSCHLAG BEI GASEN, W. Rogowski. *Archiv fur Elektrotechnik*, volume 20, May 11, 1928, pages 99–106.

4. MECHANISM OF STATIC SPARK DISCHARGE, L. B. Loeb. *Review of Modern Physics*, volume 8, July 1936, pages 267–93.


Very truly yours,


G. H. FETT (A'32)

Assistant in Electrical Engineering, University of Illinois, Urbana


## Engineers and Government

*To the Editor:*

The engineering profession has, of late, been running the gamut of sharp criticism from those of the "more abundant life" diagnosticians who like to believe that we are the cold lobsters responsible for such economic nightmares as that from which the world is just awaking.

These pragmatists are convinced that we fiddled too much with logarithms and slide rules while the world burned in the fire of so-called technological unemployment, and that hereafter we should take it upon ourselves to pay as much attention to the efficiency of our economic apparatus as to the efficiency of our industrial and power-station equipment. Thus, they would have us practice not only engineering but also economics, sociology, finance, banking, and even black magic, and thereby distend ourselves into a legion of supermen, capable of designing skyscrapers and transformers for 40 hours a week and solving the problems of money and state in our off hours.

At first thought, the very audacity of the

proposal is flattering, but upon reflection it becomes apparent that the critics are indulging in the old game of passing the buck on to the geese that squawk the least. Engineers undoubtedly are less well organized than the members of other major professions, such as the medical and the legal and hence the little squawking that we do at times is perfunctory and in no way comparable to the unanimity of the 10,000,000-decibel squawk that comes from the throat of the American Medical Association, for instance, whenever it is pricked with a pin.

So that, far from swelling with pride at the suggestion that we must become a body of cure-all practitioners, we should, in the interest of tolerance, earnestly struggle against the natural impulse to laugh in our critics' faces. For the underlying weakness of their case lies in the fact that they almost wholly lack acquaintance with engineering problems and, typical of the clan of critics the world over, they find it far easier to stand without and grimace, and denounce the inner workings of a thing, than to take the trouble to learn something about what they are denouncing, and perhaps offer some constructive suggestions.

What they believe, no doubt, is that history and political science can be neatly and conveniently contained in a hypodermic syringe of some form, to be injected into the arm or leg of the student engineer at will, and in zero time. Because, if they have the slightest inkling of what they talk about, they must recognize the fact that the engineering school curriculum of 4 years falls far short of supplying the student with even adequate engineering training, and that at least another 2 years would be necessary to fulfill this primary requisite. They should know, too, that anything less than 6 years special study in the social sciences is wholly inadequate, and if they can add 6 and 6, they might get 12. Now 12 years of organized study, besides tending to create academicians and school teachers, is an expensive proposition, and such a course would leave the engineering profession open to rich men only (which, in itself, might not be a bad ideal). Further, the field of inquiry of pure engineering is so intricate and broad that only the best minds available can cope with it in a reasonably intelligent manner, and any scheme that calls for a mind able to cope with it, plus the problems of 4 or 5 other professional groups that can't even handle their own, is sheer nonsense, and unworthy of even the third-rate politicians who voiced it.

This is not to say that we, as a profession, are totally disinterested in society's problems. On the contrary, it is my belief that the engineer, in general, has a keener appreciation of the issues involved than have any other professional groups, and we would be more than happy to assist the nation's statesmen in their work. But the trouble is that politicians take to sound advice in precisely the same manner that a gagging infant takes to cod liver oil. Past experience has demonstrated amply the inadvisability of administering counsel in any but infinitesimal doses, and the chances are about $n$ to 1 against the lawmaker digesting even those.

Very truly yours,

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54 Wendell Avenue,
Pittsfield, Mass.

## Wave Forms in Frequency-Tripling Transformers

*To the Editor:*

In the July 1936 issue of ELECTRICAL ENGINEERING the paper "Frequency Tripling Transformers," by J. L. Cantwell, shows the characteristics of one method of frequency tripling. The purpose of this letter is to show oscillograms of the wave forms of voltages and currents in Cantwell's frequency-tripler circuit.

Three similar transformers, with rated primary and secondary voltages of 110, were connected as shown in figure 1. Since the fundamental input line-to-neutral voltage was $235/\sqrt{3}$, or 136 volts, the transformers were operated at flux densities somewhat above normal. As shown in Cantwell's paper, this increase of flux density above normal increased the amount of the third-harmonic voltage output.

With no load on the secondary the third-harmonic output voltage was 206. The wave forms of the primary line-to-neutral voltage and the primary line current for this condition are shown in the oscillogram of figure 2. The voltage wave contains a very prominent third harmonic. The current wave contains a noticeable fifth harmonic.

When a resistance load was connected to the output terminals the output voltage dropped rapidly with an increase of output current. The voltage decreased from 206 volts at no load to 103 volts for a load current of 0.78 ampere. The wave forms for this load condition are shown in the oscillogram of figure 3.

In order to make easier the comparison of wave forms for no load and for some load, the oscillogram of figure 4 was taken. This oscillogram shows the wave forms of figures 2 and 3 in the correct phase positions relative to each other, and to the same scales.

Figure 4 shows that as the output current is increased the magnitude of the third-harmonic component of the voltage and the peak value of voltage are reduced. As the output current is increased the primary line current is changed somewhat in wave form, and its peak value is increased.

When a 4.73-microfarad capacitor was connected in series with the resistance load the wave forms became those shown in figure 5. In this case the voltage across the resistance load dropped only to 162 volts at a current of 1.45 amperes.

It is of interest to note that the output current $i_{S3}$ appears to contain a component which is a third harmonic with respect to it. This component thus is a ninth harmonic with respect to the fundamental.

The oscillogram of figure 6 shows the wave forms of figures 2 and 5 in the correct relationship with respect to each other. The wave $i_{L1}$ represents the same current in both figures 2 and 6 but the scale is not the same in each case.

Figure 6 shows that the use of a capacitor in series with the load increases the magni-

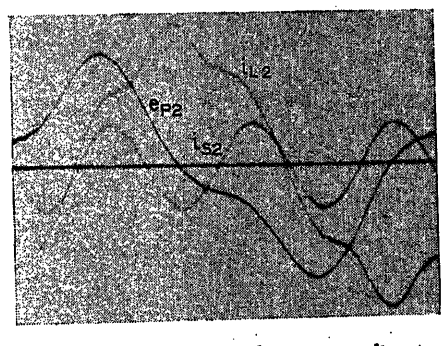



**Fig. 3. Oscillogram of primary line-to-neutral voltage, primary line current, and output current, with a resistance load**

$e_{P2}$—Primary line-to-neutral voltage
$I_{L2}$—Primary line current
$I_{L2}$—2.24 amperes, effective
$I_{S2}$—Output current
$I_{S2}$—0.78 ampere, effective
A unit length is 5.13 amperes and 445 volts

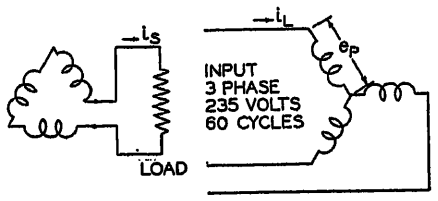



**Fig. 1. Diagram of a frequency-tripling circuit**

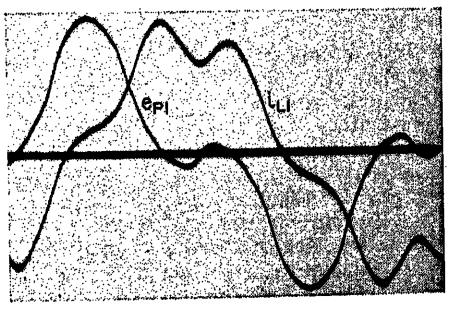



**Fig. 2. Oscillogram of primary line-to-neutral voltage and line current with no load on the secondary of the frequency-tripling circuit**

$e_{P1}$—Primary phase voltage
$I_{L1}$—Primary line current
$I_{L1}$—2.02 amperes, effective
A unit length equals 5.13 amperes and 445 volts (the base of 1/2 cycle is taken as a unit length)

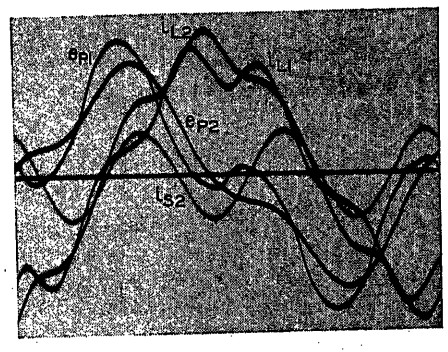



**Fig. 4. Oscillogram of primary line-to-neutral voltages and primary line currents at no load and under load, output current under load conditions**

$e_{P1}$—Primary line-to-neutral voltage at no load
$e_{P2}$—Primary line-to-neutral voltage under load
$I_{L1}$—Primary line current at no load
$I_{L1}$—2.02 amperes, effective
$I_{L2}$—Primary line current under load
$I_{L2}$—2.24 amperes, effective
$I_{S2}$—Output current
$I_{S2}$—0.78 ampere, effective
A unit length is 5.13 amperes and 445 volts

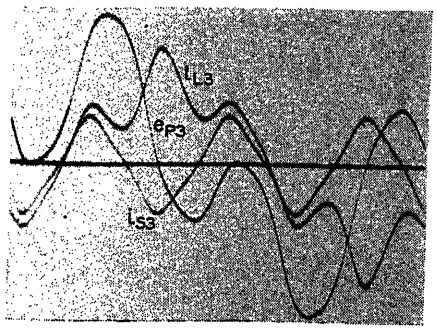



**Fig. 5. Oscillogram of primary line-to-neutral voltage, primary line current, and output current, with a capacitor in series with the resistance load**

$e_{P3}$—Primary line-to-neutral voltage
$i_{L3}$—Primary line current
$I_{L3}$—2.7 amperes, effective
$i_{S3}$—Output current
A unit length equals 9.1 amperes and 445 volts

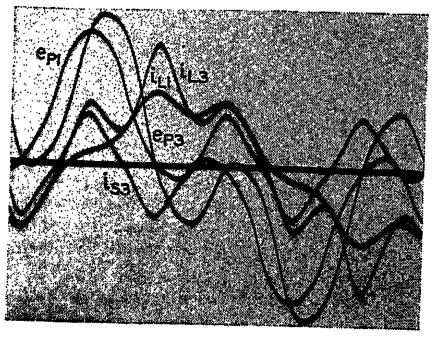



**Fig. 6. Oscillogram of primary line-to-neutral voltages and primary line currents at no load and under load, output current under load conditions**

$e_{P1}$—Primary line-to-neutral voltage at no load
$e_{P3}$—Primary line-to-neutral voltage under load
$i_{L1}$—Primary line current at no load
$I_{L1}$—2.02 amperes, effective
$i_{L3}$—Primary line current under load
$I_{L3}$—2.7 amperes, effective
$I_{S3}$—Output current
$I_{S3}$—1.45 amperes, effective
A unit length is 9.1 amperes and 445 volts

tude of the third-harmonic component of the primary line-to-neutral voltage and also the peak value of the voltage. The primary line current is changed in wave form and its peak value is increased appreciably.

The point made by Cantwell regarding possible overvoltages, when a capacitor is used, is an important one. At one time the writer connected a 10-microfarad capacitor across an open corner of the delta on 3 110-volt transformers. The voltage across the capacitor was found to be more than 1,110 volts.

The transformers used in obtaining the oscillograms shown in this letter were not designed to be used as frequency triplers. The exciting currents are rather large in comparison with the output current, but the general nature of the wave forms in a frequency tripler can be predicted from the oscillograms shown.

Very truly yours,

G. V. MUELLER (A'29, M'35)
Assistant Professor of Electrical Engineering, Purdue University, Lafayette, Ind.

## Qualitative Analysis of Self-Excited A-C Generator

*To the Editor:*

An article in the May 1935 issue of ELECTRICAL ENGINEERING on the subject of self-excited a-c generators of the induction type gave what may be regarded as an introduction outlining the possibilities of using a squirrel-cage induction motor as a generator by connecting suitable capacitance across the terminals and driving the machine mechanically. It may be inferred from this article that the electrical losses plus the load are supplied from the mechanical input; but it is not made clear just how the conversion from mechanical to electrical energy occurs. Also, the question of what determines the output frequency is not satisfactorily answered.

It is not sufficient explanation of the operation of such a machine merely to say that the capacitance draws a leading current (resulting from residual magnetism voltage) which is magnetizing, and therefore the initial voltage increases. This does not take into account the function of the rotor conductors. The operation may be partially explained by saying that a salient-pole rotor less conductors may build up on capacitive load without d-c excitation; and that the bars in a cylindrical squirrel-cage rotor tend to carry the flux around the air gap so that it cuts the stator conductors just as the salient-pole rotor does (except for slip necessary to have this effect).

Such an explanation is helpful but does not explain matters completely.

A concept of all the phenomena involved undoubtedly may be obtained by several different approaches. One approach, which would be of most value quantitatively no doubt, would be to set up equations for all voltages and currents and fluxes, applying Kirchoff's laws for the final solution. However, the following nonmathematical approach probably is as simple as any other concept.

Consider first a squirrel-cage induction motor less squirrel cage; in other words a wound stator with a cylindrical laminated-iron rotor and no rotor conductors. The stator then is merely an iron-core reactance with an air gap. A single-phase winding is taken for simplicity.

Now if a charged capacitor is connected across the terminals, its energy is dissipated through an oscillatory discharge, damped by the stator resistance. If resistance is neglected, the frequency of the current flowing will be given by

$$f_0 = \frac{1}{2\pi\sqrt{LC}}$$

Now suppose rotor bars are introduced and the rotor is driven at a speed

$$RPM = \frac{2 \times 60 f_0}{P}$$

where $P$ is the number of poles.

The rotor revolving at synchronous speed will of course cut the flux produced by the stator resulting from the current flowing of frequency $f_0$ when the charged capacitor is connected. The result will be merely to set up a cross field, and instead of the flux involved in determining the inductance $L$ being a pulsating flux, it is now rotating. This rotating field, however, supports a voltage of the same frequency and magnitude as a pulsating flux of the same maximum amplitude. The voltage in either case is

$$E = K\phi \sin 2\pi f_0 t$$

where $K$ is a constant and $t$ is time.

It is probably beside the point to discuss whether such a condition is stable; that is whether the capacitor discharges just as though the rotor had no conductors. The situation is complicated by the stator and rotor resistance always present in the practical case.

Now suppose the rotor is driven at a speed slightly above synchronous speed as previously defined. This means that if the stator flux continues to rotate at the frequency $f_0$ there is a slip resulting in low-(slip) frequency rotor current. Since the rotor conductors are pushing ahead, the slip current in the bars has a magnetizing effect. The effect of this will be to increase the flux $\phi_0$.

Now this condition may be regarded as increasing the inductance of the stator winding. This in turn reduces the natural period of oscillation, and a new frequency of current through the capacitor exists; that is,

$$(2\pi f_1)^2 = \frac{1}{(L_0 + L_r)\, C}$$

where $L_r$ is the effective increased inductance due to magnetizing effect of rotor current.

This means that the slip of the field as compared with rotor speed increases, which in turn enlarges the slip current and the magnetizing effect of the rotor conductors. A "vicious circle" results, until the machine either loads to saturation or the torque exceeds the capacity of the driver and the speed drops. Since the stator current is flowing at resonant frequency, it is limited only by the circuit resistance.

In many practical cases harmful results will appear, such as building up of voltage sufficient to cause failure of the capacitor, breakdown of generator insulation, or overheating of generator. In a capacitor type of motor with certain types of connections, circulating currents may be caused by this generating action, which produces a large negative torque preventing the motor from pulling up to speed.

It would seem desirable to have means available to control frequency of generator output, and output voltage. Perhaps the easiest method of controlling frequency is the use of a salient-pole rotor. This would also tend to control voltage build-up, since the "vicious circle" outlined previously would not exist.

Next, in order to have dependable build-up, a small d-c excitation or a permanent magnet might be introduced.

The net result is an a-c generator or magneto with a capacitor across the terminals or perhaps in series with the load to hold up or boost the delivered voltage. Such an arrangement is, of course, by no means new.

Very truly yours,

CHARLES T. BUTTON (A'26)
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# Personal Items

F. L. HUNT (A'05, F'17) director of economics and engineering of Western Massachusetts Companies, Greenfield, Mass., has been elected vice-president of that association and of each of its constituent utility companies, and assigned the duty of general charge of operations of those companies. Mr. Hunt was born at Delta, Iowa, in 1879, and was graduated from the University of Nebraska with the degree of bachelor of science in electrical engineering in 1902. Following his graduation he spent 3 years in the testing department of the General Electric Company, Schenectady, N. Y. In 1905 he was transferred to the Boston, Mass., offices of the General Electric Company, where he was in charge of construction work in New England, and later assistant district engineer. In 1913 Mr. Hunt accepted the position of chief engineer of the Turner Falls Power and Electric Company and allied companies in Greenfield, Mass., and in 1927 when Western Massachusetts Companies was formed, including the Turner Falls Power and Electric Company, United Electric Light Company, Pittsfield Electric Company, and the Greenfield Electric Light and Power Company (now Western Massachusetts Electric Company), Mr. Hunt was appointed director of economics and engineering of those companies. He has served the Institute as a member of the committees on protective devices, 1914–16 and 1919–29; standards, 1923–32; and meetings and papers (now technical program), 1926–28. Mr. Hunt is the author of several Institute papers.

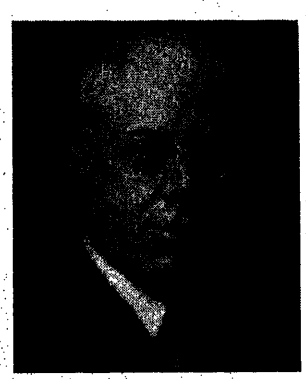
A. C. SCHWAGER (A'24, M'31) formerly chief engineer of the Pacific Electric Mfg. Corporation, San Francisco, Calif., has been elected vice-president in charge of engineering. Mr. Schwager, born in Switzerland in 1899, completed his general and technical education and began his professional career in that country as a technical assistant in the test laboratory of the Electric Manufacturing Company, at Oerlikon. Later, during 1922–23, he served as assistant professor at the Institute of Technology in Zurich. He came to the United States in 1923, whereupon he joined the staff of the Electrical Testing Laboratories, New York, N. Y., as a technical assistant on high-voltage cable research, but in the following year transferred his affiliation to the New York Edison Company, where he served as a draftsman on power-plant and substation design. During 1925–26 he continued the same type of work with the Pacific Gas and Electric Company, San Francisco, Calif. Since 1926 Mr. Schwager has been associated continuously with the Pacific Electric Mfg. Corporation, first as test engineer in charge of the test laboratory and successively as executive engineer in charge of the engineering department, as design engineer in charge of oil circuit breaker design, and as chief electrical engineer. In 1931 he was appointed chief engineer of the company. Mr. Schwager has contributed liberally to technical literature by means of articles in trade periodicals and through several papers presented before the Institute.

WALTER CARR (A'14, M'17) who was elected a vice-president of the Connecticut Railway and Lighting Company, Bridgeport, in 1936, recently was elected a director of the company, and now is in charge of the company's operations. Mr. Carr was born October 27, 1888, at Fredericton, N. B., Canada, and was graduated from Stevens Institute of Technology with the degree of mechanical engineer in 1910. Upon graduation he entered the employ of the General Electric Company, Lynn, Mass., as a test engineer, and remained there for one year before returning to Fredericton to become superintendent of the municipal lighting plant of that city. In 1912 Mr. Carr accepted a position with the United Gas Improvement Company, Philadelphia, Pa., and remained for more than 24 years, during which period his work consisted of the design, construction, and operation of street railway and motor-coach facilities.

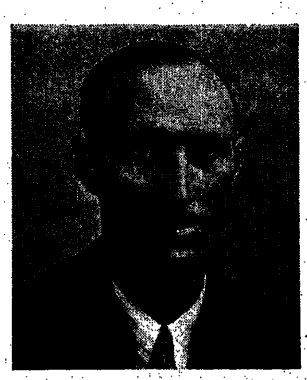
F. W. MACNEILL (A'11, M'22) district sales engineer for the Canadian General Electric Company, Vancouver, B. C., recently was elected to the council of The Engineering Profession in British Columbia to represent the electrical engineers of the province. Mr. MacNeill was born at Ormond, Ont., Canada, in 1882, and received a diploma in mechanical and electrical engineering from the faculty of applied science of the University of Toronto in 1907. During the following year he pursued postgraduate work at the same institution and received the degree of bachelor of applied science. Upon graduation in 1908, Mr. MacNeill entered the employ of the Canadian General Electric Company, and for 2 years was engaged in electrical testing and design at the Peterboro, Ont., works of that company. In 1910 he was made sales engineer in the Toronto offices of that company, but in the same year was appointed district sales manager for Alberta and eastern British Columbia. He has held his present position as district sales engineer for the Province of British Columbia since 1917. Mr. MacNeill was chairman of the Institute's Vancouver Section during 1923–24.

E. H. COLPITTS (A'11, F'12) vice-president of the Bell Telephone Laboratories, Inc., New York, N. Y., has retired from active service. Doctor Colpitts was born January 19, 1872, at Point du Bute, N. B., Canada, and received the degree of bachelor of arts at Mt. Allison College (1893) and Harvard University (1896); in 1897 he received the degree of master of arts at Harvard. He continued his work in the Harvard graduate school for $1\frac{1}{2}$ years, but received no further degree; however, in 1926 Mt. Allison College conferred upon him the honorary degree of doctor of laws. After terminating his graduate work in mathematics and physics he entered the employ of the American Bell Telephone Company, being engaged in research problems in telephone transmission. A few years later, when this department was merged with the engineering department of the American Telephone and Telegraph Company, Doctor Colpitts continued with the new company until 1907, when he was transferred to the engineering department of the Western Electric Company, New York. In 1917 he became assistant chief engineer of that company, and in 1924 was elected assistant vice-president of the American Telephone and Telegraph Company. He became vice-president of the Bell Telephone Laboratories in 1933. Doctor Colpitts has been granted many patents, and is the author of numerous technical papers. He served the Institute as a member of the committee on standards, 1916–17; telegraphy and telephony (now communication), 1919–24; and research, 1922–37. He is a member of the Institute of Radio Engineers, the American Physical Society, and several other technical organizations.

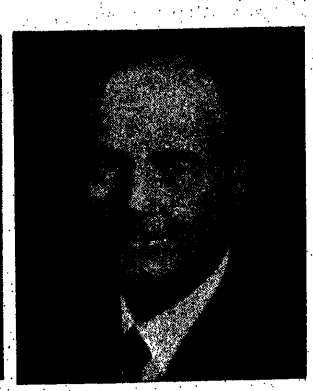
B. W. DUNKELBURGER, JR. (A'36) formerly technician and supervisor in the visual instruction department of North Dakota State College, Fargo, now is principal of The Northwood (N. D.) High School. Mr. Dunkelburger received the degree of bachelor of science in education



F. L. HUNT



A. C. SCHWAGER



WALTER CARR

at North Dakota State College in 1936, and during his undergraduate training acted as assistant principal and dean of the Boys Agricultural and Mechanics Arts High School, conducted by North Dakota State College.

W. L. WHYTE (A'35) until recently stationed at Ceará, Brazil, with the Ceará Tramway, Light, and Power Company, Ltd., recently accepted an appointment as technical adviser in electrical matters to the Uganda Government. Mr. Whyte has had broad experience in electrical construction and operation in Argentina, Brazil, Great Britain, and the Federated Malay States. He is a member of the Institution of Electrical Engineers (Great Britain).

B. E. ANDERSON (M'35) formerly assistant electrical engineer in the Public Works Department, United States Navy Yard, Mare Island, Calif., now is employed by the Phoenix Engineering Corporation, New York, N. Y. Mr. Anderson, a native (1896) of Colorado Springs, Colo., has had wide experience in public utility work in the United States and abroad.

JACK DELMONTE (A'36) has resigned his position as junior electrical engineer at the naval aircraft factory, United States Navy Yard, Philadelphia, Pa., to accept a position as laboratory technician in the engineering research laboratories of the Firestone Tire and Rubber Company, Akron, Ohio.

W. A. STELZER (A'34) who has been an electric dredge engineman, United States Engineers, Fort Peck, Mont., now is employed as a draftsman in the electrical engineering department of the Commonwealth and Southern Corporation, Jackson, Mich.

F. M. FARMER (A'02, F'13, director) vice-president and chief engineer, Electrical Testing Laboratories, New York, N. Y., has been appointed a member of the Institute's executive committee to fill the unexpired term of the late Junior Past-President E. B. Meyer.

J. S. BROWN (A'23, M'31) who has been employed in the survey department of the Potomac Electric Power Company, Washington, D. C., now is employed in the electrical engineering department of the Duquesne Light Company, Pittsburgh, Pa.

H. W. RICHTER (A'36) formerly a designer for the Dormeyer Manufacturing Company, Chicago, Ill., now is employed as an electrical engineer for the Allen Electric and Equipment Company, Kalamazoo, Mich.

L. A. HELGESSON (A'34) formerly assistant engineer in the steam heat department of the Northwestern Electric Company, Portland, Ore., has resigned to accept a position in the engineering department of L. R. Teeple Company, Portland.

R. L. SMITH (M'34) formerly an electrical engineer for the Buffalo, Niagara, and Eastern Power Corporation, Buffalo, N. Y., now is employed by the Stone and Webster Engineering Company, Boston, Mass.

L. B. ECKLES (A'36) formerly an electrical designer for the Consumers Power Company, Jackson, Mich., recently accepted a position as associate engineer with the Iowa Agricultural Business Corporation Service, Des Moines.

J. K. MOORE (A'36) who has been an electrical engineer for the Hydroelectric Commission of the State of Oregon, Salem, now is employed by the Eastern Oregon Light and Power Company, Baker.

E. J. RAMALEY (A'32) formerly senior rodman, United States Bureau of Public Roads, Denver, Colo., now is engaged in research work at Battelle Institute, Columbus, Ohio.

I. E. MOUROMTSEFF (A'25) research engineer, Westinghouse Electric & Manufacturing Company, East Pittsburgh, Pa., has been transferred to the lamp division of that company at Bloomfield, N. J.

ROBERT MACDONALD (A'28) formerly power engineer for Ericcson Telephones, Ltd., Beeston, Nottingham, England, now is employed by the Western Electric Company, Kearny, N. J.

E. D. LILJA (A'31) formerly an electrical engineer with Barber-Colman Company, Rockford, Ill., now holds a similar position with the Woodward Governor Company, Rockford.

F. R. MARION (A'26) has been transferred from the operating engineering department of Electrical Research Products, Inc., New York, N. Y., to the Western Electric Company, Kearny, N. J.

# Obituary

WILLIAM STANTON TWINING (A'05, M' 13) retired engineer, Ambler, Pa., died February 8, 1937. Mr. Twining was born February 20, 1865, near Titusville, Pa., attended Cornell University, and was graduated from Allegheny College in 1887, as a civil engineer. During the 3 following years he remained at Allegheny College as an instructor in chemistry and engineering, and in 1890 entered the railway engineering department of the Thomson-Houston Company at Boston, Mass., where his work consisted of power-station design and construction. In 1901 he was engaged as assistant engineer for the Union Railway Company and the Interborough Rapid Transit Company, New York, N. Y., and remained in that position until 1903, when he transferred his affiliation to the Peoples Traction Company, Philadelphia, Pa. In 1905 Mr. Twining was appointed chief engineer of that company and its successor, the Union Traction and Philadelphia Rapid Transit Company, in which position he was in general charge of all engineering work. From 1910 to 1914 he served as engineering manager for the consulting engineering firm of Ford, Bacon, and Davis, New York, N. Y. He then returned to Philadelphia to become the first director of transit of that city. Mr. Twining retired from active service in 1925.

EUGENE L. ALEXANDER (A'35) formerly an electrical draftsman for the New York (N. Y.) Rapid Transit Corporation, died November 1, 1936, according to word just received at Institute headquarters. Mr. Alexander was born October 1, 1882, at Tiflis, Russia, and received the degree of electrical engineer from the University of Liege (Belgium) and the Electrical Institute of Emperor Alexander III (Russia) in 1908 and 1910, respectively. Following his graduation he was appointed assistant superintendent of the electrical department of the Steel, Locomotive, and Shipbuilding Works, Soromovo, Russia, and remained in that capacity until 1914, when he was made superintendent of the electrical power plant and assistant superintendent of the electrical department in the Metallurgical Corporation of Nicopol Marioupol. During the year 1918–19 Mr. Alexander was superintendent of the municipal electric plant of the City of Marioupol, Russia, and in the following year he accepted a position as assistant superintendent of a central station of the Compagnie Ottomane d' Electricitè, Constantinople, Turkey. In 1925 he came to the United States and entered the employ of The New York (N. Y.) Edison Company as an electrical draftsman. In 1928 he transferred to the New York Rapid Transit Company in a similar position.

WALTER EDWARD BARE (A'29) general commercial manager of the Southern Bell Telephone and Telegraph Company, Atlanta, Ga., died February 5, 1937. Mr. Bare was born September 22, 1882, at Lexington, Va., and was educated in private schools in Florence, Ala. He entered the employ of the Southern Bell Telephone and Telegraph Company as a lineman in 1903 and served that company continuously, except for a brief service in the United States Army during the World War. From 1905 to 1916 he acted as manager of various local plants of the company, and in 1919 was promoted to district manager in the Montgomery, Ala., offices. During 1921–23 he held a similar position in the Birmingham offices before being appointed Alabama state manager for the company. Mr. Bare became commercial manager in 1930.

FREDERICK A. SCHEFFLER (A'93, M'96, F'12, member for life) retired electrical engineer, formerly connected with The Babcock & Wilcox Co., New York, N. Y., died

February 23, 1937. Mr. Scheffler was born December 20, 1858, at Galion, Ohio, and was graduated from the Paterson (N. J.) Seminary in 1871, following which he was associated briefly with several companies, including the Rhode Island Locomotive Works, Brown and Sharpe, and the Harris Corliss Engine Company, before joining the Edison Electric Light Company, New York, N. Y., in 1881. He was placed in charge of the engineering department of the Edison company, and in that capacity designed an electric locomotive used in experimental work by Thomas A. Edison (A'84, M'84, HM'28, John Fritz Medalist '08). In 1885 Mr. Scheffler became superintendent of the Erie City Iron Works, Erie, Pa., which position he held for 5 years before resigning to become acting general superintendent of the Westinghouse Electric & Manufacturing Company, East Pittsburgh, Pa., in 1889. Later he served as general superintendent of the Brush Electric Company (1891–93), the Sprague Electric Company (1899–1900), and the Marine Engineering and Machinery Company (1902–04). Mr. Scheffler was affiliated with The Babcock & Wilcox Co. and its subsidiary companies for many years. He served the Institute as a member of the committee on power stations from 1916 to 1919 and from 1922 to 1935, and as a member of the special committee on the Edison Memorial during 1932 and the Edison Medal committee, 1913–18, 1922-27, and 1930–33. He was a member of The American Society of Mechanical Engineers.

# Membership

## Recommended for Transfer

The board of examiners, at its meeting on March 17, 1937, recommended the following members for transfer to the grade of membership indicated. Any objection to these transfers should be filed at once with the national secretary.

**To Grade of Fellow**

**Baldwin, R. L.**, consulting engineer, Burns and McDonnell Engineering Company, Kansas City, Mo.

**Conrad, Frank**, assistant chief engineer, Westinghouse Electric & Manufacturing Company, East Pittsburgh, Pa.

2 to Grade of Fellow

**To Grade of Member**

**Anderson, C.**, headquarters sales and application, instruments and measuring devices, Westinghouse Electric and Manufacturing Company, Newark, N. J.

**Balch, E. C.**, chief engineer, Michigan Bell Telephone Company, Detroit, Mich.

**Balet, J. W.**, engineer, Consolidated Edison Company of New York, Inc., New York, N. Y.

**Boehne, E. W.**, design engineer, General Electric Company, Philadelphia, Pa.

**Bronaugh, J.**, sales representative, Allis-Chalmers Manufacturing Company, Richmond, Va.

**Carroll, J. S.**, associate professor, electrical engineering department, Stanford University, Calif.

**Gardner, J. E.**, electrical engineer, Chicago, Burlington and Quincy Railroad Company, Chicago, Ill.

**Joboolian, E.**, squad boss, Gibbs and Hill, New York, N. Y.

**Johnson, G. E.**, chief engineer and general manager, The Central Nebraska Public Power and Irrigation District, Hastings, Neb.

**King, R. T.**, industrial power representative, Public Service Electric and Gas Company, Trenton, N. J.

**Logan, K. H.**, senior electrical engineer, National Bureau of Standards, Washington, D. C.

**McCormack, J. E.**, distribution engineer, New York and Queens, Electric Light and Power Company, Flushing, N. Y.

**Michaels, A. P.**, consulting engineer, A. P. Michaels Engineering Firm, Orlando, Fla.

**Walker, E. W.**, proprietor, E. W. Walker, Birmingham, England.

**Zangler, R. M.**, standardization of mfg. practices and engineering data, Anaconda Wire and Cable Company, Hastings-on-Hudson, N. Y.

15 to Grade of Member

## Applications for Election

Applications have been received at headquarters from the following candidates for election to membership in the Institute. If the applicant has applied for direct admission to a grade higher than Associate, the grade follows immediately after the name. Any member objecting to the election of any of these candidates should so inform the national secretary before April 30, 1937 or June 30, 1937, if the applicant resides outside of the United States or Canada.

Abramowitz, A., 579 East 140th Street, New York, N. Y.

Adams, J. T. (Member), Public Service Company of Oklahoma, McAlester, Okla.

Alenius, E., Bell Telephone Laboratories, Inc., New York, N. Y.

Allen, T. O., Humble Oil and Refining Company, Anahuac, Texas.

Anders, R. D., Philadelphia Electric Company, Phoenixville, Pa.

Anderson, C. B., 318 Public Service Building, Tulsa, Okla.

Angier, J. F., National Bureau of Standards, Washington, D. C.

Anthony, B. M., Tennessee Valley Authority, Wilson Dam, Ala.

Arnn, E. L., General Electric Company, Philadelphia, Pa.

Aruck, M., Bell Telephone Laboratories, Inc., New York, N. Y.

Babcock, K. L., Underwood Elliott Fisher Company, Hartford, Conn.

Babin, B. P., Westinghouse Electric & Manufacturing Company, New Orleans, La.

Bader, R. D., Philadelphia Storage Battery Company, Philadelphia, Pa.

Bailey, A. (Member), American Telephone and Telegraph Company, New York, N. Y.

Balfour, M. W., Public Service Company of Northern Illinois, Chicago, Ill.

Banks, J. F., Commonwealth Edison Company, Chicago, Ill.

Barnes, C., Jr., 1153 N. Dearborn Street, Chicago, Ill.

Barrett, W. G., 10 West 90th Street, New York, N. Y.

Basore, N. D., Public Service Company of Oklahoma, Hartshorne, Okla.

Baum, D. C., 5001 Goodridge Avenue, Riverdale-on-Hudson, N. Y.

Bazak, H. V., Consolidated Edison Company of New York, Inc., New York, N. Y.

Beatty, F., University of Kentucky, Lexington, Ky.

Beck, J. M., Jr., Westinghouse Electric and Manufacturing Company, Wichita, Kans.

Behm, T. R., Syracuse Lighting Company, Syracuse, N. Y.

Behrens, H. J., Consolidated Edison Company of New York, Inc., New York, N. Y.

Bejarano, J. R., 87 Grove Street, Lynbrook, N. Y.

Bell, R. O., 1501 South 77th Street, Milwaukee, Wis.

Benson, B. T., Foreign and Domestic Commerce, Washington, D. C.

Bernard, W. B., 1407 West University Avenue, Gainesville, Fla.

Bingham, W. H. (Member), Westinghouse Electric Supply Company, New York, N. Y.

Birmingham, Paul V., 1285 Oak Grove Avenue, Burlingame, Calif.

Bischof, L. J., General Electric Company, New York, N. Y.

Bishop, R. H. (Member), Public Servic Company of Oklahoma, Tulsa, Okla.

Blom, L. A., 2306 N. Knox, Chicago, Ill.

Boehr, J. W., Westinghouse Electric and Manufacturing Company, Sharon, Pa.

Borton, J. R., Puget Sound Power and Light Company, Seattle, Wash.

Bossard, G. E., General Kontrolar Company, Inc., Dayton, Ohio.

Bottum, E. L., Carnegie Illinois Steel Corporation, Gary, Ind.

Boyd, A. G., General Electric Company, Schenectady, N. Y.

Bradstock, M. C., General Electric Company, Cleveland, Ohio.

Brazeel, J. P., Public Service Company of Oklahoma, Okemah, Okla.

Brewer, L. G., Montana Power Company, Havre, Mont.

Brewer, R. D., Ford Motor Company, Dearborn, Mich.

Bridegam, W. J., E. M. Gilbert Engineering Corporation, Reading, Pa.

Brignac, E. M., Industrial Electric Company, New Orleans, La.

Brody, E. W., Line Material Company, South Milwaukee, Wis.

Brown, J. G., General Electric Company, Schenectady, N. Y.

Brown, J. T., Jr., Carolina Power and Light Co., Raleigh, N. C.

Burleigh, C. LeM., Jr., Harvard Business School, Boston, Mass.

Campbell, R. P., Tennessee Valley Authority, Wilson Dam, Fla.

Carioni, H. M., Canadian Westinghouse Company, Ltd., Hamilton, Ont.

Carlberg, H. A., Wisconsin Public Service Corporation, Green Bay, Wis.

Carroll, D. R., Bell Telephone of Pennsylvania, Pittsburgh, Pa.

Chambers, M. A., Standard Oil Company, Shreveport, La.

Cherry, J. S., Westinghouse Electric and Manufacturing Company, East Pittsburgh, Pa.

Clough, F. P., Y. M. C. A., 8 East 3rd Street, New York, N. Y.

Cobert, C. S., Clark Controller Company, Cleveland, Ohio.

Coho, O. C., Jr., General Electric Company, Schenectady, N. Y.

Coleman, I. M., 581 Academy Street, New York, N. Y.

Colquhoun, W. H., in care of Maurice R. Scharff, New York, N. Y.

Connolly, D. E., 1738 Webster Avenue, New York, N. Y.

Contardi, A., Jr., 959 Middlesex Avenue, Metuchen, N. J.

Cooper, D. T., Brown Instrument Company, Philadelphia, Pa.

Crooks, W. E., 41 Duggan Avenue, Toronto, Ont., Canada.

Crosby, T. H., Canadian Westinghouse Company, Ltd., Vancouver, B. C., Canada.

Dalrymple, H. C., 46 Colony Drive East, West Orange, N. J.

Darrah, M. D., 4417 Swiss Avenue, Dallas, Texas.

Deardorff, R. W., Pacific Telephone and Telegraph Company, Portland, Ore.

DeBlois, W., Lincoln Electric Company, Boston, Mass.

deCarrera, R., General Electric Company, Schenectady, N. Y.

Degentesh, H. E., Square D Company, New York, N. Y.

Dermond, F., Bell Telephone Laboratories, Inc., New York, N. Y.

Dickinson, H. C., General Electric Company, Lynn, Mass.

Dingman, J. E. (Member), American Telephone and Telegraph Co., New York, N. Y.

Doede, H. C., Swift and Company, Chicago, Ill.

Doherty, J. F., Westinghouse Electric and Manufacturing Company, East Pittsburgh, Pa.

Dollins, C. B., Jr., Tennessee Valley Authority, Wilson Dam, Ala.

Dubsky, F. H., Commonwealth Edison Company, Chicago, Ill.

Dudley, R. B., The Jeffrey Manufacturing Company, Columbus, Ohio.

Duncan, A. H., Westinghouse Electric and Manufacturing Company, Wilkinsburg, Pa.

Ebert, K. W., 776 N. Cass Street, Milwaukee, Wis.

Eckert, J. D., Box 67, Flagler, Colo.

Ecklund, R. A., C. T. Main, Inc., Boston, Mass.

Eddy, W. L., Western Electric Company, Chicago, Ill.

Ellicott, C. R., Jr., Westinghouse Electric and Mfg. Co., Wilkes-Barre, Pa.

Ellsworth, C. E., Selectric Products Corporation, Louisville, Ky.

Elwood, E. S., Jr., General Electric Company, Schenectady, N. Y.

Emmons, P. A., Jr., 1233 North President Street, Jackson, Miss.

English, G. T., Triad Radio Tube Manufacturing Company, Pawtucket, R. I.

Ericson, A. E., 3950 North Farwell Avenue, Milwaukee, Wis.

Estoppey, R. F., Weston Electrical Instrument Corporation, Newark, N. J.

Ewert, A. C., Radio Station WMFJ, Daytona Beach, Fla.

Fagerlund, A. C., 2918 Jefferson Avenue, Cincinnati, Ohio.

Fallon, R. C., General Electric Company, Schenectady, N. Y.

Falls, O., General Electric Company, Pittsfield, Mass.

Feinberg, E., 3255 Cortland Avenue, Detroit, Mich.

Feiner, J. S., 551 E. 178th Street, New York, N. Y.

Fickel, L. V. (Member), Westinghouse Electric and Manufacturing Company, Tulsa, Okla.

Flagg, L. F., W. E. Kingswell, Inc., Washington, D. C.

Fluke, J. M., General Electric Company, Schenectady, N. Y.

Foley, R. B., General Electric Supply Company, New York, N. Y.
Forman, W. B., Westinghouse X-Ray Company, Pittsburgh, Pa.
Forsyth, J. E., Canadian Controllers, Ltd., Toronto, Ont., Canada.
Francis, F. W., Zerbe Township Public School, Trevorton, Pa.
Frank, D. W., Southwestern Light and Power Company, Lawton, Okla.
Freas, R. L., Pennsylvania State College, Conshohocken, Pa.
Friedman, H., Mackay Radio and Telephone Company, New York, N. Y.
Froling, R. O., General Electric Company, Pittsfield, Mass.
Fuller, A. L., Oklahoma Gas and Electric Company, Oklahoma City, Okla.
Fuller, M. A., Miller Rubber Company, Inc., Akron, Ohio.
Fullman, J. B., Westinghouse Electric and Manufacturing Co., Sharon, Pa.
Gallagher, J. J., Narragansett Electric Company, North Swansea, Mass.
Gardner, E. M., New York Telephone Company, New York, N. Y.
Gerhold, R. A., Signal Engineering and Manufacturing Company, New York, N. Y.
Gilreath, W. W., 2510 San Antonio Street, Austin, Texas.
Golub, E., 405 Quentin Road, Brooklyn, N. Y.
Gould, G. G., Porcelain Products, Inc., Parkersburg, W. Va.
Gramstedt, G. M. E., Hayg Electric Company, New York, N. Y.
Green, G. M., Black, Sivalls and Bryson, Inc., Kansas City, Mo.
Grigg, E. G., General Electric Company, Philadelphia, Pa.
Groenewold, A. W., Public Service Company of Oklahoma, Tulsa, Okla.
Guggenbuehler, C. R., Wagner Electrical Corporation, St. Louis, Mo.
Gulick, H. E., 718 North Louise Street, Glendale, Calif.
Hackenjost, H. F. (Member), Tennessee Valley Authority, Wilson Dam, Ala.
Hanson, C. F. (Member), Irvington Varnish and Insulator Company, Irvington, N. J.
Hart, L. B., Ohio Power Company, Coshocton, Ohio.
Hammer, O. S. C., Tennessee Valley Authority, Knoxville, Tenn.
Hamrick, G. W., Florida Power and Light Company, Dania, Fla.
Harry, W. R., Bell Telephone Laboratories, Inc., New York, N. Y.
Haun, R. C., Public Service Company of Oklahoma, Stigler, Okla.
Haupt, G. H., Samson-United Corporation, Rochester, N. Y.
Hebert, M., Jr., Gulf Oil Corporation, Port Arthur, Texas.
Henderson, R. H., Minneapolis Honeywell Company, New York, N. Y.
Henkes, G., Jr., Public Service Company of Oklahoma, Henryetta, Okla.
Herweh, A. C., 3739 Woodburn Avenue, Cincinnati, Ohio.
Heyburn, R. D., Firestone Tire and Rubber Company, Akron, Ohio.
Higginson, H., 414 N. Kilkea Drive, Los Angeles, Calif.
Hildebrandt, J. P., Humble Oil and Refining Company, Harlingen, Texas.
Hively, H. L., Jones and Laughlin Steel Corporation, Pittsburgh, Pa.
Hobson, C., General Electric Company, Pittsfield Mass.
Hoch, E. G., Jr., Electric Heating Equipment Company, Philadelphia, Pa.
Holston, S. C., Liebel Flarsheim Company, Cincinnati, Ohio.
Hopper, F. E., Crocker Wheeler Electric Manufacturing Company, Ampere, N. J.
Hoss, W. B. (Member), Oklahoma Power and Water Company, Sand Springs, Okla.
Howmiller, S., Harnischfeger Manufacturing Company, Milwaukee, Wis.
Huff, P. D., Duke Power Company, Salisbury, N. C.
Hunter, H. H., Public Service Commission of West Vriginia, Charleston, W. Va.
Hunter, M. V., Bell Telephone Laboratories, Inc., New York, N. Y.
Husted, E. W., Michigan Associated Telephone Company, Muskegon, Mich.
Hutson, M. B., Industrial Electric Company, New Orleans, La.
Insull, F. W. (Member), Southwestern Light and Power Company, Tulsa, Okla.
Jacobs, Y., 626 Garrard Street, Covington, Ky.
James, J. R., James G. Biddle Company, Philadelphia, Pa.
Jeffers, G. N., R. R. No. 1, Chilo, Ohio.
Johnson, F. B. (Member), Commonwealth Edison Company, Chicago, Ill.
Johnson, J. H., 826—43rd Street, Brooklyn, N. Y.
Johnson, W. B., Ohio Brass Co., Mansfield, Ohio.
Jones, A. L., Jr. (Member), General Electric Company, Tulsa, Okla.
Jones, R. H., Hartford, Electric Light Company, Hartford, Conn.
Kanyuck, R. A., Bethlehem Steel Company, Sparrows Point, Md.
Kay, J. S., Pacific Gas and Electric Company, Chico, Calif.
Keating, C. J., New York, Telephone Company, New York, N. Y.
Keator, E. C., South Fallsburg, N. Y.
Keck, J. N., Moloney Electric Company, St. Louis, Mo.
Kehoe, W., City Light and Water Utilities, Fort Wayne, Ind.
Kern, P. H., Western Electric Company, Chicago, Ill.
Kerr, W. E. (Member), Pennsylvania Transformer Company, Pittsburgh, Pa.
Kessel, R. L., Cline Electric Manufacturing Company, Chicago, Ill.
Keyser, A. G., Jr., 1777 Lanier Place, N. W., Washington, D. C.
Kidd, J. A. I., Canadian General Electric, Peterborough, Ont., Can.
Klebanoff, J. H., State Highway Planning Survey, Sacramento, Calif.
Klein, M., Otis Elevator Co., Yonkers, N. Y.
Knost, C. P. (Member), Moloney Electric Co., New Orleans, La.
Kopenitsi, C. T., Oilgear Company, Milwaukee, Wis.
Kralosky, F. B., 2622 Bartold Street, N. S., Pittsburgh, Pa.
Kulikowski, E. F., Jensen Radio Manufacturing Co., Chicago, Ill.
Kyes, J. M., 1946 Washington Street, San Francisco, Calif.
Lane, R. K. (Member), Public Service Company of Oklahoma, Tulsa, Okla.
Lantz, L. E., Jr., Jacksonburg, W. Va.
Lawson, S. A., Gustav Hirsch Organization, Columbus, Ohio.
Lee, H. B., Rural Electrification Administration Washington, D. C.
Lefthes, N., 11 Ward Street, Salem, Mass.
Legg, V. E. (Member), Bell Telephone Laboratories, Inc., New York, N. Y.
Lenhardt, W. C., Bethlehem Steel Company, Cornwall, Pa.
Levine, M. E., Tung-Sol Lamp Works, Newark, N. J.
Lobosco, R. R., Linde Air Products Company, Newark, N. J.
Lovoff, A., 3496 Anderdon Street, Detroit, Mich.
Ludden, J. H., 80 Mill Street, Athens, Ohio.
Lundgren, L. O., Kennecott Wire and Cable Company, Phillipsdale, R. I.
MacAllister, C. C., General Electric Company, Lynn, Mass.
MacKay, E. L., General Electric Company, Schenectady, N. Y.
Mansfield, T. E. (Member), Oklahoma Power and Water Company, Sand Springs, Okla.
Marshall, M. B., Jr., General Electric Company, Erie, Pa.
Martin, W. L., Triad Manufacturing Company, Pawtucket, R. I.
Martini, J. A., American Telephone and Telegraph Company, New York, N. Y.
Matheo, M., Consolidated Edison Company, New York, N. Y.
Matzinger, J. R., American Electric Switch Corporation, Minerva, Ohio.
May, M. H., Interstate Power Company, Albert Lea, Minn.
Mayer, J. A., Graybar Electric Company, Cleveland, Ohio.
Mayers, J. H., 917 Druid Hill Avenue, Baltimore, Md.
McArthur, D., General Electric Company, West Lynn, Mass.
McCormack, C. M., Phelps-Dodge Copper Products Corporation, Yonkers, N. Y.
McCrary, J. H. (Member), Public Service Company of Oklahoma, Tulsa, Okla.
McDowell, E. P., General Electric Company, Schenectady, N. Y.
McLeod, G. R., General Electric Company, West Lynn, Mass.
Mearns, W. J., Continental-Diamond Fibre Company, Bridgeport, Pa.
Messler, W. H., Winchester Repeating Arms, New Haven, Conn.
Michaelis, J. L., Pittsburgh Plate Glass Company, Barberton, Ohio.
Miller, R. E., Allis-Chalmers Manufacturing Company, Milwaukee, Wis.
Mooney, V. J., General Electric Company, Schenectady, N. Y.
Morgan, L. W., Commonwealth Edison Company, Chicago, Ill.
Morris, R. V., Gary Heat, Light and Water Company, Gary, Ind.
Morrison, H. A., Central Nebraska Public Power and Irrigation District, Hastings, Neb.
Moss, A. G. (Member), Public Service Company of Oklahoma, McAlester, Okla.
Mostrom, J., Phillips Petroleum Company, Bartlesville, Okla.
Motz, C. A., General Electric Company, Schenectady, N. Y.
Murphy, J. T., Shell Petroleum Corporation, Plaquemine, La.
Nauert, A. G., American Telephone and Telegraph Company, New York, N. Y.
Nelson, C. T., Public Service Company of Oklahoma, Okmulgee, Okla.
Nickerson, G., Texas Development Corporation, Lafitte, La.
Nimmer, F. W., Ohio Edison Company, Akron, Ohio.
Norton, T. P., 3 Bradford Street, Salem, Mass.
Olsta, E., Consolidated Edison Company of New York, Inc., New York, N. Y.
O'Meara, F. E. (Member), Westinghouse Electric & Manufacturing Company, Tulsa, Okla.
Pacanovsky, G. J., 7908 Halle Avenue, Cleveland, Ohio.
Papp, A., Jr., General Electric Company, Philadelphia, Pa.
Park, A. J., Graybar Electric Company, Cleveland, Ohio.
Parker, C. V., Bell Telephone Laboratories, Inc., New York, N. Y.
Parker, F. D., 106 Northern Avenue, New York, N. Y.
Parker, R. S., c/o H. B. Parker, 602 East Broadway, Madisonville, Ky.
Paterson, J. M., 7200—28th Avenue, N. W., Seattle, Wash.
Patterson, E. F., General Electric Company, Tulsa, Okla.
Patterson, G. W. (Member), Patterson Electric, Ltd., Toronto, Ont., Canada.
Pauler, E. A., Electric Storage Battery Company, Chicago, Ill.
Pearce, T. C. (Member), Potomac Electric Power Company, Washington, D. C.
Pence, I. E., 1120 North Milwaukee Street, Milwaukee, Wis.
Perlman, I., Air-King Radio Products Company, Brooklyn, N. Y.
Perrine, T. F., Jr., Jersey Central Power and Light Company, Allenhurst, N. J.
Perry, F. W., Jr., Brown and Sharpe Manufacturing Company, Providence, R. I.
Perry, W. J. (Member), Public Service Company of Oklahoma, Weleetka, Okla.
Perschbacher, H. V., Milwaukee Electric Railway and Light Company, Milwaukee, Wis.
Person, H. O., State Wide Highway Planning Survey, Howard, S. Dak.
Phillips, G. H., Georgia Power Company, Atlanta, Ga.
Phillips, N. W., Alabama Power Company, Decatur, Ala.
Phinney, J. A., Hugo District Public Service Company of Oklahoma, Hugo, Okla.
Pobst, J. W., General Electric Company, Schenectady, N. Y.
Post, L. E., New Jersey Bell Telephone Company, Newark, N. J.
Pryor, T. S., Southern Cotton Oil Company, Montgomery, Ala.
Rand, R. V., Box 237, Bismarck, N. D.
Regan, P. G., Minneapolis Honeywell Regulator Company, Boston, Mass.
Reichel, A. N., Western Electric Company, Kearny, N. J.
Rhodes, C. F., Templeton-Kenly and Company, Ltd., Chicago, Ill.
Rice, W. O., West Penn Power Company, Springdale, Pa.
Ridgway, D. P., Robbins & Myers, Inc., Springfield, Ohio.
Roberts, C. F., Jr., Texas Electric Service Company, Wichita Falls, Texas.
Roberts, R. C., Tennessee Valley Authority, Wilson Dam, Tenn.
Rothschild, G. R., Republic Flow Meters Company, Chicago, Ill.
Ruffle, L. E., Federal Shipbuilding and Dry Dock Company, Kearny, N. J.
Ruonavar, W. T., Ford Motor Company, Dearborn, Mich.
Rushmer, R. H., General Electric Company, Fort Wayne, Ind.
Russell, W. J. (Member), Westinghouse Electric & Manufacturing Company, Mansfield, Ohio.
Ryan, G. D. (Member), 39 Arcade Building, Columbia, S. C.
Rylander, L. F. (Member), Public Service Company of Oklahoma, Tulsa, Okla.
Salton, H. D. (Member), Pennsylvania Transformer Company, Pittsburgh, Pa.
Saunders, B. W., Narragansett Electric Company, Providence, R. I.
Sauter, B. W., RCA Radiotron, Harrison, N. J.
Saveland, W. T., Jr., Allis-Chalmers Manufacturing Company, Milwaukee, Wis.
Scattergood, E. R., Tennessee Valley Authority, Wilson Dam, Ala.
Schaefer, D. A., Indiana Bell Telephone Company, Indianapolis, Ind.
Schene, M. M., Public Service Company of Oklahoma, McAlester, Okla.
Schmidt, V. W. J., Cutler Hammer Inc., Milwaukee, Wis.
Schmitz, J. M., American Telephone and Telegraph Company, New York, N. Y.
Schumacher, H., Atlantic Gas and Electric Appliance Company, Los Angeles, Calif.
Schwan, C. F., Apex Electrical Manufacturing Company, Cleveland, Ohio.
Schweers, C. W., Allis-Chalmers Manufacturing Company, New Orleans, La.
Sealy, W. J., Canadian Railroad Service, Toronto, Ontario, Canada.
Segebarth, R. A., 1141 Ardsley Road, Schenectady, N. Y.
Seifried, D. B., F. C. Frederick Company, Summit Park, Spring Valley, N. Y.
Sepavich, V. F. P., 69 Harrison Street, Worcester, Mass.
Shaffer, J. A., Jones and Laughlin Steel Corporation, Pittsburgh, Pa.
Sharp, R. M., American Can Company, Newark, N. J.
Sheftelman, E. H., Automatic Diesel Electric Company, New York, N. Y.
Sherlin, G. C., Jr., Southwestern Bell Telephone Company, Little Rock, Ark.
Shew, W. W., General Electric Company, Schenectady, N. Y.
Shimer, R. B., Kenyon Transformer Company, New York, N. Y.
Shinn, G. H., Gibbs and Cox, Inc., New York, N. Y.
Shively, R. DeW., The B. F. Goodrich Company, Akron, Ohio.

Shumard, C. C. (Member), R. C. A. Manufacturing Company, Harrison, N. J.
Shutko, F. W., Jr., Detroit Edison Company, Trenton, Mich.
Siegel, E. M., Westinghouse X Ray Company, New York, N. Y.
Simons, R. L., Carolina Power and Light Company, Raleigh, N. C.
Simpson, J. L., Jr., Georgia Power Company, Athens, Ga.
Skina, F. A., 626 Ash Street, Moscow, Idaho.
Slemmer, W. E., Public Service Company of Oklahoma, Tulsa, Okla.
Smith, A. J., General Electric Company, Schenectady, N. Y.
Smith, H. G., Cornell University, Ithaca, N. Y.
Smith, R. G., General Electric Company, Tulsa, Okla.
Smith, W. J., Houston Armature Works, Houston, Texas.
Snyder, C. J., Indiana and Michigan Electric Company, South Bend, Ind.
Spangler, W. H., 240 North Meridian Street, Indianapolis, Ind.
Spitzglass, A. F. (Member), Republic Flow Meters Company, Chicago, Ill.
Spooner, E. K., Allis-Chalmers Manufacturing Company, Norwood, Ohio.
Stonestreet, N. V. (Member), Suburban Resettlement, Washington, D. C.
Strobel, H. C., Potomac Electric Power Company, Washington, D. C.
Sutherland, A. H., Public Utility Engineering and Service Corporation, Chicago, Ill.
Tarvin, E. B., Public Service Company of Oklahoma, Okmulgee, Okla.
Taussig, O. C., New York Power and Light Corporation, Schenectday, N. Y.
Taylor, H. C., Houston Lighting and Power Company, Houston, Texas.
Teague, T. S., General Electric Company, Schenectady, N. Y.
Teigen, T. N., Fairbanks, Morse and Company, Beloit, Wis.
Teller, W. A., American Telephone and Telegraph Company, New York, N. Y.
Templeton, L. O., Pacific Gas and Electric Company, San Jose, Calif.
Tholke, J. G., 480 Lexington Avenue, New York, N. Y.
Thomas, C. W. (Member), Public Service Company of Oklahoma, Bartlesville, Okla.
Thorpe, J., American Telephone and Telegraph Company, New York, N. Y.
Topf, S. B., Premier Electric Motor Company, New York, N. Y.
Tuepker, D. J., Public Service Company of Oklahoma, Tulsa, Okla.
Unholtz, K., 3536—8th Avenue, Los Angeles, Calif.
Upley, A. S., Chase-Shawmut Company, Newburyport, Mass.
Van Allen, W. G., 920 Livingston Avenue, New Brunswick, N. J.
Van Zeeland, F. J., Milwaukee School of Engineering, Milwaukee, Wis.
Vladikov, E., c/o Mr. Linero, 2115–8th Avenue, New York, N. Y.
Wagner, D. A., Cutler Hammer, Inc., Milwaukee, Wis.
Wald, G. E. (Member), Mortgage Commission Servicing Corporation, New York, N. Y.
Walsh, J. E., Bethlehem Steel Company, Sparrows Point, Md.
Ward, P. A., General Electric Company, Bloomfield, N. J.
Ward, T. V. (Member), Room 11, District Building, Washington, D. C.
Warner, D. F., General Electric Company, Schenectady, N. Y.
Wasilchuk, S., Western Electric Company, Kearny, N. J.
Watson, S. R., Jr., Carolina Power and Light Company, Marion, S. C.
Weaver, C. H., Westinghouse Electric & Manufacturing Company, East Pittsburgh, Pa.
Weber, J. A., New York, Power and Light Corporation, Albany, N. Y.
Wellons, R. S., Columbia University, New York, N. Y.
Welsch, G., Knapp Monarch Company, St. Louis, Mo.
Wentz, J. K., General Electric Company, Schenectady, N. Y.
Werner, H. F., Jr., Equitable Equipment Company, Inc., New Orleans, La.
Wetzel, J. J., Chrysler Corporation, Detroit, Mich.
Wheeler, W. M., General Electric Company, Pittsfield, Mass.
Whinery, W. D., Jr., General Electric Company, Pittsfield, Mass.
Whittenton, J. M., General Electric Company, Lynn, Mass.
Wiley, B. F., Phillips Petroleum Company, El Campo, Texas.
Wilsey, H. R., 48 Caroline Road, Upper Montclair, N. J.
Wilson, W. V., 480 Lexington Avenue, New York, N. Y.
Winslow, R. C., Automatic Diesel Electric Company, New York, N. Y.
Winterhalter, F. M., Allis-Chalmers Manufacturing Company, Norwood, Ohio.
Wood, J. N., Kansas State College, Manhattan, Kans.
Wrensch, B. E., 2945 North 4th Street, Milwaukee, Wis.
Wulfken, A. J., 1050—79th Street, Brooklyn, N. Y.
Wyman, J. H., Triad Manufacturing Company, Inc., Pawtucket, R. I.
Young, D. L., 1050 Mar Vista Avenue, Pasadena, Calif.
Zappo, N. W., The Teleregister Corporation, New York, N. Y.
Zindar, L. J., Cutler Hammer, Inc., Milwaukee, Wis.
Zinser, H. J., Heyer Products Company, Inc., Belleville, N. J.

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**Foreign**

Bonilla, R. B., 250 David Street, Manila, P. I.
Chang, P. F., Shanghai Power Company, Shanghai, China.
Dahlby, G. O. H., ASEA, Vasteras, Sweden.
de Velasco, J. F. (Member), Rio Grandense Light and Power Syndicate Ltd., Brazil, S. A.
Elliott, J. S. (Member), Hoover Electric Cleaner Company, Perivale, Greenford, Middlesex, England.
Mier, M. L., P. O. Box 471, San Juan, Puerto Rico.
Mohindra, S. L., North Western Railway, Scheranpur, India.
Nardi, M., Soc. Meridionale di Elettricitá, Naples, Italy.
Oliphant, W. D., British Electrical and Allied Industries Research Association, London, W. C. 2, England.

9 Foreign

## Addresses Wanted

A list of members whose mail has been returned by the postal authorities is given below, with the addresses as they now appear on the Institute record. Any member knowing of corrections to these addresses will kindly communicate them at once to the office of the secretary at 33 West 39th St., New York, N. Y.

Godoy, Ernesto R., Cia. Tel. y Tel. Mex., 16 de Septiembri No. 13, Mexico, D. F., Mex.
Hale, Edward E., Public Service Commission of New York, 80 Centre St., New York, N. Y.
Little, Leroy C., 3414—17th St., N., Cherrydale, Va.
Moore, Everett, 821 Sunset Blvd., Los Angeles, Calif.
Nash, G. H., 2-A Holland Road, London W.14, England.
Peach, Paul S., Upperville, Va.
Pollastro, John B., Helper, Utah.
Sawyer, Fred E., 811 E. Wisconsin Ave., Milwaukee, Wis.
Wickel, F. A., Pier 42, Dollar S. S. Lines, San Francisco, Calif.

9 Addresses Wanted

# Engineering Literature

## New Books in the Societies Library

Among the new books received at the Engineering Societies Library, New York, recently, are the following which have been selected because of their possible interest to the electrical engineer. Unless otherwise specified, books listed have been presented gratis by the publishers. The Institute assumes no responsibility for statements made in the following outlines, information for which is taken from the preface of the book in question.

ELECTRON TUBES in INDUSTRY. By K. Henney. 2nd edition. New York and London, McGraw-Hill Book Company, 1937. 538 pages, illustrated, 9x6 in., cloth, $5.00. Discusses the practical uses of thermionic and light-sensitive tubes outside the communication field.

ELEMENTS of ELECTRICITY. By W. Esty, R. A. Millikan, and W. L. McDougal. Chicago, American Technical Society, 1937. Illustrated, 9x6 in., cloth, $2.00. A textbook for beginners.

INTRODUCTORY STUDY of ELECTRICAL CHARACTERISTICS of POWER and TELEPHONE TRANSMISSION LINES. By F. W. Norris and L. A. Bingham. Scranton, Pa., International Textbook Company, 1936. 272 pages, illustrated, 9x5 in., leather, $2.50. Adaptable to an introductory course in the principles of electrical transmission. Aims to develop the student's ideas of the electric and magnetic fields and his ability to deal with circuits involving distributed constants.

JONES RADIO HANDBOOK. By F. C. Jones. 1937 edition. San Francisco, Pacific Radio Publishing Company, 1936. 456 pages, illustrated, 9x6 in., paper, $1.50. Presents the theory of radio communication and gives practical instruction upon the construction of transmitters and receivers, and radio-therapeutic apparatus; intended for the radio amateur.

(KEMPE'S) ENGINEER'S YEAR-BOOK of Formulae, Rules, Tables, Data, and Memoranda for 1937, 43rd Annual Issue, revised by L. St. L. Pendred. London, Morgan Brothers, 1937. 2,676 pages, illustrated, 7x5 in., leather, 31s. 6d. Deals with every phase of engineering and affords a survey of modern practice.

OUTLINE of the HISTORY of MATHEMATICS. By R. C. Archibald. 3rd edition. Oberlin, Ohio, Mathematical Association of America, Inc. 62 pages, 9x6 in., paper, $0.50. A sketch of the development of mathematics based upon 2 lectures delivered in 1931 at a summer school for engineering teachers organized by the Society for the Promotion of Engineering Education.

PROCEDURE HANDBOOK of ARC WELDING, DESIGN, and PRACTICE. 4th edition. Cleveland, Ohio, Lincoln Electric Company, 1936. 819 pages, illustrated, 9x6 in., leather, $1.50. Discusses in a practical manner the equipment and technique of arc welding, the design of arc-welded machinery and structures and the applications of arc welding in manufacturing, construction, and repairs.

The RENAISSANCE of PHYSICS. By K. K. Darrow. New York, Macmillan Company, 1936. 306 pages, illustrated, 9x6 in., cloth, $3.00. Intended primarily for the layman. Discusses the constitution of matter, transmutation, and other basic questions. Based upon a course of lectures at Lowell Institute.

STATISTICAL YEAR-BOOK of the WORLD POWER CONFERENCE. No. 1. 1933 and 1934. Edited, with an Introduction and Explanatory Text by F. Brown. London, World Power Conference, Central Office; American Committee, Interior Building, Washington, D. C., 1936. 111 pages, tables, 11x9 in., paper, $5.00. Contains statistics of the resources, stocks, imports, exports, and consumption of power and power sources during 1933 and 1934 for all countries for which it was possible to obtain information.

STEAM-ELECTRIC POWER STATIONS. By C. F. John. Scranton, Pa., International Textbook Company, 1936. Illustrated, 8x5 in., leather, $1.50. An elementary descriptive text on power-plant equipment and operation, designed for operating men.

STORM LOADING and STRENGTH of WOOD POLE LINES and a STUDY of WIND GUSTS. By R. H. Sherlock, M. B. Stout, W. G. Dow, J. S. Gault, and R. S. Swinton. University of Michigan, Ann Arbor; sponsored by Edison Electric Institute, New York, 1936. 183 pages, illustrated, 9x6 in., cloth, $2.00 to members; $5.00 to others. Contains information about the wind forces acting against the poles and conductors of a power line during storms, of determining the strength of wood poles under these conditions and of studying the structure of winds during storms.

Die TRANSFORMATOREN. (Die Wechselstromtechnik, edited by I. L. la Cour. Bd. 2.) By I. L. la Cour and K. Faye-Hansen. 3rd edition. Berlin, Julius Springer, 1936. 699 pages, illustrated, 9x6 in., cloth, 48 rm. Discusses the theory, construction, calculation, and operation of transformers.


**Engineering Societies Library**
29 West 39th Street, New York, N. Y.

MAINTAINED as a public reference library of engineering and the allied sciences, this library is a co-operative activity of the national societies of civil, electrical, mechanical, and mining engineers.

Resources of the library are available also to those unable to visit it in person. Lists of references, copies or translation of articles, and similar assistance may be obtained upon written application, subject only to charges sufficient to cover the cost of the work required.

A collection of modern technical books is available to any member residing in North America at a rental rate of five cents per day per volume, plus transportation charges.

Many other services are obtainable and an inquiry to the director of the library will bring information concerning them.

# Industrial Notes

**General Electric Sales Up.**—At the March meeting of the Board of Directors of the General Electric Co. President Gerard Swope announced that orders received for the first two months of 1937 amounted to $64,000,000, an increase of 79 per cent over the corresponding period of last year, and that sales billed in the first two months were $45,000,000, an increase of 39 per cent over the same period last year. Sales billed for 1936 amounted to $268,545,000, compared with $208,733,000 for 1935, an increase of 29 per cent.

**Construction Work Gains.**—According to F. W. Dodge Corp., the total construction work started in the first two months of 1937 in the 37 eastern states amounted to $431,434,800, a gain of 22 per cent over the corresponding two-months total of $355,211,900 for 1936. Residential building amounted to $141,435,400 or a gain of more than 100 per cent over the total of $68,615,000 for the first two months of 1936. Public works and utilities started during the first two months of 1937 totaled $128,079,200 as against $133,506,200 for the same two months of last year. The decline from last year in this division of the construction industry is entirely due to the slowing-up of the PWA program.

**Aerovox Condensers Now Made in Canada.**—The control of the former Polymet Delta Co. of Hamilton, Ont., has been taken over by Aerovox Corporation. Henceforth the Canadian plant will operate as Aerovox Canada Limited, producing a line of Aerovox dry and wet electrolytic condensers, also mica and paper condensers, for the Canadian trade. The output will conform with the engineering and production standards of the Brooklyn plant according to S. I. Cole, president of the parent company.

**Westinghouse Reports Increased Business.**—The annual report for 1936 of the Westinghouse Electric & Mfg. Co. shows orders received amounting to $182,521,304, an increase of 48 per cent over the previous year. Sales billed totaled $154,469,031, an increase of 26 per cent over 1935. Unfilled orders at the end of the year amounted to $48,490,919 compared with $27,137,075 at the end of the previous year.

**New Battery Tester.**—An instrument for quickly checking the working condition of glass jar type cells used in railway signal service has been developed by the Electric Storage Battery Co., Philadelphia, Pa., termed the Exide "Minute Man." The test is made by discharging the cell at approximately its one minute rated capacity. In this manner the same practical results are obtained as from a 1- or 8-hour-rate discharge test.

**New Molding Materials.**—Many molded plastic parts, due to the conditions under which they are used, require better resistance to shock or impact than is afforded by general purpose molding materials. In order to meet the varied requirements for impact strength, Bakelite Corp., New York, has developed a new line of Bakelite molding materials which range in impact strength on an A.S.T.M. standard test specimen from 0.22 to 2.0 ft. lbs. energy to break (2.75 to 25 ft. lbs. per inch square). These new molding materials are particularly suitable for handset telephones, instrument cases, junction boxes, and other parts requiring relatively high impact or shock resistance.

# Trade Literature

**Relays.**—Bulletin GEA-2524, 8 pp. Describes undervoltage and phase-rotation relays, type ICR, instantaneous-time delay, for the protection of motors and synchronous converters. General Electric Co., Schenectady, N. Y.

**Service Equipment.**—Catalog, 96 pp. Describes a wide range of general purpose and safety switches, panels and cabinets, switch-centers, breakers, industrial cable ducts and fittings, etc. Bull Dog Electric Products Co., Detroit, Mich.

**Voltage Regulators.**—Bulletin 1170B, 36 pp. Describes type AFR automatic feeder voltage regulators. The purpose, construction, and advantages of such equipment, illustrated throughout, are treated at length. Allis-Chalmers Mfg. Co., Milwaukee, Wis.

**Watthour Meters.**—Cat. Sec. 42-215, 16 pp. Describes polyphase watthour meters for house service. Application, construction, performance characteristics, wiring diagrams and ratings for the various available types are included. Westinghouse Electric & Mfg. Co., E. Pittsburgh, Pa.

**Motor Generator Sets.**—Bulletin 501, 4 pp. Describes and illustrates various types of motor generator sets, built in sizes up to 500 kw and supplied in a variety of combinations. Reliance Electric & Engg. Co., 1086 Ivanhoe Road, Cleveland, O.

**Distribution Capacitors.**—Bulletin GEA-2494, 20 pp. Describes Pyranol-filled, pole-type distribution capacitors. According to the bulletin, 99.82 per cent of the Pyranol capacitors manufactured in the last 6 years have a perfect operating record. General Electric Co., Schenectady, N. Y.

**Building Wires and Cables.**—Bulletin BW3, 48 pp. Describes electrical conductors for industrial power and lighting circuits for building of all types; includes tables on wire gauges, formulae for calculating electrical properties of circuits, conversion tables, electrical symbols for architectural plans, etc. General Cable Corp., 420 Lexington Ave., New York.

**Noise Meter.**—Bulletin, 4 pp. Describes the new type 759-A sound-level meter for measuring noise. Features of the new meter include standardized readings, unusual sensitivity, non-directional pick-up, self-contained and portable, weighing only 23½ lbs. The new device is very easy to operate and is comparatively low priced. Bulletin 20, a comprehensive manual on noise measurements, is also available. General Radio Co., Cambridge, Mass.

**Wiring Survey.**—32 pp., "Industrial Guide for Selection of Wire & Cable." A comprehensive, practical treatise on electrical conductors used for industrial purposes and methods of modernizing circuits. Chapters included cover the factors affecting the selection of wire and cables; guide to determining types of insulation; how to use charts; power circuits; standard building wire and cable; flexible cords and cables; control circuits. Anaconda Wire & Cable Co., 25 Broadway, New York City.

**Circuit Breakers.**—Cat. 6-Sec. 9, 2 pp. Describes a new class TCR-1 indoor, oil-tight circuit breaker with a rating of 75,000 kva interrupting capacity, available in ratings up to 2,000 amperes, 5,000 volts, and for both automatic and non-automatic operation and in both two pole and three pole types. According to the manufacturer there has been no NEMA standard breaker between 50,000 and 100,000 kva interrupting capacity. Roller-Smith Co., 12 Park Pl., New York City.

**Wires and Cables.**—Bulletin, 4 pp. Describes various types of insulation and coverings; rubber jacketed, lead sheathed and varnished cambric cords and cables, together with weather-proof wire and cable, armored bushed cable, Cresflex, a non-metallic sheathed cable, parkway cables and special cables. Data on building wire and cable and conduit sizes for rubber-covered building wire are set up in convenient table form for ready reference. Crescent Insulated Wire & Cable Co., Trenton, N. J.

**Lubrication Studies.**—A series of effectively illustrated, large page booklets entitled "Panorama of Lubrication," described as "an educational series, dedicated to executives, engineers, salesmen and students whose interest in the subject of lubrication demands simplicity." The first three issues of the series, each 24 pages, are now available: 1—The Fundamentals of Lubrication; 2—Lubricating Friction Type Bearings; 3—The Modern Motor Oil. The latter details refining processes and the sources and nature of crude oils. Shell Petroleum Corp., Shell Bldg., St. Louis, Mo.

**New Circuit Breaker Feature.**—Bulletin 237, 6 pp. Describes the new thermo-magnetic overload feature, applicable to all a-c types of I-T-E motor-protecting circuit breakers and available for all types of a-c motors up to 1,000 hp., 550 volts. The new feature discriminates with unfailing accuracy between normal and unsafe overloads. It permits full-voltage starting even when the accelerating period is unusually long and the inertia load exceptionally heavy. The breaker is tripped before dangerous temperatures are reached in a motor or in the device itself. With overcurrents of short-circuit intensity, tripping is instantaneous. I-T-E Circuit Breaker Co., 19th and Hamilton Sts., Philadelphia, Pa.

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Registered U. S. Patent Office

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### The Cover

Mighty Niagara, a point of interest for those attending the Institute's North Eastern District meeting in Buffalo, N. Y., May 4–6



# High Lights

**Summer Convention.** Milwaukee and vicinity and the State of Wisconsin offer unusual opportunities to those wishing to combine attendance at the Institute's 1937 summer convention with their vacations. The program includes 10 technical sessions and one special "general" session. The usual sports competitions and a splendid array of interesting inspection trips and entertainment features provide a well-rounded program (*pages 635–9*).

**Employment of Engineers.** During the 5-year period from 1929 to 1934, the number of persons in the engineering profession increased by 25 per cent, which was much in excess of available engineering employment opportunities. This is one conclusion reached by the United States Bureau of Labor Statistics in analyzing the employment data obtained in its 1935 survey of the engineering profession (*pages 524–31*).

**Some Engineering Contributions.** In 1920, 41 million tons of coal was required to produce 27 billion kilowatt-hours of electric energy in power stations in the United States; in 1934 the same amount of fuel produced 57 billion kilowatt-hours. This is but one of the many engineering contributions to society which have resulted in providing the public with a dependable supply of electric power at low rates (*pages 518–23*).

**Student Activities.** Representative of activity of Student Branches throughout the Institute's various Districts, were the annual Student Branch conference of the Southern District (*pages 641–2*) and the annual convention of Student Branches in the eastern portion of the Middle Eastern District (*pages 640–1*), both of which were held recently.

**Cable Saturants.** Physical and electrical properties of several saturants for paper-insulated cables have been investigated in a series of tests, and correlations made with the viscosity index and chemical composition of the oils and resins. Gaseous ionization in insulation voids was found to exert pressure and accelerate oxidation (*pages 566–76*).

**Lightning-Arrester Performance.** From manufacturers' data pertaining to breakdown characteristics of lightning arresters under standard rates of voltage rise, and $IR$ drops for crest values of current of 1,500, 3,000, and 5,000 amperes, the protective characteristics of 3- to 15-kv line-type arresters have been determined (*pages 576–77*).

**Magnetic Contactors.** Because of some fundamental limitations, the use of magnetic contactors as commutating devices for the application of power during brief periods has not been entirely satisfactory. A method of avoiding these limitations, and at the same time providing great accuracy of timing the periods of power application, has been evolved (*pages 583–8*).

**Sphere-Gap Calibration.** Much progress has been made in extending and revising the calibrations of the grounded sphere gap for both 60-cycle and impulse voltages. A paper in this issue presents some of these revisions, and, in addition, describes the effect of ultraviolet irradiation of the sphere gap (*pages 594–6*).

**Expulsion Gaps.** Guarding overhead power lines against damage from lightning by the use of expulsion protective gaps which conduct the lightning current to ground and break the power current that follows has been practiced for several years. Information obtained from field experience and tests is now available (*pages 551–7*).

**Coincidental Electric Drives.** Individual motors are used in some industrial applications to drive units of a machine that may require either a constant or a varying speed relation among the motors. Principles of operation are given in a general description of this type of drive (*pages 578–82*).

**Economic and Engineering Progress.** The development of the modern economic system has closely paralleled the growth of scientific knowledge, says a well-known authority in discussing progress in the interdependent fields of engineering and economics (*pages 510–17*).

**Motor Protection.** Thermal overload devices such as solder-film or bimetallic-strip relays commonly are used for the protection of a-c motors. Comparison of the proper motor and relay data provides a basis for the determination of adequate overload protection (*pages 589–93*).

**Corona Loss.** Most mathematical formulas for computing corona loss on transmission lines do not agree entirely with observed data for all conditions; therefore, a purely empirical method of computing corona loss has been derived from co-ordination of experimental observations (*pages 558–65*).

**Outages on Shielded Lines.** From the observation that flashover of transmission-line towers with 2 overhead ground wires occurs only when the product of tower-footing resistance and tower surge current exceeds the insulation strength, the probable outages may be determined (*pages 597–600*).

**Police Radio.** Law-enforcement agencies always are concerned with improving their methods of transmitting intelligence. In the last few years municipal and state police departments have turned to radio as the most rapid and effective means of dispatching patrol cars (*pages 532–44*).

**Industrial Lighting.** A broadening of the scientific knowledge of the relations of light to the process of seeing has suggested a new approach to the specification of lighting for industrial processes (*pages 545–50*).

**Year Book.** The Institute's 1937 Year Book is now available to members having use for it (*page 641*).

# DISCUSSIONS

Appearing in this issue are discussions of the following papers:

## Electrical Machinery


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Arc Characteristics Applying to Flashing on Commutators—Hellmund . . . . . 603
Contact Drop and Wear of Sliding Contacts—Baker & Hewitt . . . . . 605
Self-Regulated Compounded Rectifiers—Goodhue & Power . . . . . 606
An Analysis of the Shaded-Pole Motor—Trickey 612
Induction Motors on Unbalanced Voltages—Reed & Koopman . . . . . 621
Capacitor Motors With Windings Not in Quadrature—Puchstein & Lloyd . . . . . 634


## Electrophysics


Expansion Theorems for Ladder Networks—Malti 601


## Power Transmission


Lightning Investigation on a 220-Kv System—II—Bell . . . . . 622
Lightning Investigation on Transmission Lines—VI—Lewis & Foust . . . . . 624
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## Tensor Analysis


Dyadic Algebra Applied to 3-Phase Circuits—Sah 610
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# Electrical Engineering

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# The President Meets the Sections

"ON what subject would you like a message from the president?" I asked 2 young engineers who have recently joined the AIEE. Their answer was, "Tell us about the work of the other Sections." So I was led to review my pleasant travels of the last 9 months, and the many Sections I have been privileged to visit.

Why does the president visit the Sections? Primarily because they invite him to do so; and it is his pleasure and duty, as far as possible, to accept these invitations from those who have elected him. It is certain that these visits inspire him and acquaint him with the activities and needs of the organization. It is hoped that from him each Section visited learns of national affairs, of the work of the other Sections, of projected policies, and from him receives some degree of inspiration, leading to greater Section activity.

The courtesy, hospitality, and interest shown by every Section visited, have made this phase of my Institute activity one which I long shall remember. In the last 9 months, I have visited 33 Sections and 18 Branches, and attended 2 conventions and a District meeting. In the next 4 months, I shall visit 11 Sections and 4 Branches, and attend a District meeting, a District student convention, and a national convention. While visits to Sections are desirable, inspiring to the President and, I hope, to the Sections, visits to Branches I consider even more desirable, for within the Branches are found the engineering leaders of the future.

Last November I told you something of my early trips and my pleasure in attending the twin meetings at Knoxville and Chattanooga, which initiated the active participation of the East Tennessee Section in Institute affairs. October and November were marked by a Western trip, with meetings at St. Louis and Kansas City, Mo., on the way to the South West District meeting at Dallas, Texas. The automobile drive from Kansas City to Dallas, with E. T. Mahood, past chairman of the Kansas City Section, and Mrs. Mahood, familiarized me with the great Southwest, and permitted a preliminary social visit with the officials of the Oklahoma City Section. Reviewing the 3-day Dallas meeting, I was indeed surprised that 6 of the 9 meals were in the company of Vice-President L. T. Blaisdell. This same vice-president accompanied me to the Houston Section meeting and, returning with me to Dallas, drove me to the Oklahoma Section meeting approximately 350 miles away. The following morning I inspected the Oklahoma oil field and saw a 110-horsepower motor, 10 inches in diameter and 20 feet long. Guided by the proverb "all work and no play," the afternoon was devoted to golf.

In quick succession followed enthusiastic Section meetings at Salt Lake City and Denver, with Branch meetings at the Universities of Colorado and Utah.

Stealing a Sunday en route from Denver to Los Angeles, I realized a 40-year-old ambition: a trip to the bottom of the Grand Canyon on mule back. It is highly recommended. In Los Angeles a noonday meeting with the Section executive committee preceded a joint meeting with the technical societies of Los Angeles, addressed by Dr. Von Kleinschmid, president of the University of Southern California, and myself. I strongly favor these joint meetings with other engineering societies.

A plane trip to San Francisco made possible a Branch meeting at the University of California, with a Section meeting the following evening. Then came Portland, Seattle, Vancouver, Spokane, with Branch meetings at Washington State College and the University of Idaho. At Bozeman, there was a meeting of the Montana State College Branch at 11:00 a.m., luncheon with the faculty, and a Montana Section meeting in the evening. The following day another lifetime ambition was realized. Professor J. A. Thaler and his delightful wife drove me to Yellowstone Park. Over a railroad electrically operated through its mountain divisions, I reached Milwaukee, Wis., and was entertained at lunch by the entire 1937 summer convention committee. In the evening was the joint Milwaukee-Madison Section meeting at the Allis-Chalmers Club. (Do not miss the Milwaukee convention this June.)

The trip back to Cleveland was enlivened by a luncheon with the Chicago Section executive committee, and attendance at the regular Chicago Section dinner meeting where, fortunately, I had the opportunity of hearing another speaker.

Participation in Section meetings at the neighboring cities of Pittsburgh and Erie, Pa., was easily accomplished.

Going to the New York winter convention by the way of a Toronto Section dinner meeting was a most pleasant experience, and approaching Miami, Fla., by the way of a Caribbean cruise was equally delightful. (See message in March issue.)

Such an extensive Section as Florida required 2 meetings, at Miami and Jacksonville, one of which unfortunately was missed because weather conditions prevented the scheduled sailing of a plane.

The best method of transportation through Florida was found to be by the use of a Ford car rented in Miami and delivered at Jacksonville; a stop was made at Gainesville for a meeting of the University of Florida Branch and a radiobroadcast.

By a zigzag route and close co-operation from Institute members, we attended an all-afternoon Section meeting at Raleigh, N. C., a pre-organization meeting at Columbia, S. C., visited the Broad River power development, met with the Branches at Clemson College, Georgia School of Technology, Alabama Polytechnic Institute, and the University of Alabama, and addressed the Atlanta and Alabama Sections at enthusiastic dinner meetings. National Secretary Henline joined me at Raleigh, and ably participated in all the meetings that followed.

The March trip through New England was distinctive. It was completely arranged by Vice-President A. C. Stevens and District Secretary R. G. Lorraine. They, with Mr. Henline and myself, made up an official visiting delegation. Through their efficient organizing, we were able to attend 6 Section meetings in 5 days: Connecticut, Lynn, Boston, Providence, Worcester, and Springfield. Three of these were joint Branch-Section meetings. This was one of the most inspiring trips of the year.

Ahead of me is the privilege of attending the meeting of the North Eastern District at Buffalo, N. Y., the Student Branch convention of the North Central District at Brookings, S. D., the Milwaukee national convention, as well as visiting the following Sections: Chicago, Philadelphia, Sharon, Baltimore, Minneapolis, Cincinnati, Rochester, Ithaca, and Lehigh Valley. Last, but not least, is the annual meeting of my own Section, to be held in Cleveland on May 20.

This is the story of my travels, and the roster of the Sections and Branches with which I have been fortunate to become acquainted. Next month I shall take the opportunity of telling you what I learned of these Sections and Branches, their activities, and their plans for the future. I hope that each Section and Branch may receive help and inspiration from the record of what the other Sections and Branches are doing.



# Engineering Progress and Economic Progress

By HAROLD G. MOULTON
President, The Brookings Institution

**The advance of engineering has a vital bearing upon economic progress; in turn, though perhaps less obviously, the operation of the economic system largely determines the rate at which new engineering discoveries may be applied in the actual production of wealth. From this point of view Doctor Moulton discussed progress in the interdependent fields of engineering and economics in the Eleventh Steinmetz Memorial Lecture,* full text of which is presented here.**



ENGINEERING is concerned with the application of scientific knowledge to the processes of wealth production. Economics is concerned with the basic resources and factors upon which wealth production depends and with the forces and institutions that influence or control the operation of what we call the economic system. It is readily apparent, therefore, that the advance of engineering has a vital bearing upon economic progress. In turn, though perhaps less obviously, the operation of the economic system largely determines the rate at which new engineering discoveries may be applied in the actual production of wealth. This truth is brought sharply to our attention in periods of acute business depression, when the introduction of improvements of demonstrated value is indefinitely deferred, and the process of discovery and invention itself is slowed down; but even in times of prosperity the installation of new methods and devices is not infrequently retarded because of general economic considerations.

In view of this intimate relationship between engineering and economics, it affords me especial pleasure to join with you in considering problems of mutual interest on a forum dedicated to the memory of a great scientist and engineer, who was at the same time deeply concerned with the relationship of his profession to the development of civilization.

## Science and Economic Development

The development of the modern economic system has in fact closely paralleled the growth of scientific knowledge. By way of introduction, let me briefly recapitulate the history of the last 3 centuries in terms of engineering and economics. Though not commonly realized, developments in the field of the so-called natural sciences paved the way for the modern political and economic system.

It was in the sixteenth and seventeenth centuries that such men as Galileo, Kepler, and Newton discovered and formulated the basic laws that operate in the physical world. In due course these scientific discoveries came to exert a profound influence upon men's ideas in other realms of thought. Was not man, the creation of God, as much a part of and subject to an ordered universe as the physical earth on which he had his setting?

The view arose that there existed a system of *natural law* which, if it were not interferred with by governments or other human institutions, would always lead to progress. Blackstone, the great English jurist, for example, contended that there had been established by the Creator a simple system of natural law or ethics, and that the constitution and frame of humanity had been so contrived that if we but pursued our own "true and substantial happiness" we could not fail to be in tune with the universe of nature. Moreover, according to Adam Smith, the great Scottish philosopher who founded a system of thought known as political economy, each of us in pursuing his own welfare and happiness is led as by the Divine Hand to promote the welfare of his fellowmen.

This new philosophy of *natural law* led in due course to practical results of great significance. First, innumerable laws restricting the freedom and the initiative of the individual were repealed. Second, industry and trade were relieved from a multitude of hampering regulations. Third, national boundaries came largely to be ignored through the removal of barriers and restrictions against the free international movement of trade and currency, and against the migration of people from country to country. The conception of a world society was born, in which men should be free not only to develop their individual capacities to the utmost, but also to live in whatever spot on the globe they desired and to conduct their business operations without reference to any national boundaries.

All this, it may be seen, constituted a *theory* of economic and social evolution or a *science of society*. New conceptions resulting from discoveries in the field of natural science came in time to be the foundations of social science. Moreover, the practical application of scientific discoveries

* Eleventh Steinmetz Memorial Lecture delivered by Doctor Moulton under auspices of the Steinmetz Memorial Foundation at a meeting of the AIEE Schenectady, N. Y., Section on April 6, 1937.

HAROLD G. MOULTON received the degree of doctor of philosophy from the University of Chicago in 1914, and was a member of the faculty until 1922. At that time he resigned the post of professor of political economy to become director of the Institute of Economics, Washington, D. C. The institute was amalgamated with the Institute for Government Research and the Robert Brookings Graduate School of Economics and Government in 1927, and Doctor Moulton was appointed president of the newly formed Brookings Institution. He is the author of many books on economic and allied subjects.

to the processes of production gave to the business organizer an ever expanding scope for his enterprise. One need cite only the influence of steam, electric, and gasoline power on transportation development to indicate the significance of science in broadening the area over which business enterprise can successfully operate.

## Rising Standards of Living

In the short interval of time since the founding of the American Republic, man's power over nature has been increased vastly more than in all preceding history. If we were to let the span of human history be represented on the face of a clock, the period elapsing up to the last 2 centuries would be roughly the equivalent of the time from noon to 10 minutes before 12 midnight. The last 10 minutes would represent the period during which science, engineering, and the system of free business enterprise have been dominant. Economic progress during these last 10 minutes has greatly exceeded that of the preceding 710 minutes. The standards of living of the masses today, notwithstanding an extraordinary increase in population, are higher than those of the classes of former times.

Statistical measurements as to the rate of economic progress are available only for comparatively recent years. But in the era of expansion from 1900 to 1929 production per capita in the United States increased by about 38 per cent; and there was a 13-per cent shortening of the hours of labor. In manufacturing industry the increase in efficiency was, of course, much greater. In the 7-year period from 1922 to 1929 efficiency in manufacturing increased by 25 per cent.

## Retardation of Economic Growth

Despite the remarkable developments that have occurred under the capitalistic system, no one who thoughtfully surveys the economic history of recent times can well be complacent. Not only do we have periodic depressions which destroy accumulated wealth and income; but even at best the performance of the economic system leaves something to be desired. It would seem, when one stops to think carefully about it, that the rate of economic progress ought to be a constantly accelerating one—since each new generation starts with larger margins above the requirements for subsistence and builds upon greater accumulations of scientific knowledge and experience. Certain observed tendencies, however, are disquieting. Apart from the long periods of business depression and stagnation, one notes that the older and more mature a nation becomes the less rapid seems to be the rate of economic progress. In any event, the question sharply presents itself: Do conditions develop in the operation of the economic system which seriously retard further applications of engineering knowledge, and hence further progress?

It has been with a view to throwing light upon this basic question that the Brookings Institution in recent years has carried through a series of investigations under the broad general title of the distribution of income in relation to economic progress. Some of the results of these studies are here brought to your attention by means of a series of charts.

Before presenting these charts let me briefly recapitulate some of the conclusions reached.

1. It was found that there is a substantial margin of unused productive capacity, even in periods of prosperity. In the boom period, 1925-29, the economic system as a whole was not producing at more than 80 per cent of capacity; we did produce about 81 billion dollars worth of goods and services in 1929, but we might have produced about 96 billions.

2. The failure to use all of our productive capacity could not be attributed to an existing excess of production as compared with human needs. Production in the United States in 1929 amounted to only about $660 per person—about $2,600 per family. It would have required a vast increase in output to provide reasonably satisfactory standards of living for the American people.

3. The failure to produce more was attributable to an inability to find markets adequate to absorb full productive capacity.

4. The lack of adequate markets reflected inadequate purchasing power on the part of the masses of the people having large unfulfilled desires.

5. The inability of the masses to buy larger quantities was a result of the discrepancy between their money incomes and the prices at which goods were offered in the markets.

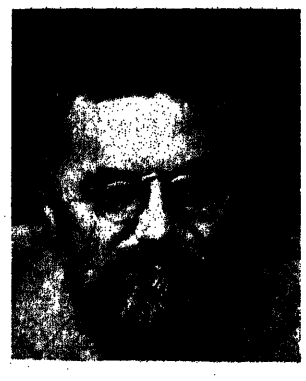
This last point will be developed at some length in the course of the discussion, but first let us have a brief look at the charts that bear upon the conclusions just stated (figures 1 to 9, inclusive).

## Effects of the World Depression

Figures 1 to 5 relate chiefly to the predepression situation and are concerned solely with the United States

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THE Steinmetz Memorial Lectures were established in 1925 by the Schenectady Section of the AIEE, as a means of recalling periodically to the members of the Section and the general public the personality and achievements of Charles Proteus Steinmetz. The interest aroused by these lectures has been such that his friends and admirers have raised an endowment fund to place the memorial on a permanent basis, independent of the future success of the Schenectady



Section of the AIEE. This fund will insure that the memory of Doctor Steinmetz will be recalled frequently in a way most appropriate to commemorate a man who combined a lovable personality and a broad human interest with the highest grade of scientific attainment. Previous lectures have been delivered by M. I. Pupin, E. J. Berg, R. A. Millikan, Max Mason, D. S. Kimball, W. E. Wickenden, K. T. Compton, C. E. K. Mees, R. E. Doherty, and Gerard Swope.

The next series of charts (figures 6 to 8) is focussed directly on the effects of the depression upon economic progress both in the United States and the world at large.

All the diagrams thus far mentioned fail to portray fully the effects of the depression because the factor of general growth is not included. With the population of the United States in 1936 about 5 per cent greater than in 1929—indeed with the population of working age about 9 per cent greater—we should expect a proportionally larger output than in 1929. In fact, had it not been for the depression we might have expected the supply of capital and the efficiency of production to continue at something like its usual rate of increase, with a corresponding expansion in per capita output. The next chart (figure 9) indicates in a rough way the effects of the depression by comparing actual production since 1929 with the amount of production that we would have had if predepression trends had been continued.

Figure 9 shows that in 1936 the average production (including agricultural and mineral as well as manufacturing) should have been about 20 per cent higher than in 1929; in fact, it was less than 90 per cent of the 1929 level. In other words, the output was not quite $^3/_4$ as great as it would have been had there been no interruption to progress.

The results of this curtailment of production are of course clearly revealed in the statistics of national income.

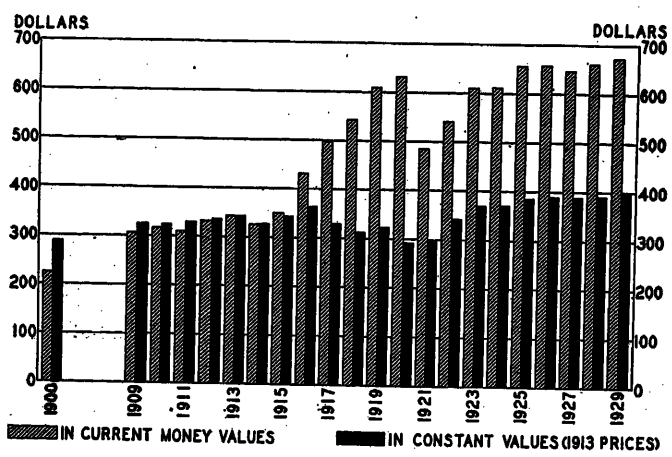



**Fig. 1. Per-capita income from current production**

This diagram reveals the growth of national income over the 30-year period of expansion from 1900 to 1929. As already stated, the increase amounted to about 38 per cent per capita, while at the same time there was a 13-per cent reduction in working hours. The cross-hatched bars indicate the amount of income as measured in actual dollars. The dark ones indicate the amount when adjustment is made for the fluctuations in commodity prices. It is of course the latter that represent the real growth in income

Had there been no depression and had the prewar trend of production continued, the total national income in 1936 would have been more than 97 billion dollars (as measured by 1929 prices). The actual income in 1936, including that received by individuals engaged in work relief, was only about 70 billions (again as measured by 1929 prices).

## Engineering and Economic Fundamentals

In the light of these graphic illustrations of economic retardation, we may now return to the discussion of engineering progress and economic progress. We shall center our attention not so much upon the phenomenon of the depression itself as upon the longer-run persistent factors or tendencies that affect the rate of progress.

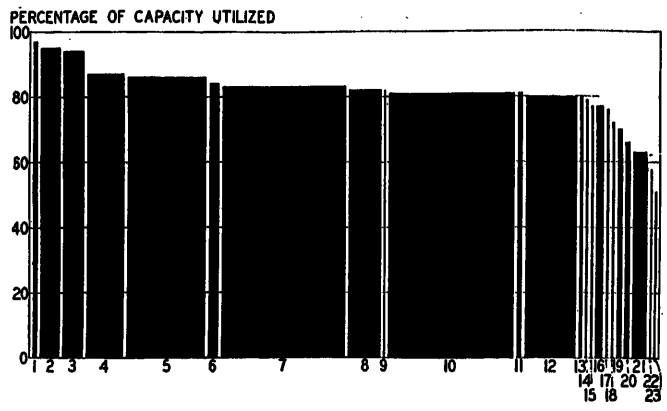



**Fig. 2. Utilization of mineral capacity**

This diagram indicates the percentage of capacity that was actually utilized in the various divisions of the mineral industries in 1929. Each bar represents a particular division of the industry, the width indicating roughly its relative importance. The highest degree of utilization is found in electrolytic copper refineries and the lowest in black powder mills. It may be observed that in the main the utilization was in the neighborhood of 80 per cent. The large area labeled 5 is petroleum refineries; 7 is bituminous coal mines; 10, crude oil; and 12, anthracite collieries

The engineering attitude always has been direct and fundamentally simple. Moreover, its validity is not open to challenge. It is based upon the elementary assumption that the function of engineering is to apply the new knowledge that is continuously accumulating to the improvement of productive instruments and processes, with a view to increasing the efficiency of mankind in adapting natural resources to the satisfaction of human wants. Increasing efficiency simply means producing more with the same effort—in consequence of which standards of living will be raised.

If it be agreed that the engineering conception of progress is indubitably true, then it must follow that the test of an economic system is to be gauged by its efficiency in promoting the engineering ideal. The system of private business enterprise, as it has often been expounded by both professional economists and business leaders, does in fact embody this engineering conception of progress. The nature of the problem is complicated, however, by the fact that under the capitalistic system production is financially organized and controlled.

Business managers use money in the hiring of labor and

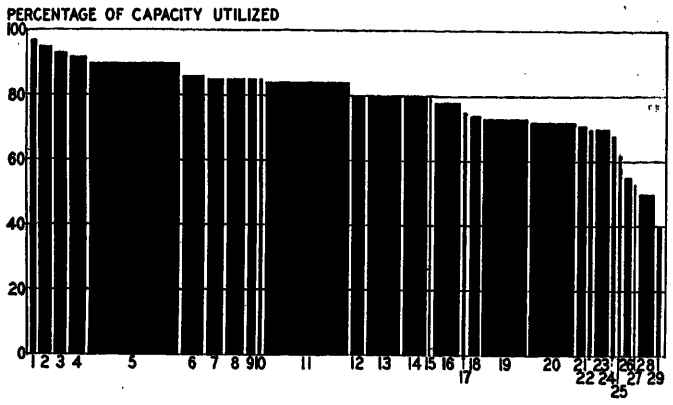



**Fig. 3. Utilization of manufacturing capacity**

This shows the degree to which manufacturing capacity was utilized on the average in the 5-year period from 1925 to 1929. A somewhat wider range is indicated here, but again the general average is not far from 80 per cent. The highest degree of utilization is in full-fashioned hosiery establishments, and the lowest in locomotive plants. The large area, 5, is printing and publishing; 11 is automobiles; 13, cotton manufactures; 14, boots and shoes; 16, men's clothing; 19, rolled-steel products; and 20, lumber

in the purchase of materials and supplies, and they sell their products for money. The aggregate amount of money received from sales of course must exceed the aggregate disbursements if profits are to be realized. Thus, business has its setting in a structure of monetary costs, prices, and profits; and the economic requirements for progress must accordingly be analyzed in these terms. The incentives and mechanisms by which the competitive system has been supposed to insure rapid economic progress and higher standards of living may be summarized briefly as follows:

1. It is contended that each business manager naturally stands to gain by increasing efficiency and thereby reducing costs. He may accomplish this by the construction of a larger and more efficient plant, by the installation of better equipment, by the introduction of superior internal management, by improved methods of marketing, by integrating various stages in the productive process, or by a combination of various methods.

2. Having reduced costs of production he is in a position to increase his profits in one or another of 2 ways: He may continue to sell at the same price as before, enjoying the advantage of a wider margin between cost and selling price, or he may expand the volume of his business by means of price concessions. It was reasoned that since the increase in efficiency which is responsible for the reduction in costs commonly involved an expansion of productive capacity, and since the maximum economies can be obtained when operating at full capacity, the greatest profits will result if sales are expanded by means of a reduction of prices. In short, increased efficiency makes possible lower prices, while the profit incentive was held to insure an actual reduction of prices.

3. The process naturally involves the continuous elimination of obsolescent or otherwise inefficient high-cost establishments. The industrially fit, as gauged by ability to sell at a minimum price, alone survive; moreover, the efficient of today promptly become the inefficient of tomorrow. A particular business man, firm, or corporation may indeed survive over a long period of years, but only if the production methods employed keep always abreast of changing times. It may be seen that with the system thus operating, standards of living would steadily rise. The progressive reduction of prices as efficiency increases would, of course, constantly increase the purchasing power of the masses—giving them an increasing volume of goods for the same money.

It should be carefully noted that this theory of progress implies that the reduction in money costs must result

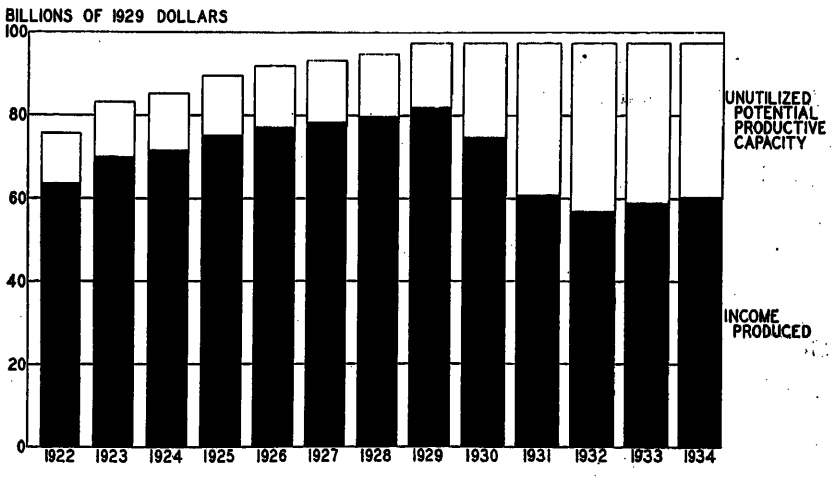



**Fig. 4. Productive capacity and actual production**

Here is a rough picture of the economic loss to the nation over a period of years resulting from our failure to make full use of our productive capacity. The black portions of the bars show the actual income produced in the years 1922 to 1934, inclusive. The upper areas indicate the additional amounts that might have been produced had our resources been fully utilized. For lack of adequate data as to the growth of productive capacity after 1929, the height of the bars has not been extended above the 1929 level. Since in the absence of depression productive capacity would have continued to expand, the diagram materially understates the true situation. A later diagram (figure 9) serves to reveal the indirect losses resulting from the depression

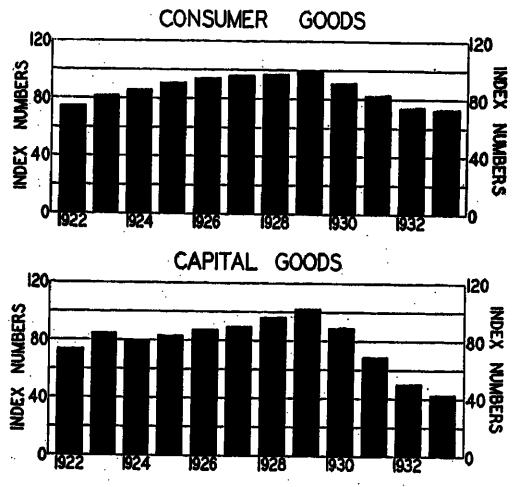



**Fig. 5. Fluctuations in production of consumer and capital goods**

The most striking result of a depression is the extraordinary decline in the rate of construction of new plant and equipment. That is to say, the application of scientific and engineering knowledge to the further expansion of productive capital is seriously impeded. This diagram shows that the amount of new capital construction at the depth of the depression in 1933 was only 40 per cent of that in 1929, being confined almost entirely to replacement as distinguished from new capital construction. Even after 3 years of recovery the rate of capital construction is still far below predepression levels

from increased efficiency rather than from a mere reduction in money wage rates. A reduction in wage rates may indeed lower money costs and prices; but since it neither increases efficiency nor the purchasing power of the masses there is no resulting economic advancement.

In order to reveal more distinctly what is involved in raising living standards in a *pecuniary* society, I would lay down 2 principles as follows:

1. *The process of raising the standard of living of wage earners necessarily involves increasing the spread between wage rates and prices.* That is, a wage earner can increase the volume of his purchases from year to year only if wage rates are increased relative to the prices of the commodities he buys. If he gets more dollars and prices remain unchanged, his purchasing power is expanded; if he gets the same number of dollars and prices decline, his purchasing power is expanded. It cannot be expanded, however, unless the spread between wages and prices is increased.

2. *An increasing spread between wage rates and prices depends fundamentally upon increasing the efficiency of production.* While minor and temporary increases in wages sometimes may be achieved by trenching upon profits, a progressive increase in the wage-to-price ratio depends directly upon the acceleration of technical advancement, improved management, increased labor efficiency, etc. Any practices or policies that tend to work in this direction are economically sound; any that work in the opposite direction are economically unsound.

We may now leave for a moment the discussion of principles and requirements and turn again to the factual record. The great increase in living standards over the past 200 years to which reference has been made has been brought about by increasing efficiency and an increasing spread between wage rates and prices. The statistics of wages and prices indicate that at certain periods increased purchasing power has resulted mainly from wage increases and at other periods mainly from price reductions. Sometimes also improvements in living standards have come about simply by the process of a more rapid rise in wages than in prices.

The trend of wholesale prices in relation to weekly wages over the period from 1800 to 1930 is shown by the next chart (figure 10). It may be observed that wholesale prices show several high peaks occurring in war periods, with fluctuating but generally downward trends in between. Money wages, however, show a persistent upward trend over the period as a whole. In consequence, the general trend of real wages is sharply upward.

For recent years data with respect to wages and prices are more detailed and precise. The next chart (figure 11) shows hourly earnings in manufacturing industries and both wholesale and retail prices of finished manufacturing products for the 15-year period 1932 to 1936.

It may be observed that during the prosperity period of the twenties wholesale prices showed a slight irregular decline, while retail prices remained practically stationery. Hourly earnings increased sharply in 1923 but very moderately thereafter. Real wages, however, did not increase as fast as productive efficiency.

During the course of the depression hourly earnings fell somewhat less rapidly than either wholesale or retail prices. Since the beginning of the recovery period hourly earnings have risen much more than either wholesale or retail prices. In fact, hourly earnings at the end of 1936 were actually above the 1929 level, whereas prices were nearly 20 per cent below.

In concluding this discussion it should be noted again that the benefits of technological advancement may be disseminated *either* by increasing money wages or by decreasing prices. Which of these alternative means is the more effective?

The answer is decreasing prices. The wage increase method enhances the purchasing power of only that portion of the population which works for wages—and this constitutes only about 40 per cent of the entire population. When prices are reduced, on the other hand, everybody is benefited; wage earners, salaried employees, farmers, and professional groups alike are able to get more for their money. This method not only gives a maximum increase

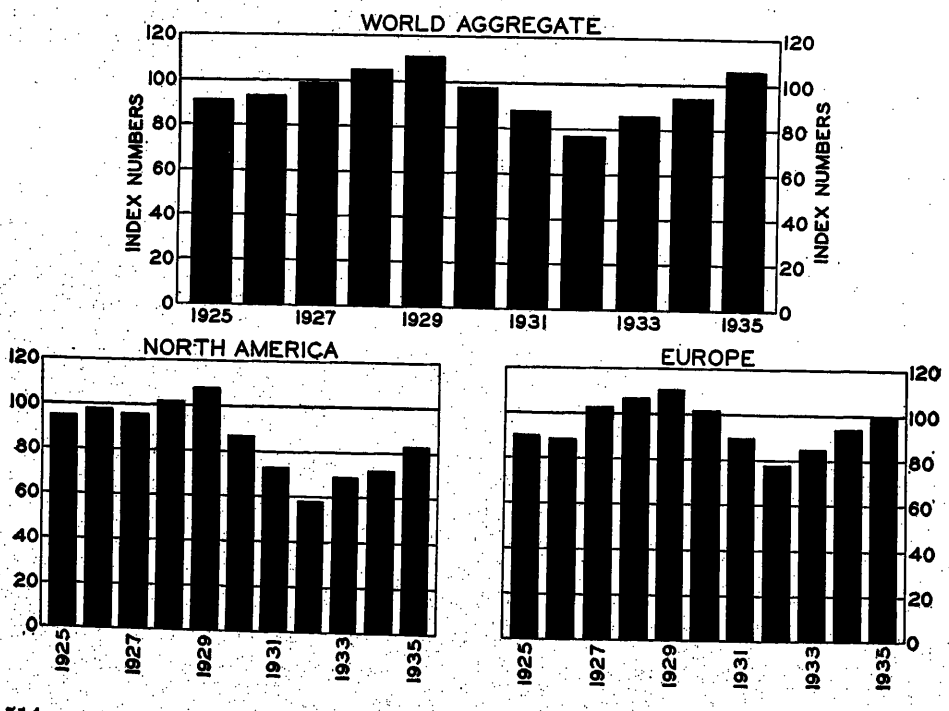



**Fig. 6. World manufacturing activity, 1925–35**

(1925–29 average = 100)

It may be observed that the aggregate volume of manufacturing in the world at large was steadily expanding from 1925 to 1929; that during the next 3 years it fell precipitately, reaching a level substantially below that of predepression years; and that after 3 years of recovery we were still below the level of 1929. Data for the year 1936 are not yet available, but it is probable that the total for that year will be slightly above that for 1929. It should be borne in mind in this connection, however, that world population has meanwhile increased by at least 6 per cent. It will be noted also that the decline was appreciably greater in North America than in Europe and that the degree of recovery has been somewhat less

in purchasing power, but it also serves to maintain a better balance between different divisions of our economic system, particularly between industry and agriculture.

It does not follow, however, from the indubitable fact that the broadest possible dissemination of income is attained through reductions of prices, that this method

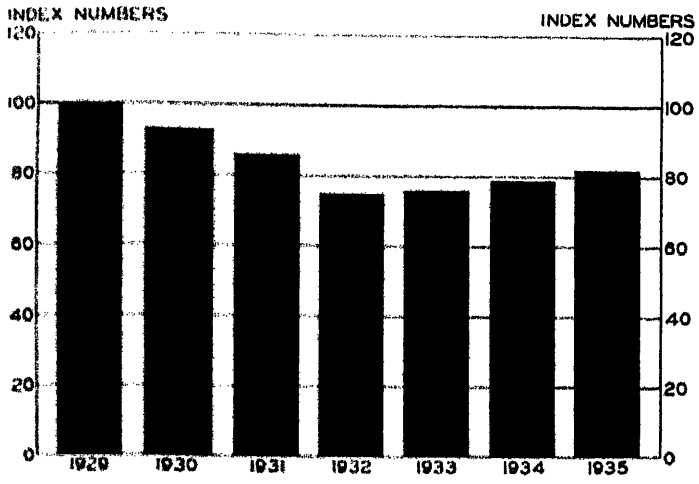



**Fig. 7. Volume of world trade**

The volume of world trade declined from 100 in 1929 to 75 in 1932. In 1935 it had returned to only 82 per cent of the 1929 level, and there was only a moderate increase in 1936. Exchange depreciation and controls, tariffs, and other commercial restrictions, and the drying up of international credit, have served to prevent any material recovery in international trade

must be given sole consideration. Psychological and other practical factors may also warrant wage advances. Profit sharing also may have an important rôle to play. It may be concluded, however, that price reductions—because of the universal character of their effects—should constitute the primary means of disseminating the benefits of technological improvements.*

## Price Restriction Policies

From the preceding discussion of the operation of the economic system and the progressive rise in standards of living, it would almost seem that the operation of the economic system is highly satisfactory. But such a conclusion is obviously not warranted in the light of the earlier discussion of the ineffective utilization of productive capacity. The truth of the matter is that the price mechanism of increasing purchasing power does not always freely operate.

Over the last 50 years interferences have been developing to the free functioning of the price mechanism. Instead of reducing prices as a means of expanding markets, there has been a growing tendency to maintain prices and to let well enough alone.

* In this brief summary statement only the high points of the analysis can be given. The interested reader may find the full appraisal with supporting data in 4 volumes published by the Brookings Institution under the titles "America's Capacity to Produce"; "America's Capacity to Consume"; "The Formation of Capital"; and "Income and Economic Progress."

Interferences with competitive price movements have occurred as a result of the development of at least 3 major types of business organization. The first is the unified monopoly or industrial combination under single management. The second, found chiefly in Europe, is the cartel or "collective monopoly" under which there is group control of production with a view to stabilizing prices in a given industry. The third is the trade association which seeks, usually through informal co-operation, to stabilize certain conditions within particular industries without interfering with the control of production. There are, of course, many different types of trade associations, and not all are able to exert an influence upon prices; but, by and large, trade associations consciously or unconsciously promote price stability. These associations, unlike consolidations, have generally been viewed with favor by the United States government as a means of stabilizing business.

The results of these policies have been most clearly manifested in the decade of the twenties. This was a

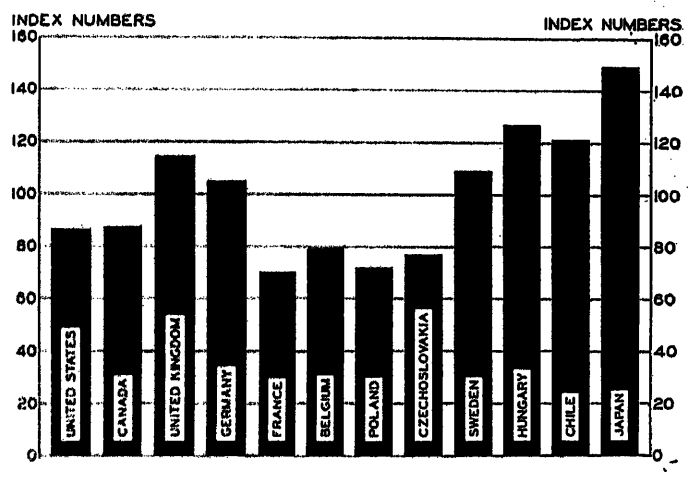



**Fig. 8. Industrial production in selected countries**

In this diagram the output in the year 1929 is taken as 100. Several of the countries included, notably Japan, Hungary, Chile, and the United Kingdom, show production in June 1936 at a level substantially above that of 1929. The United States and Canada stand in an intermediate position, at about 85 per cent, while France, Belgium, Poland, and Czechoslovakia lag materially

period of remarkable advancement. Both the amount of capital and the efficiency of its use increased in nearly all lines of production. In manufacturing industry generally the increase in efficiency was something like 25 per cent. But the benefits of this increasing efficiency were not automatically passed on to the masses of consumers either through the medium of proportional wage increases or proportional price reductions. Wholesale prices of manufactured commodities declined a scant 5 per cent and retail prices did not decline at all. The rate of profits showed a considerable increase during these years. During the recovery period from the beginning of 1934 until the last quarter of 1936 the wage-price mechanism appeared to be working in a very satisfactory manner. As has already been revealed, prices of manufactured goods

fell somewhat, while hourly earnings rose materially. The result was a substantial increase in the wage-to-price ratio. Since this improvement in the wage-to-price ratio was matched by a more or less corresponding increase in efficiency, profits were not reduced. On the contrary, the fuller utilization of capacity that came with an expansion in the total volume of business served to increase the net income of corporations.

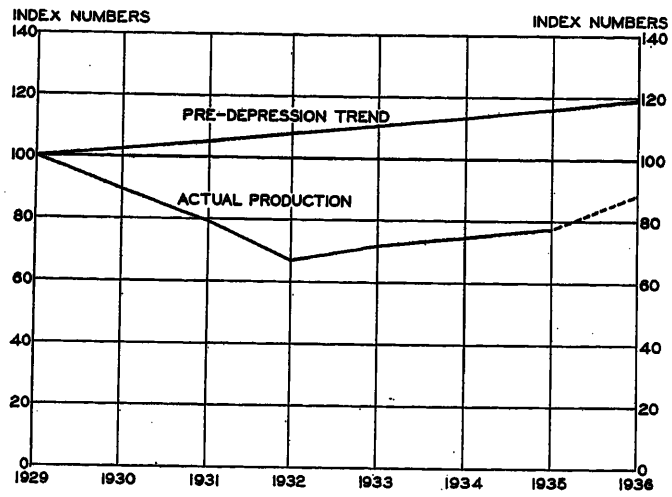



**Fig. 9. Actual production compared with predepression trends**

The upper line is an extension of the predepression trends of production from 1929 to the end of 1936. The lower line shows the actual production, the figures for 1936 being estimated as shown by the dotted projection of the line

## Current Trends

At the end of 1936 the economic situation appeared in many ways exceptionally favorable. Production was steadily increasing, purchasing power was being broadly disseminated among the masses, speculative business activity was not in evidence, inventories remained low, and the general balance between production and consumption was satisfactory. Moreover, there existed clearly defined production requirements adequate, as some studies have shown,* to absorb all the unemployed.

In recent months, particularly since February, the situation has changed in one vitally important respect. Not only have prices of raw materials been rising, but we have had sharp increases in wage rates. These wage increases, ranging from 20 to upward of 30 per cent, have not been related to increases in efficiency. Partly because of this fact, but also in part because of shortsighted industrial policy, the prices of manufactured products are being rapidly advanced. While it is too early to make reliable comparisons of the precise degree to which wages and prices respectively have advanced, there is apparently a strong disposition to assume that prices must be raised in at least equal proportion to the wage advances. The requirement obviously is to restrain the price increases just as much as possible, in order that purchasing power may not be undermined.

The possible effects of the sharp increases in wages and industrial prices must be viewed with apprehension, for they are laying the basis for an old-time vicious spiral of inflation. Rising costs lead to rising prices, and higher prices in turn lead to further advances in wages, costs, and prices. Moreover, a new maladjustment disruptive of balanced relationships is being introduced into the economic situation. While the particular labor groups that receive higher wages may stand to gain for a time, and while the industries in question may temporarily pass on the higher costs to consumers, further extensive expansion appears to be threatened.

The advance in the prices of such basic products as iron and steel and other metals, and building materials, may well serve as a direct impediment to the expansion of production in certain very important lines. The financial condition of the railroads has only recently improved sufficiently to permit extensive physical reconstruction of properties; but now with the prices of steel rising rapidly and railway wage increases also in immediate prospect, it

* See "The Recovery Problem in the United States," published by the Brookings Institution.

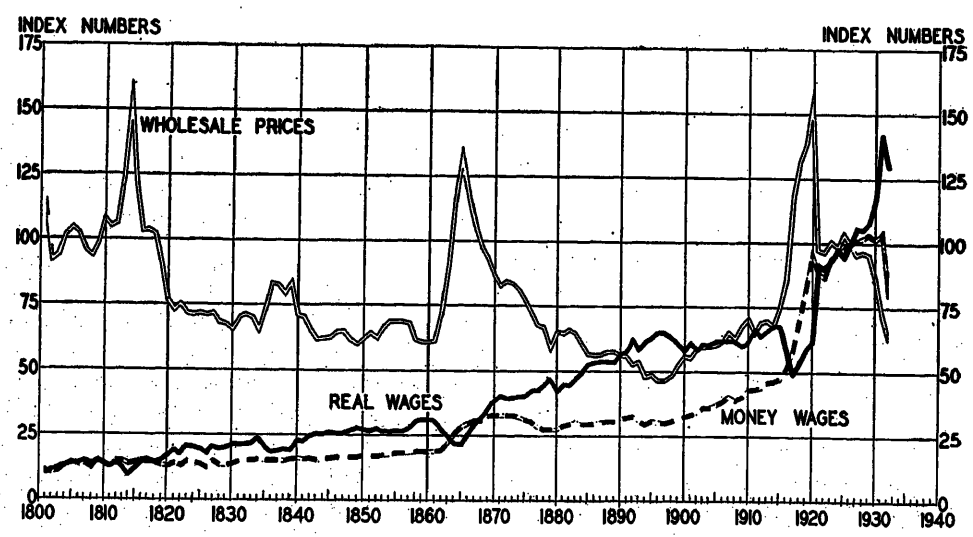



**Fig. 10. Movement of wholesale prices and weekly wages**

The upper line indicates the movement of wholesale prices; the lower one the movement of money wages; and the middle the trend of *real wages* as measured by the relation of prices to wages

is doubtful whether the railroads will be able to carry out the comprehensive programs of rehabilitation that have been prepared. Similarly, the building of new houses, apartments, and other structures may well be held in check by the rising prices of building materials. If this happens, the recent trends will have served to prevent the absorption of the unemployed and the attainment of the higher standards of living which are so greatly desired.

It may be noted also that large sections of the population would soon suffer as a result of a rapid rise in prices, such as: (1) the farmers who do not work for wages; (2) individuals who are working for fixed salaries; and (3) those living on incomes from investments. All these number more than 50 per cent of the total population. Perhaps the most serious phase of the problem relates to the disparity that may again result between industrial and agricultural prices. This is one of the reasons why the government has become so seriously concerned over recent developments.

## Temporary Stimulating Effects

One must note, however, that the adverse effects upon production may be considerably delayed. This is because a rise in prices usually provides an immediate stimulus to industrial activity. With prices going up, business men and others hasten to place orders and buy extra quantities in order to be ahead of the price advance. This expansion of orders accelerates business activity and for a time increases the demand for labor. This expansion of demand in turn serves to increase the demand for products and to raise prices more rapidly. In due course, however, this process serves to intensify the disturbance in price relationships in the different parts of the economic system.

Profits that result from increasing efficiency and an expansion in the total volume of business are soundly based, but profits derived merely from advancing prices are not. Rising prices may indeed stimulate an increase in production and bring on an industrial boom; but since the buoyant activity that results merely from price increases is not accompanied by a corresponding expansion in the purchasing power of the masses, it is not self-sustaining.

It should be clear even from this brief and inadequate analysis of the factors and forces involved in the operation of the economic system that we cannot hope to have economic progress commensurate with the potentialities opened up by modern science and engineering unless governmental, industrial, and labor policies alike are based upon knowledge and understanding of economic fundamentals. The paramount need is for the development and adoption of policies that will promote ever increasing efficiency and ever rising standards of living.

Instead of having reached the limit of progress under the capitalistic system, we should be merely on the threshold of economic advancement. Building on the economic accumulations of the past and on the foundations of modern science, we should be able to look forward to a rate of economic progress in the future that would dwarf anything known in the past. The problem is simply one of the recognition of certain fundamental requirements and the operation of the economic—and political—system in the light of those requirements.

## The Road to Progress

In conclusion I would summarize the fundamental requirements for sustained progress in the following terms:

There must be constantly increasing efficiency in production on the part of both labor and capital. Only by everlastingly improving technical processes and lowering the costs of production can we obtain progressively higher standards of living. To try to accomplish this result in any other way means simply tugging in vain at our collective bootstraps.

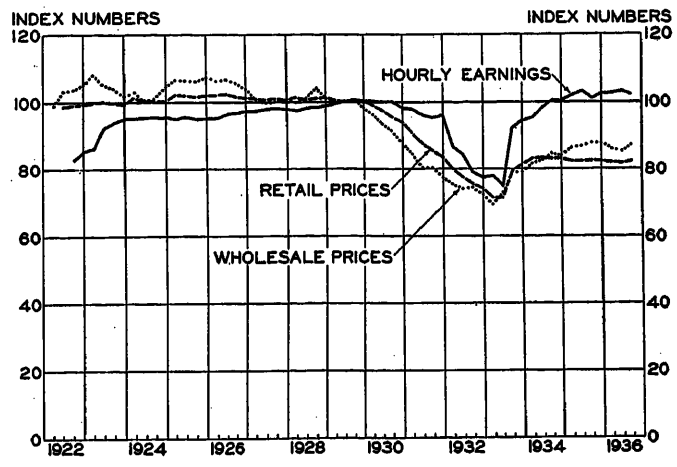



**Fig. 11. Hourly earnings in manufacturing and prices of finished manufactured products**

As efficiency is increased, the benefits must be broadly disseminated among the masses by means of high wages, low prices, or a combination thereof. This is essential for a double reason:

First, it is a fundamental requirement for social and political stability and the well rounded growth of a democracy. It is doubtful indeed if any economic or political system can permanently maintain itself unless it does maintain the goal of the greatest good for the greatest number.

Second, a broad dissemination of the benefits of technical progress is necessary to provide the market demands for an expanding industry. Under our capitalistic system we produce to sell goods in the market. If we increase capacity to produce without correspondingly increasing the capacity of the masses to purchase, we simply reach an impasse. Production schedules have to be restrained, with an accompanying retardation of the rate of economic progress.

Industrial growth, development, progress, require the expansion of consuming power step by step with the expansion of producing power. To put the matter in the simplest possible terms: Growth in the economic organism like growth in any other organism must proceed from the deepest and strongest possible rootage. It must rest on the expanding well-being of the entire population.

# Some Engineering Contributions to Society

By R. C. MUIR
FELLOW AIEE

**Getting more power from less fuel, and consequently providing the public with a dependable supply of electric power at low rates, is the goal toward which power engineers have aimed for many years. In striving toward this goal, they have made significant contributions to society, some of which are indicated in this article**

RESEARCH and engineering have for their ultimate objectives the improvement of social and economic conditions and the conservation of natural resources. Some of the important advances achieved by power engineers in striving toward these objectives briefly are reviewed in this article. It is hoped that this discussion may give engineers a better appreciation of what they have done in this important field, but at the same time may serve as an antidote to complacency, as there yet remains much to be done.

Figure 1 shows data pertaining to the annual production of electric power from fuel for public use in the United States. In 1920, 27 billion kilowatt-hours were produced with 41 million tons of coal; in 1934, 57 billion kilowatt hours were produced and the coal consumption was just the same, 41 million tons. Thus, engineers have given the public more than twice the electric power without increasing the fuel consumption—a notable achievement in the conservation of fuel resources.

Figure 2 shows the improvement in fuel-power electric stations year by year, the performance of the best stations, and the still further improvement possible with the perfection of the mercury-steam station. As may be noted, it took 15 years for the *average* steam-station economy to equal the economy of the *best* station. Hence, 15 years from now the average steam-station economy might be expected to equal the best of today; in other words, for each unit of fuel used then the electric power produced will be $1^2/_3$ times as great as is produced by one unit of fuel today. Were it possible to have all fuel-burning stations equal to the best, only 26 million tons of fuel would be required to produce the 57 billion kilowatt-hours shown in figure 1 for 1934.

Fuel is only one item in the cost of power, and the engineer has not overlooked other items, the most important of which is reliability or availability factor. Coincident with the improvement in efficiency, the reliability has increased, so that the capacity factor has increased and the power generated per dollar of plant investment has materially increased.

It would be impracticable in this article to cover many of the engineering phases that have brought about this improvement, but the turbine generator is representative of the progress made and the problems confronting the engineer.

One of the most important factors in recent power-plant development is the ability to utilize high-temperature steam: that is, steam at 850 to 925 degrees Fahrenheit. This is permitting an increase in the use of high-pressure steam without resuperheating and its attendant complication, and gives a low-cost, simple, and highly efficient installation.

The ability to use high-temperature steam has been dependent upon the development of alloy steels having high creep strength at high temperatures. Ordinary steels are subject to a slow growth or plastic deformation called "creep" at these temperatures when under any appreciable stress.

This precluded the development, up until a few years ago, of turbines to utilize steam at temperatures higher than 750 degrees Fahrenheit. Now, materials are available that permit a stress at high temperatures of from 3 to 4 times what would have been permissible with older materials. This makes it possible to utilize parts of practicable proportions.

The General Electric Company has developed what might be called a second line of defense against high temperature by building some high-temperature turbines with a "double shell." In this construction, the turbine wheels are surrounded by an inner shell carrying its own bolting flange. This shell in turn is surrounded by a second shell which also is bolted at the horizontal joint. The space between is filled with steam at a pressure of about 40 to 50 per cent of the pressure of the steam in the inner shell and at a temperature 50 to 75 degrees lower. The stresses thus are divided between 2 shells so that each can be made thinner than it would otherwise have to be. Figure 3 shows this principle embodied in an actual design.

One of the most outstanding recent advances in the generation of electric power is the superposition on existing steam plants of high-pressure turbines operating at high back-pressure. These turbines take in high-pressure high-temperature steam, develop a certain amount of power, and discharge the steam from their exhausts into the present steam headers of the low-pressure stations. In this way it is possible to increase the capacity of present stations from 40 to 90 per cent, depending upon conditions.

Theoretically, the increased capacity should require an increased coal consumption of about $^1/_3$ pound per kilowatt-hour chargeable to the capacity so installed. Actually, the increased efficiency of the new boilers required by the superposition so reduces the fuel consump-

Essential substance of an address presented at a meeting of the AIEE New York Section, December 9, 1936.

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tion chargeable to the old station as to make the 40 to 90 per cent additional capacity obtainable at no increase in fuel consumption whatever.

Since the additional capacity obtained by means of superposed turbines entails no additional fuel cost, it is in this respect on the same basis as a water-power plant; and since the installation cost is from $1/2$ to $1/3$ the cost of a water-power plant, it can be seen that generating capacity obtained in this way is achieved at a very great economy. That the industry is fully alive to this is attested by the fact that the turbines of this type ordered by public utilities during the past 2 years comprise about $1/3$ the capacity of all turbines ordered by them during that period. The remainder, of course, have been condensing turbines. A typical superposed installation is shown in figure 4.

One of the outstanding recent installations of condensing turbines is at the River Rouge Plant of the Ford Motor Company in Detroit, Mich. In the space originally occupied by 2 12,500-kw turbines, 2 new 110,000-kw units have been installed—9 times the capacity in the same space. The fuel consumption per kilowatt-hour is but 60 per cent as much as formerly.

The design and testing of a new type of steam-generating unit of good efficiency and relatively light weight, and requiring minimum space, recently was announced jointly by the General Electric, Babcock & Wilcox, and Bailey Meter companies. This new unit has been named the "steamotive." In it, steam is generated at high pressure and temperature; and fully automatic control in response to changes in demand has been incorporated. The units are intended for capacities of from 2,000 to 10,000 horsepower.

Two such units already have been built. The first, now in service in the Lynn, Mass., works of the General Electric Company, is used to test marine and other small turbines (see figure 5). It has an output of 21,000 pounds of steam per hour at a pressure of 1,500 pounds per square inch. The other, a completely co-ordinated power-generating plant incorporating the "steamotive" and turbine-generator, with a capacity of 10,000 pounds per hour and furnishing steam to a turbine at 1,200 pounds per square inch and 950 degrees Fahrenheit, is being installed in a small isolated plant of a large industrial concern to supply electric power and low-pressure steam for building heating. Both are oil-fired.

Two oil-fired "steamotive" units, each with a capacity of 40,000 pounds of steam per hour, are now being constructed for the Union Pacific Railroad for driving 2 2,500-horsepower electric locomotives. These units will furnish steam to the turbines at 1,500 pounds per square inch and 950 degrees Fahrenheit.

Indicating the compactness of the "steamotive" unit, the one for Lynn was shipped complete from Schenectady on a railroad flatcar.

Objectives sought in the design of the new equipment are high steam pressure and temperature, minimum weight and size per unit of steam produced, wide range of capacity with ability of the unit to respond quickly to wide variations in load conditions, adaptability to wide range of fuels, completely co-ordinated auxiliaries, completely co-ordinated automatic control, and units of simple design and constructed in sizes small enough to be portable.

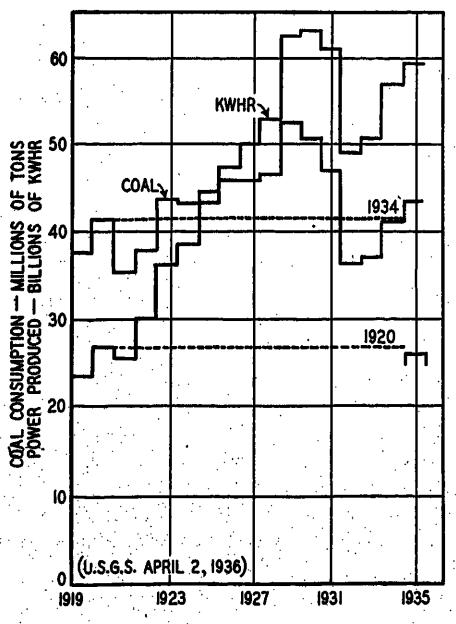



**Fig. 1. Electric power produced for public use, and fuel consumed, in steam-electric stations in the United States from 1919 to 1935, inclusive**

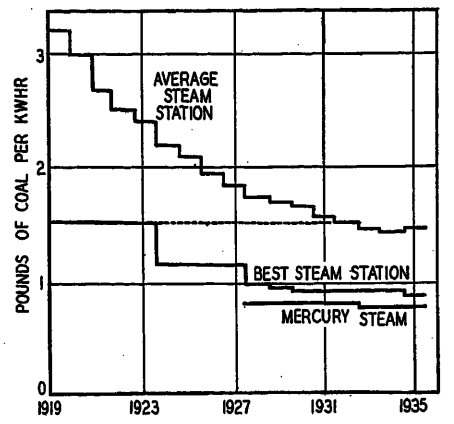



**Fig. 2. Fuel consumed per unit of electric power produced in stations in the United States from 1919 to 1935, inclusive**

## Hydrogen Cooling

A notable example of the value of engineering research in effecting a more economical use of construction materials, and greater economy of machine operation, is the development of hydrogen cooling as applied to rotating electrical machines. For years practically all classes of rotating electrical machinery were cooled with air, chiefly because it was more convenient to use than anything else. Then research showed that this practice was wasteful—that machines would operate more efficiently in gases other than air, and with a greater output per pound of material. Chief among these gases is hydrogen. This gas has a density only $1/14$ that of air, and as a result the windage and ventilation losses of a rotating machine operating in hydrogen would be reduced to $1/14$ of their value in air. The thermal properties of hydrogen also are distinctly superior to those

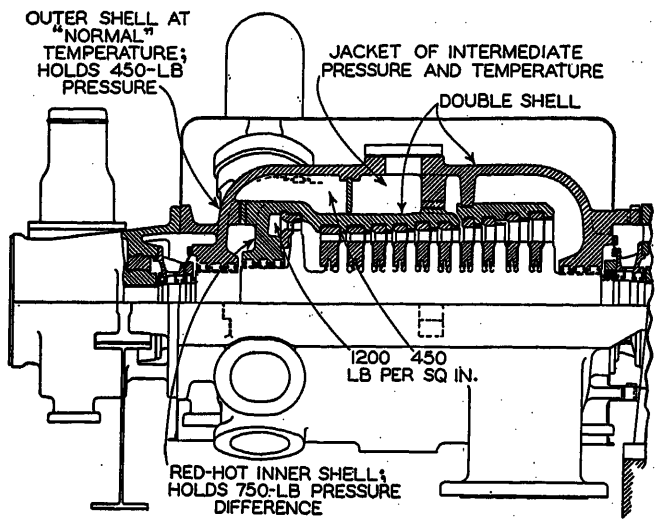



**Fig. 3. Diagram showing construction of double-shell steam turbine for high pressure and temperature**

of air. Hence, by operation in hydrogen, instead of air, up to 25 per cent greater output may be obtained from a machine of given physical dimensions for the same temperature rise of the parts.

The first applications of hydrogen cooling to rotating machines were to synchronous condensers and frequency changers. So successful have these applications been, that in the past 8 years 17 hydrogen-cooled machines of these types, having a combined capacity of nearly 500,000 kva, have been placed in service.

An even greater economic gain may be realized in the application of hydrogen cooling to high-speed turbine generators. With this class of machines, the windage and ventilation losses with air cooling comprise about half the full-load losses. Hence the use of hydrogen reduces the total losses by nearly half, corresponding to a gain of about 1 per cent in efficiency.

In one type of hydrogen-cooled turbine-generator, heat is extracted from the hydrogen in 4 surface coolers located within the generator housing and through which water is circulated. Because of the smaller losses and the improved performance of these coolers in hydrogen, their size is only about 40 per cent of that of the coolers of an air-cooled machine of equal rating. The volume of active material in such a machine is about 20 per cent less than would be required for an air-cooled machine of equal rating. To prevent the escape of hydrogen from the generator housing along the rotating shaft projections a sealing gland is provided in each bearing, which is supplied with vacuum-treated oil from a system operating in parallel with the bearing lubricating system.

In another type of hydrogen-cooled turbine-generator only the rotor is cooled with hydrogen, the stator being cooled by a number of hollow metal pads located between the core laminations and through which water is circulated. At the center of the core, pads with radial fins are provided, which serve both to remove the heat from the stator and to extract the losses from the hydrogen which has cooled the rotor. This type of installation requires the circulation of about 50 per cent less hydrogen than the other type, thus making possible the use of smaller fans and a shorter machine.

Commercial development of the hydrogen-cooled turbine-generator has just begun, but its importance to the industry is indicated by the fact that 17 machines of this type, with a combined output of nearly 850,000 kw, are now under construction. The yearly fuel saving for these 17 machines, as the result of using hydrogen cooling, is an item of some magnitude.

## Improvements in Distribution

After the power is generated, it must be delivered to the consumer with as little loss as possible, in suitable form as to constancy of voltage, and under suitable conditions as to continuity of service or availability. This is not a matter of just using large electrical conductors, but rather a scientific arrangement of interconnections of conductors, placement of transformers, protective and regulating devices, and a reduction of losses in trans-

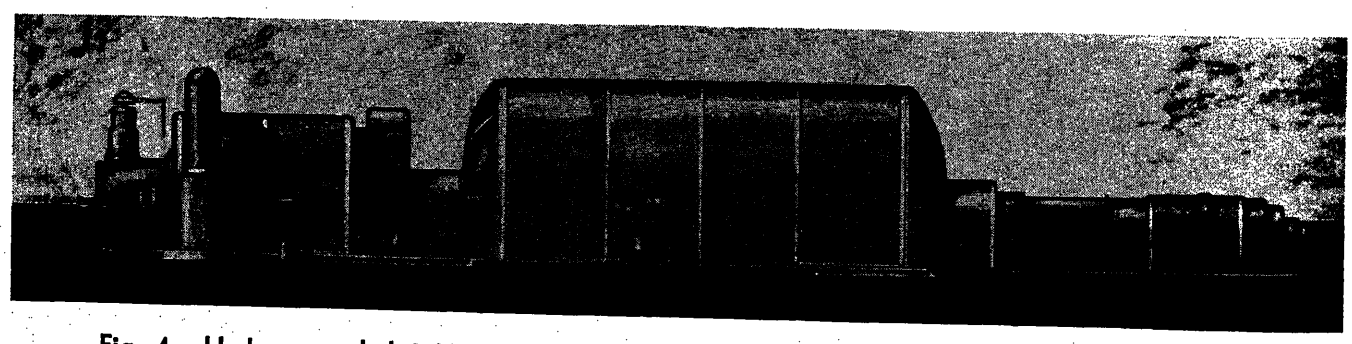


**Fig. 4. Hydrogen-cooled 3,600-rpm 40,000-kw generator driven by high-pressure high-temperature turbine, now being built for superposed installation in the Logan, W. Va., station of the American Gas and Electric Company**

**Turbine:** Pressure, 1,250 pounds per square inch; temperature 925 degrees Fahrenheit (red hot). Double-shell construction. Superposition of this unit will add 86 per cent to station capacity but with only a moderate increase in fuel consumption

**Generator:** Windage losses reduced (by use of hydrogen) to 10 per cent of what these losses would be if the machine were operated in air. Water-cooled stator. Aluminum field winding. Full load losses 1.4 per cent; full load efficiency 98.6 per cent

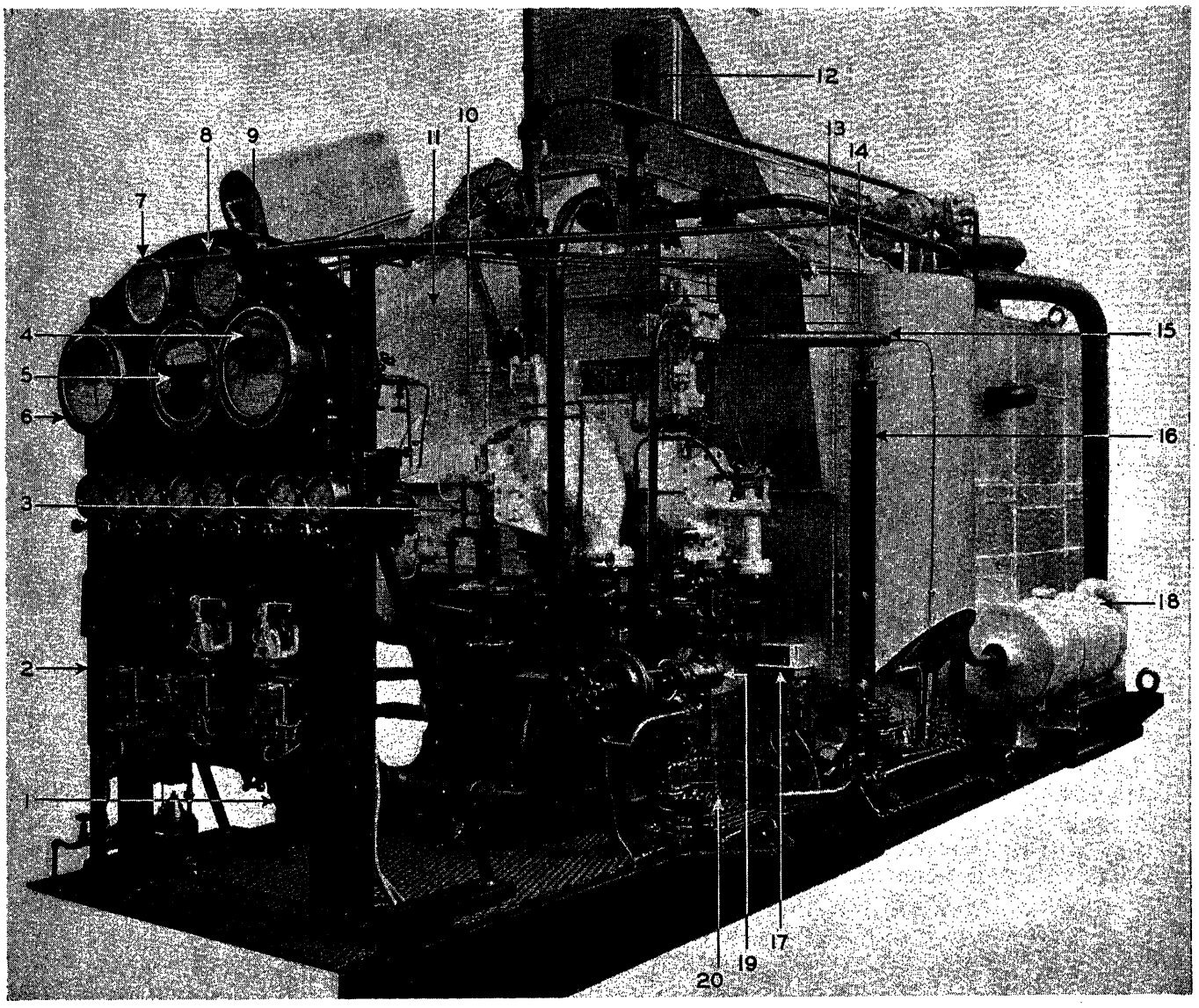



**Fig. 5. Developmental "steamotive" unit**

1. Governor control valve
2. Automatic lighting equipment
3. Drive-turbine steam valve operator
4. Oil flow-air flow controller
5. Steam-flow indicator
6. Drum-level controller
7. Steam-temperature indicator, high-temperature trip
8. Steam-pressure controller, high-pressure trip
9. Steam-output regulating valve
10. Auxiliary-set drive turbine
11. Blower
12. High-pressure surge chamber
13. Boiler feed pump
14. Fuel-oil pump
15. Fuel-oil temperature control
16. Fuel-oil heater
17. Fuel-oil shut-off valve for automatic lighting equipment
18. Feedwater heater
19. Fuel-oil control valve
20. Fuel-oil measuring orifice

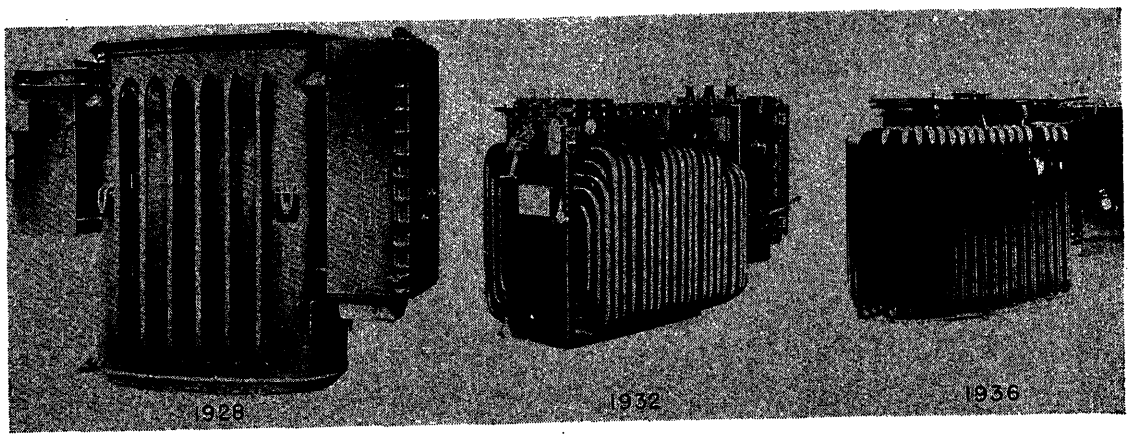
formers and regulating devices. The average distribution losses of the power systems of the United States in 1920 were 21½ per cent; in 1936 this had been reduced to 15 per cent.

The marked and continuing improvement of transformer efficiency has played an important part in reducing the distribution losses. Since 1920 the losses of distribution transformers have been reduced an average of 20 per cent. The average full-load losses of power transformers have been reduced 45 per cent, while the core losses have been reduced 62½ per cent over the same period. Figure 6 illustrates the rapid advance in the design of network transformers.

## Improvements in Power Cable

Paralleling the improvement in transformers, it is interesting to note the progress made in paper-insulated cable since 1920. Previous to 1921 the highest voltage underground cable in use in the United States was 3-conductor 26-kv Y-grounded cable. In 1921, the first 3-conductor 33-kv cable in the United States was installed, but trouble developed and the operating voltage had to be reduced to 22 kv. In 1923 the first 66-kv single-conductor solid-type paper-insulated cable in the United States was installed, and in 1927 *the first* commercial installation in the world of 132-kv oil-filled cable

**Fig. 6. Comparison of 1928, 1932, and 1936 network distribution transformers**




| | 1928 | 1932 | 1936 |
|---|---|---|---|
| Approximate vault space required (feet) | 17 by 4.5 by 9 deep | 14 by 4.5 by 8 deep | 11 by 4 by 6 deep |
| | 100% | 56.5% | 29.7% |
| Efficiency | 98.5% | 98.7% | 98.7% |
| Weight (oil-filled) | 100% | 82.5% | 82.5% |

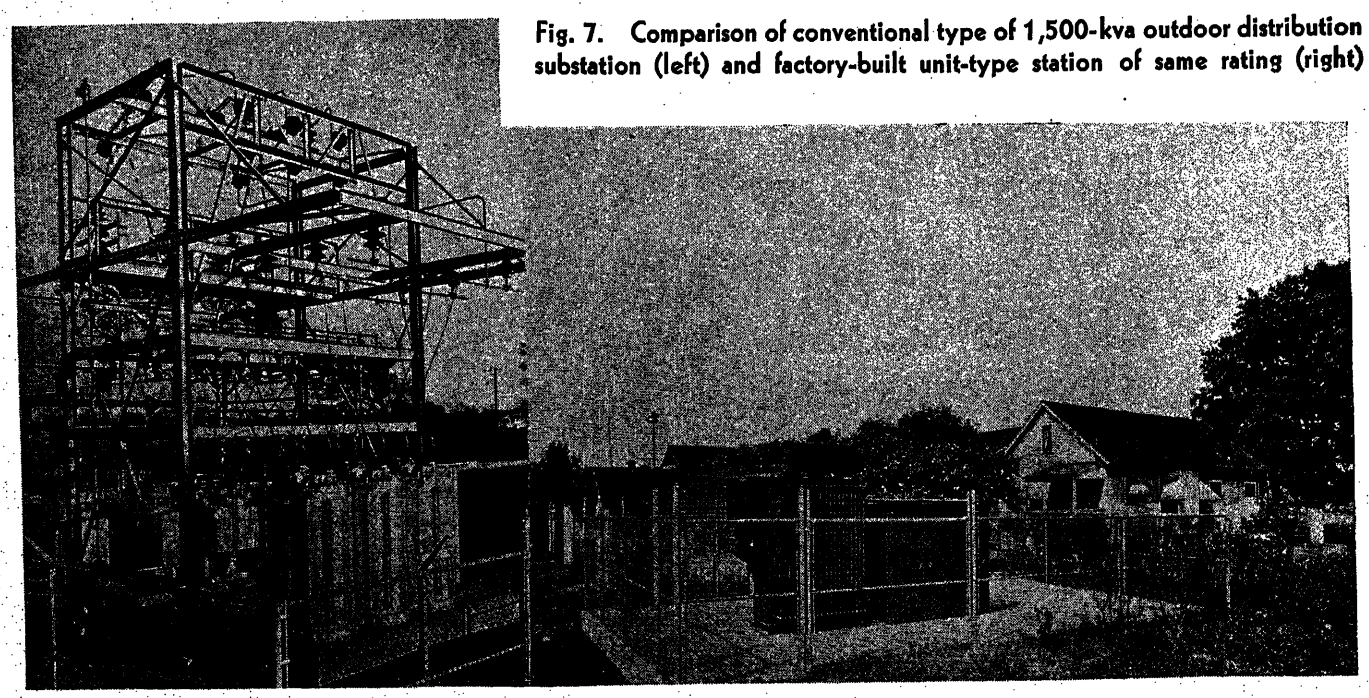
was put into service in the United States. Approximately 900 miles of oil-filled cable is now in service, and there has not been a single electrical failure in this cable in the United States. There is an installation of 230-kv oil-filled cable abroad but none operating at this voltage in this country, although manufacturers are prepared to supply it. Laboratory and field tests have been carried on for several years to determine if 230-kv oil-filled cable is feasible, and these tests are favorable.

Progress in the development and application of high-voltage paper-insulated cable has been made possible by improved materials and better manufacturing methods, and also by the development of the oil-filled cable. Thoroughly washed wood-pulp paper has taken the place of the oiled manila paper, and fluid oils have taken the place of the old petrolatum compounds. Low ionization has resulted from much better vacuum equipment and the complete filling of the cable with insulating oil; dielectric losses have been greatly decreased by the improvements in the paper and the oil. Dielectric losses at operating temperatures have been greatly reduced since 1925. This reduction in losses in the solid type of cable has been approximately 60 per cent, and in the oil-filled cable since 1927 approximately 40 per cent.

Another advance in distribution equipment is illustrated in figure 7.

Direct-current power transmission is very attractive from many points of view. It offers the possibility of operating cables with negligible dielectric losses at greatly increased voltages with consequent reduction in cable cost, and also a means of obtaining nonsynchronous ties between power stations. The General Electric Company has a developmental installation, but at present this is regarded as just another laboratory step which ultimately may come into commercial use and still further reduce transmission losses.

**Fig. 7. Comparison of conventional type of 1,500-kva outdoor distribution substation (left) and factory-built unit-type station of same rating (right)**



## Improvements in Electric Appliances

After the power has reached the consumer, it should be used efficiently in his appliances. As examples, improvements in 2 appliances will be cited—the incandescent lamp and the household refrigerator.

More than 880,000,000 incandescent lamps were manufactured in 1936. For each kilowatt-hour the users of these lamps will receive $^1/_3$ more light than they did from lamps of the same wattage in 1920, and each lamp will cost $^2/_3$ less than in 1920.

At no time in the past has there been more activity in lighting research than at present. Illumination studies are under way on a more extensive scale than ever before, and illuminating engineers have many new types of lamps to experiment with—the sodium lamp, the high-intensity mercury-vapor lamp, and fluorescent lamps, all subject to further development.

There are in service now approximately 7,000,000 household electric refrigerators. Today, 3 electric refrigerators operate with the same electric-power consumption as one required in 1926, and the user may purchase a much superior unit for less than half the amount he paid in 1926. Great advances have been made in styling or in improving the appearance of refrigerators and all household devices. This is illustrated in figure 8.

This improvement has been a matter of putting into these devices the same research, high technical ability, and ingenuity as has been applied to larger apparatus.

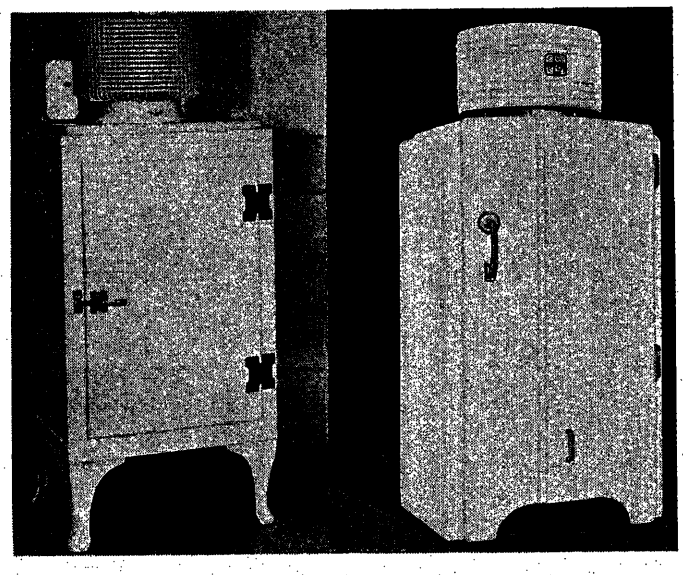
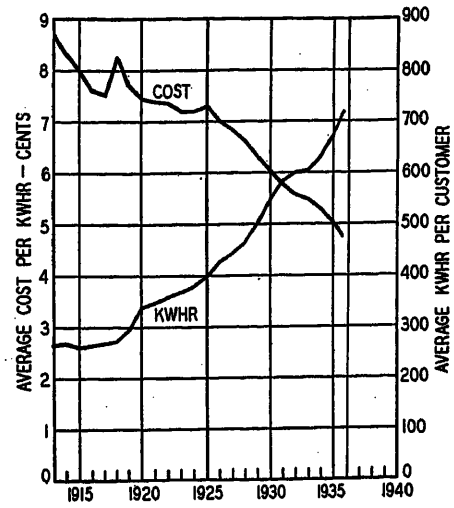


**Fig. 8. Comparison of 1927 and 1937 domestic electric refrigerators**

| | 1927 | 1937 |
|---|---|---|
| Net volume (cubic feet) | 6 | 6 |
| Installed price (approximate) | $310 | $200 |
| Capacity, Btu per hour | 340 | 530 |
| Economy, watt-hours per Btu | 450 | 340 |
| Ice-freezing rate, pounds per hour | 0.66 | 2.04 |
| Average kilowatt-hours per month | 55 | 28 |
| Pounds weight per Btu (unit only) | 0.662 | 0.258 |

**Fig. 9. Consumption of electricity in domestic service and average cost per kilowatt-hour, since 1913**




Similar advances have been made in electric ranges and water heaters, washing machines and ironers, radios, food mixers, toasters, and heating appliances.

Air conditioning is getting under way and will be greatly extended. One of the big problems in air conditioning is the quiet and efficient movement of air; this has stimulated fan research, the results of which already have effected remarkable improvements.

A new household servant has appeared in the disposal unit which macerates waste food from the kitchen, and discharges it into the sewage system. Some day, perhaps, this will be as compulsory as the sewage system itself is today.

The result of all this is shown in figure 9, which depicts how the power companies have taken advantage of these engineering achievements in power generation and transmission and distribution, and have passed them along to the user in the way of lower and lower rates so that the average rate to the domestic consumer today is but little more than half what it was in 1916. The consumer has taken advantage of the lower rates, and of the new and improved lamps and devices, and has increased the average domestic use from 260 kilowatt-hours per year to 709, or more than double. Furthermore the service has improved as to reliability, continuity, and constancy of voltage. What does the consumer pay for this service? If he uses the average 700 kilowatt-hours per year and pays the average rate, he pays just one week's wages for the average American workingman. What else can he purchase that does so much for him—a whole year's electric service for one week's pay? He can buy an electric refrigerator for one month's pay, a better refrigerator than the working man in Europe can buy for 3 months' pay.

In conclusion, then, it may be said that the research and engineering objective of power engineers is to obtain more and more electric power from each unit of fuel, to lose less and less of that power in distributing it to the user, and to have each unit of power do more and more for the user, all to the end that the maximum benefits may be obtained from our natural resources to the best social and economic interest of the nation.

# Employment in the Engineering Profession

**Between 1930 and 1934 there was a substantial net loss of employment among those engineers in the United States who entered the profession before 1930, and a considerable absorption in employment of newcomers to the profession. This is one important conclusion reached by the Bureau of Labor Statistics of the United States Department of Labor after analyzing reports from 52,589 professional engineers obtained in the 1935 survey of the engineering profession conducted by the Bureau at the request and with the co-operation of American Engineering Council. This article,* third in the series reporting the results of this survey, presents data pertaining to the employment of engineers during 1929–34.**

ANALYSIS has been made by the Bureau of Labor Statistics, United States Department of Labor, of reports from 52,589 professional engineers, showing the kinds of employment engaged in at specified periods. The study was undertaken in May 1935, at the request of the American Engineering Council. The following general findings were established by this analysis:

Over the 5-year period ending December 1934, the number of persons in the engineering profession increased by 25.3 per cent. This rate of increase was much in excess of available engineering employment opportunities. The growth among the several professional classes over the period 1930–34 ranged from 17.6 per cent for mining and metallurgical to 62.5 per cent for chemical and ceramic engineers.

The lack of opportunities for engineering employment differed markedly among the professional classes. Thus, over the 5-year period, and for the profession as a whole, private engineering employment declined by 8.2 per cent, but it increased by more than a third for chemical and ceramic engineers. There was little increase or decrease for electrical, mining and metallurgical, and mechanical and industrial engineers. In the case of the civil engineers, however, there was a decrease of about $^1/_8$ in private engineering employment.

All professional classes participated in the increases in employment of engineers by public authorities. The civil engineers were most affected. The proportion of this group employed by public authorities increased from 40.0 per cent in 1929 to 48.5 in 1934.

The fact that available engineering opportunities did not keep pace with the increase in the number of men trained to enter the profession brought about changes in the proportions of those who were unemployed or engaged in nonengineering work.

In 1929 private engineering furnished by far the greatest employment for engineers. For civil engineers this covered 54.3 per cent. There was a range of from 80.6 to 87.3 per cent among the 4 remaining professional classes. By December 1932 private engineering among civil engineers had dropped to 37.6 per cent, and by December 1934 to 31.8 per cent. There was also a continuous decline in this type of employment among electrical engineers; only 63.1 per cent reporting such employment in December 1934. There was only a slight improvement over 1932 for the remaining professional classes. In 1934 these 3 averaged 69.1 per cent.

Nonengineering employment increased sharply from 1929 to 1932 and in equal measure for all professional classes, absorbing many more engineers than did public engineering, in which employment also increased. But despite the fact that the proportions of all engineers in nonengineering employment rose from 6.3 per cent in 1929 to 12.0 per cent in 1932, there was an even larger increase in unemployment. This situation was common to all professional classes.

Between December 1932 and December 1934 there were further increases in nonengineering employment for all professional classes. The increases were not so great as between 1929 and 1932. Unemployment declined for all professional classes, except for civil engineers.

The sharpest increases in public-engineering employment occurred in the period 1932–34.

Of all engineers who reported being professionally active prior to 1930, only 46.2 per cent were in the employ of private firms in 1934; in 1929, 62.2 per cent were so engaged. Federal government employment provided for 10.1 per cent in December 1934; in 1929, this field gave employment to only 5.3 per cent.

Over the period 1930–34 there was a remarkable stability in the number of engineers classified as independent consultants, and those engineers engaged in the teaching of engineering subjects. This was also true of those in the employ of state and county, and municipal and other public authorities, especially if considered together.

The net new private-firm employment that developed between 1930 and 1934 was secured by newcomers who entered the profession in this period. In absolute number, 5,003, or 16 per cent, of the engineers active in the profession before 1930 suffered loss of engineering employment. Some 3,112, or 18 per cent, of the new entrants found engineering work with private firms. The increase in public engineering employment was shared by both older and younger engineers.

## Scope and Method of Study

The primary objectives of this analysis were to determine what kinds of engineering employment were most stable, and what types of substitute employment pro-

* An article prepared by Andrew Fraser, Jr. of the Division of Hours, Wages, and Working Conditions, Bureau of Labor Statistics, United States Department of Labor, which article was published in the April 1937 issue of *Monthly Labor Review*. Articles reporting other phases of this survey were published in ELECTRICAL ENGINEERING as follows: "Professional Aspects of Engineering Education," August 1936, pages 863–7; "Unemployment in the Engineering Profession," February 1937, pages 216–23. A detailed report of the survey will be published later in bulletin form by the Bureau of Labor Statistics.

## Table I—Distribution of All Professional Engineers by Employment Status Reported at End of 1929, 1932, and 1934

(Figures adjusted as explained on page 525)

| Employment Status | Number | | | Per Cent | | | Increase or Decrease in Number | | |
|---|---|---|---|---|---|---|---|---|---|
| | 1929 | 1932 | 1934 | 1929 | 1932 | 1934 | 1929 to 1932 | 1932 to 1934 | 1929 to 1934 |
| Grand total, United States | 31,252 | 35,691 | 39,161 | 100.0 | 100.0 | 100.0 | +4,439 | +3,470 | +7,909 |
| Engineering employment | 29,051 | 27,787 | 30,299 | 93.0 | 77.9 | 77.4 | −1,264 | +2,512 | +1,248 |
| Private[a] | 22,456 | 19,797 | 20,619 | 71.9 | 55.5 | 52.7 | −2,659 | + 822 | −1,837 |
| Public[b] | 6,595 | 7,990 | 9,680 | 21.1 | 22.4 | 24.7 | +1,395 | +1,690 | +3,085 |
| Nonengineering employment | 1,969 | 4,290 | 5,523 | 6.3 | 12.0 | 14.1 | +2,321 | +1,233 | +3,554 |
| Unemployment | 232 | 3,614 | 3,339 | 0.7 | 10.1 | 8.5 | +3,382 | − 275 | +3,107 |

*a.* Includes those engineers in the employ of private firms, independent consultants, reporting "any other employment," and teaching.
*b.* Includes those engineers in the employ of federal, state, county, municipal governments, and other public authority.

fessional engineers found during the depression years, 1930–34, inclusive.

The engineer was requested to check his employment status against only 1 of 14 items for each of the 3 years ending December 31, 1929, 1932, and 1934. In view of the small number reporting in some categories, similarity in the detailed distributions, and the desirability of discussing unemployment and related data as a whole, these 14 categories were reduced to 8 and are designated in this article thus: (1) private firm,[1] (2) independent consultant, (3) teaching, (4) Federal, (5) state and county, (6) municipal and other public authority, (7) nonengineering employment, (8) total unemployment.[2] In the ensuing discussion items 1 to 3 inclusive, and 4 to 6 inclusive are hereafter referred to, respectively, as private engineering employment and public engineering employment, and these 2 in combination as total engineering employment.

### Employment Status of Engineers, 1929–34

During the period 1930 to 1934, inclusive, the total number of engineers seeking employment was increased by almost 10,000 per year, largely through the addition of new college graduates. Thirty-two per cent of these recent college graduates reported to the bureau, in contrast to 15 per cent of those who were actively engaged in the profession prior to 1930. This disparity necessitated adjusting the sample to obtain the over-all distributions of employment status for 1932 and 1934, thus: The number of engineers graduating in 1930–34 and reporting employment status for 1932 and 1934 were reduced in the ratio of 15 to 32. These derived totals were then added to the remaining reports for 1932 and 1934. This was possible because for separate age groups among both the younger and older engineers the percentage of replies shows homogeneous sampling within these 2 groups. In determining the adequacy of these samples no allowances were made for deaths or severances from the profession occurring between December 1929 and December 1934.

These distributions for the years 1929, 1932, and 1934 are presented in table I for the profession as a whole.

Between December 1929 and December 1932 the total number of professional engineers in the sample increased by 4,439, from 31,252 to 35,691. There was a further increase of 3,470 to 39,161 by December 1934. The total increase from 1929 to 1934 amounted to 25.3 per cent.

This increase took place during 5 years of depression in which available engineering opportunities were insufficient to absorb the supply of engineers. For December 1932, 3,614 reported unemployment. The percentage of those reporting unemployment declined from 10.1 at the end of 1932 to 8.5 at the end of 1934. But in the face of the continuing influx of engineers, the absolute number of those unemployed declined only slightly to 3,339 at the end of 1934. Furthermore, while the presence of 6.3 per cent of the professional engineers in nonengineering employment in 1929 indicates this was even then an established and normal outlet for them, there was an enormous increase in such work between 1929 and 1932. There was a further, but smaller, increase in nonengineering work between 1932 and 1934. The number reporting themselves as engaged in such work increased from 1,969 in 1929 to 5,523 by December 1934. Among the engineers reporting, 12.0 and 14.1 per cent were engaged in nonengineering work in December 1932 and 1934, respectively. There is reason to believe, from a preliminary examination of income data, that the specific nonengineering work of many of those reporting in 1934 was much more frequently of a makeshift character than in 1929.

Engineering employment as a whole declined 4.4 per cent between 1929 and 1932. There was a rise by December 1934. The number in the adjusted sample engaged in engineering work increased from 29,051 in December 1929 to 30,299 in December 1934, but this was due primarily to the increases in the public employment of engineers. Private employment decreased by 11.8 per cent from 1929 to 1932. Despite some increase from 1932 to 1934, it was still 8.2 per cent below the 1929 level at the end of the 5-year period 1930–34.

The dependence upon public employment is further evidenced by the fact that although both classes of engineering employment increased between December 1932 and December 1934, the absolute increase reported in private employment was only half of that obtaining in employment with public authorities. Relative to the numbers so employed in 1932, the rate of increase in public employment was almost 5 times as great as that in private employment.

1. Includes also those reporting as employees of private consulting firms and under "any other employment" in question 6.

2. Includes also those reporting work relief and direct relief.

## Table II—Employment Status at End of 1929, 1932, and 1934 of All Engineers Reporting, by Professional Class

(Figures adjusted as explained on page 525)

| Professional Class | Number of Engineers | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Total | | | In Engineering Employment | | | | | | In Nonengineering Employment | | | Unemployed[c] | | |
| | | | | Total Private[a] | | | Total Public[b] | | | | | | | | |
| | 1929 | 1932 | 1934 | 1929 | 1932 | 1934 | 1929 | 1932 | 1934 | 1929 | 1932 | 1934 | 1929 | 1932 | 1934 |
| Total, United States | 31,252 | 35,691 | 39,161 | 22,456 | 19,797 | 20,619 | 6,595 | 7,990 | 9,680 | 1,969 | 4,290 | 5,523 | 232 | 3,614 | 3,339 |
| Chemical and ceramic | 1,470 | 1,931 | 2,389 | 1,217 | 1,322 | 1,640 | 103 | 122 | 143 | 143 | 320 | 459 | 7 | 167 | 147 |
| Civil, agricultural, and architectural | 13,786 | 15,330 | 16,365 | 7,477 | 5,760 | 5,191 | 5,510 | 6,620 | 7,941 | 694 | 1,413 | 1,556 | 105 | 1,537 | 1,677 |
| Electrical | 6,112 | 7,276 | 8,117 | 5,238 | 4,940 | 5,137 | 350 | 456 | 623 | 493 | 1,155 | 1,759 | 31 | 725 | 598 |
| Mechanical and industrial | 8,455 | 9,587 | 10,609 | 7,374 | 6,729 | 7,512 | 504 | 643 | 802 | 517 | 1,190 | 1,518 | 60 | 1,025 | 777 |
| Mining and metallurgical | 1,429 | 1,567 | 1,681 | 1,150 | 1,046 | 1,139 | 128 | 149 | 171 | 122 | 212 | 231 | 29 | 160 | 140 |

*a.* Includes employees of private firms, independent consultants, "any other employment," and teaching.
*b.* Includes federal state county, and municipal governments, and other public authority.
*c.* Includes direct relief and work relief.

The preceding analysis is concerned only with the engineering profession as a whole. Corresponding data for each professional class are presented on an adjusted basis in table II.

Over the 5-year period ending December 1934, the number of persons in the engineering profession increased by 25.3 per cent. The corresponding increases for the separate professional classes ranged from 17.6 per cent for mining and metallurgical engineers to 62.5 per cent for chemical and ceramic engineers (table III).

In no professional class did total engineering employment keep pace with the growing number of engineers. The closest balance between the increase in number of engineers and the increase in total engineering employment was 62.5 per cent to 35.1 per cent for chemical and ceramic engineers. That is, without displacement of such engineers in the profession in 1929 about half of their increase in number could have been absorbed in engineering work. The next highest increase in number, namely, 32.8 per cent, occurred among electrical engineers. This was met by an increase of only 3.1 per cent in their total engineering employment. Mechanical and industrial engineers fared somewhat better. Their numbers increased by 25.5 per cent, while opportunities for engineering employment increased by 5.5 per cent. Roughly, 1/6 of the total increase in number of all engineers between 1930 and 1934 was provided for by the growth of new jobs. Clearly, the wide variations in the rates of increase in these professional classes had an important bearing upon the nature of their employment distributions in the period 1929–34.

The data for private and public engineering in table III accentuate the differences in available engineering opportunities for each professional class. Thus, over the 5-year period, and for the profession as a whole, although private engineering employment declined by 8.2 per cent it increased by more than 1/3 for chemical and ceramic engineers. There was little increase or decrease for electrical, mining and metallurgical, and mechanical and industrial engineers; but for the civil engineers, there was a decrease of about 1/3 in private engineering employment.

By contrast, no professional class was excepted from the increases which took place in public engineering employment. It was the civil engineers, however, who were most affected. For them public employment was an important field in 1929 when 40 per cent of all civil engineers were so engaged. The 44.1 per cent increase by 1934 in the amount of such employment reported meant an absolute increase of 2,431 jobs over the 5-year period. In contrast, less then 6.0 per cent of electrical and mechanical engineers had been employed by public authorities in 1929. By December 1934, although the numbers of them so engaged had increased by 78 and 59.1 per cent, respectively, the absolute increases in jobs reported were only 273 for electrical and 298 for mechanical and industrial engineers. For chemical and ceramic, and mining and metallurgical engineers, the absolute increases were, respectively, 40 and 43.

Since the available engineering opportunities did not keep pace with the increases in men trained to enter the profession, there must obviously have been changes in the proportions, first, of those engaged in engineering and second, of those unemployed,[3] or engaged in nonengineering work. This is evidenced by considering the adjusted data presented in table IV.

## Table III—Per Cent of Change in Engineering Employment, by Professional Class, 1929 to 1934

(Figures adjusted as explained on page 525)

| Professional Class | Per Cent of Increase in Each Professional Class, 1929–34 | Per Cent of Increase or Decrease, 1929–34 in— | | |
|---|---|---|---|---|
| | | Total Engineering Employment | Private[a] Engineering Employment | Public[b] Engineering Employment |
| Total, United States | +25.3 | +4.4 | −8.2 | +46.8 |
| Mining and metallurgical | +17.6 | +2.5 | −1.0 | +33.6 |
| Civil, agricultural, and architectural | +18.7 | +1.1 | −30.6 | +44.1 |
| Mechanical and industrial | +25.5 | +5.5 | +1.9 | +59.1 |
| Electrical | +32.8 | +3.1 | −1.9 | +78.0 |
| Chemical and ceramic | +62.5 | +35.1 | +34.8 | +38.8 |

*a.* Includes employees of private firms, independent consultants, "any other employment," and teaching.
*b.* Includes employees of federal, state, county, and municipal governments and other public authority.

3. For detailed discussion, see "Unemployment in the Engineering Profession," ELECTRICAL ENGINEERING, February 1937, pages 216–23.

Private engineering employment furnished by far the greatest amount of employment to engineers. In 1929, even among civil engineers, 54.3 per cent were so employed. For the remaining 4 professional classes, the percentages ranged from 80.6 for mining and metallurgical to 87.3 for mechanical and industrial engineers. These proportions dropped sharply from 1929 to 1932 because of a decrease in the number of private jobs and an increase in the number of engineers. By December 1932, only 37.6 per cent of the civil engineers reported being in private engineering. The range for the remaining 4 professional classes was from 66.8 to 70.2 per cent. By the end of 1934, there was a further decrease in the proportions privately employed among both civil and electrical engineers. The former decreased to 31.8 per cent. Among electrical engineers, private engineering work had employed 67.8 per cent in 1932 as compared with 63.1 per cent in 1934. There was only a slight improvement over 1932 for the remaining professional classes.

In all classes, excepting chemical and ceramic engineers, the proportions engaged in public engineering increased from 1929 to 1934. The most pronounced shift occurred among the civil engineers, namely, from 40.0 per cent in 1929 to 48.5 per cent in 1934. This is some measure compensated for the large decline in the private engineering employment of this professional class. Indeed, as a result of public employment, the proportion of civil engineers in total engineering employment in both 1932 and 1934 was slightly higher than in any other professional class.

Lack of engineering employment opportunities in the period 1929–32 led to increases in both nonengineering employment and unemployment for all professional classes. In general, the loss of private employment occurred from 1929 to 1932. Nonengineering employment increased sharply, absorbing many more engineers than public engineering work, in which employment also increased. But despite the fact that the proportion of all engineers in nonengineering rose from 6.3 per cent in 1929 to 12.0 per cent in 1932, there was an even larger increase in unemployment. This situation was common to all professional classes.

There were further increases in the proportions engaged in nonengineering work among all professional classes in the period 1932–34. Among electrical engineers, the rate of increase in the proportion who were in nonengineering employment was $^3/_4$ of that which occurred in 1929–32. But for the remaining professional classes the corresponding rates of increase were only $^1/_3$ or less. In the case of civil engineers and mining and metallurgical engineers, there were almost no increases in the proportions engaged in nonengineering employment. For each of these groups there was a greater increase from 1932 to 1934 in public than in nonengineering employment. For civil engineers it was much larger. For mechanical engineers the proportions in public engineering rose from 6.7 per cent in 1932 to 7.6 per cent in 1934, whereas nonengineering embraced 12.4 per cent of all mechanical engineers in 1932 and 14.3 per cent in 1934. For mechanical engineers, therefore, the rate of expansion in public engineering employment was less than that which occurred in nonengineering employment.

## Employment Status in Comparable Age Groups

Comparison of the distribution of employment status in 1929 of all engineers who entered the profession in the period 1925–29, with that in 1934 of a comparable group who entered the profession between 1930 and 1934, reflects the pressures to which new entrants were subjected during the depression years. It also emphasizes the abnormality of the employment status of the latter in 1934.

In 1929 only 5.3 per cent of the most recent graduates with professional training were in nonengineering work and 0.4 per cent were unemployed. In other words, all but $^1/_{20}$ of those who entered the profession in these 5 years were employed in engineering work in 1929 (table V). But in 1934, $^2/_5$ of the comparable group of recent engineering graduates[4] were not in regular professional engineering work. No less than 10.6 per cent of them were unemployed in December 1934, while 29.4 per cent reported being engaged in nonengineering work.

Of all recent engineers, both in 1929 and in 1934,

4. The term "engineering graduate" is used interchangeably with "entered the profession." The tabulations cover predominantly those who received first degrees in engineering in the years specified, but also include all "other" engineers (such as those whose college work was incomplete) who were 23 to 27 years old at the date of reported employment.

**Table IV—Percentage Distribution of Engineers Reporting, by Employment Status and Professional Class, at End of 1929, 1932, and 1934**

(Figures adjusted as explained on page 525)

| Professional Class | Per Cent of Total in Each Professional Class Reporting— | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Engineering Employment | | | | | | Nonengineering Employment | | | Unemployment[c] | | |
| | Private[a] | | | Public[b] | | | | | | | | |
| | 1929 | 1932 | 1934 | 1929 | 1932 | 1934 | 1929 | 1932 | 1934 | 1929 | 1932 | 1934 |
| Total, United States | 71.9 | 55.5 | 52.7 | 21.1 | 22.4 | 24.7 | 6.3 | 12.0 | 14.1 | 0.7 | 10.1 | 8.5 |
| Chemical and ceramic | 82.8 | 68.5 | 68.7 | 7.0 | 6.3 | 5.9 | 9.7 | 16.6 | 19.2 | 0.5 | 8.6 | 6.2 |
| Civil, agricultural, and architectural | 54.3 | 37.6 | 31.8 | 40.0 | 43.2 | 48.5 | 5.0 | 9.2 | 9.5 | 0.7 | 10.0 | 10.2 |
| Electrical | 85.6 | 67.8 | 63.1 | 5.8 | 6.3 | 7.8 | 8.1 | 15.9 | 21.7 | 0.5 | 10.0 | 7.4 |
| Mechanical and industrial | 87.3 | 70.2 | 70.8 | 5.9 | 6.7 | 7.6 | 6.1 | 12.4 | 14.3 | 0.7 | 10.7 | 7.3 |
| Mining and metallurgical | 80.6 | 66.8 | 67.9 | 8.9 | 9.5 | 10.1 | 8.5 | 13.5 | 13.7 | 2.0 | 10.2 | 8.3 |

a. Includes employees of private firms, independent consultants, "any other employment," and teaching.
b. Includes employees of federal, state, county and municipal governments, and other public authority.
c. Includes direct relief and work relief.

approximately 1/6 were engaged in the 3 categories of public engineering. In so far as any differences existed, there appears to have been a slight decline in the proportions of the 1930–34 group that secured public employment. The decrease in the percentage in state and county employment was only from 8.8 to 7.5. But municipal and other public authorities in 1929 had employed 5.4 per cent of the 1925–29 engineers, whereas in 1934 they employed only 2.4 per cent of those who entered the profession in the period 1930–34. On the other hand, the federal government employed a larger percentage of the recent graduates in 1934 than it had in 1929. For 1929, 6.5 per cent of the 1925–29 engineers reported themselves as having been employed by the federal government, whereas 9.2 per cent of the recent entrants to the profession were so employed in 1934.

In 1929 nearly 3/4 of the recent engineers were in private engineering employment. Only 40.9 per cent of the 1930–34 engineers so reported for December 1934. Clearly, the abnormally large proportion of the new entrants to the profession who were unemployed or were compelled to find work of a nonengineering nature in 1934 was due primarily to the lack of opportunities in the principal field of engineering activity. A contributory factor of substantial importance, however, was that the number of those graduated from engineering courses in colleges was about 20 per cent higher from 1930 to 1934 than from 1925 to 1929. In number, this increase was about 10,000 individuals.

This dependence upon private engineering employment is common to the greater part of the engineering profession. A substantial number, however, is normally in the employ of public authorities. This is borne out by considering the distributions of employment status of all engineers reporting. These data are shown in table VI, divided into 3 broad classes, by age.[5]

Of all older engineers reporting for December 1929, it may be noted that 71.9 per cent were engaged in private engineering, 21.1 per cent in public engineering, 6.3 per cent in nonengineering work and only 0.7 per cent were unemployed. Of the 71.9 per cent in private engineering, 62.2 per cent were in the employ of private firms, 4.2 per cent in independent consulting work, and 5.5 per cent in teaching. In public engineering, the percentages for federal, state, and county, and municipal and other public authorities ranged from 5.3 to 7.4. This situation had an important bearing on the changes which occurred in the subsequent period, especially with regard to substitute employment.

Over the 5-year period there was a net change in the distributions of employment affecting 16.8 per cent of the "older" engineers; that is, of engineers who had entered the profession prior to 1930. In other words, out of every 1,000 engineers reporting, there were net changes in the employment status of 168 between 1929 and 1934. In absolute numbers, there were shrinkages of 5,255 jobs for engineers graduating prior to 1929. No less than 5,002 were separated from private firms. The remaining net losses of employment were distributed among those engaged in independent consulting (60), in teaching (16), and in municipal and other public employment (177). These decreases in employment opportunities for older engineers were not counterbalanced by increases in the other classes of engineering employment. In fact, 2,270 engineers reporting graduation prior to 1930 were still unemployed in December 1934, while 1,233 found employment in nonengineering work. Only 1,752 had been absorbed by increases in public engineering employment, 1/6 with state and county authorities, and 5/6, or 1,502, with the federal government.

The major part of the loss of employment for older engineers occurred from 1929 to 1932. In this period net shifts in employment had affected the status of 14.7 per cent of these men. The net change in the period 1932–34 involved only 4.0 per cent of them. Obviously, by December 1932 the engineering profession had suffered the major impact of the depression. Between December 1929 and December 1932 there were net losses of employment involving 4,608 engineers. Only 2 of the categories of employment were involved, namely, that with private firms, and that with municipal and other public authorities. But of the 4,608 positions concerned, the shrinkage of employment with private firms affected 4,530; the latter, only 78. Of these engineers, only 884 were able to find other types of engineering employment by December 1932; nearly 50.0 per cent of them entered federal-government employment, while 1/3 entered state and

5. Table VI presents the absolute figures for all reports received without adjustment. It deals with the older and younger engineers separately and, therefore, no adjustment was required in these broad age classifications, though allowance did have to be made for the relatively large number of reports received from young engineers when the groups were treated in combination.

Older engineers comprise all those who were active in professional engineering prior to 1930. The younger engineers are those who entered the profession in the years 1930–34, inclusive, and are divided into 2 broad age groups, each designated by the graduating classes which they embrace, namely, 1930–32 engineers and 1933–34 engineers. Furthermore, in tabulating the data on employment status, homogeneity of the older and 1930–32 engineers was maintained. That is, in the case of the former, only those reporting for the 3 years 1929, 1932, and 1934 were used; in the case of the latter, only those reporting for the 2 years 1932 and 1934 were included. Analysis shows that the percentage eliminated was small.

**Table V—Comparative Employment Status of 2 Groups of Younger Engineers**

| Age Group | Total | In Private[a] Engineering Employment | In Public Engineering Employment: Federal | State and County | Municipal and Other Public Authority | In Nonengineering Employment | Unemployed[b] |
|---|---|---|---|---|---|---|---|
| | Number of Engineers | | | | | | |
| 1925–29 engineers, who were 23 to 27 years of age in 1929 | 6,997 | 5,151 | 452 | 618 | 375 | 371 | 30 |
| 1930–34 engineers, who were 23 to 27 years of age in 1934 | 16,872 | 6,910 | 1,544 | 1,272 | 401 | 4,959 | 1,786 |
| | Per Cent | | | | | | |
| 1925–29 engineers, who were 23 to 27 years of age in 1929 | 100.0 | 73.6 | 6.5 | 8.8 | 5.4 | 5.3 | 0.4 |
| 1930–34 engineers, who were 23 to 27 years of age in 1934 | 100.0 | 40.9 | 9.2 | 7.5 | 2.4 | 29.4 | 10.6 |

*a.* Includes employees of private firms, independent consultants, "any other employment," and teaching.
*b.* Includes work relief and direct relief.

## Table VI—Distribution of Older and Younger Engineers Reporting, by Employment Status, at End of 1929, 1932, and 1934

| Employment Status | Number | | | | | | Per Cent | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Older Engineers[a] | | | Younger Engineers | | | Older Engineers[a] | | | Younger Engineers | | |
| | | | | 1930–1932[b] | | 1933–1934[c] | | | | 1930–1932[b] | | 1933–1934[c] |
| | 1929 | 1932 | 1934 | 1932 | 1934 | 1934 | 1929 | 1932 | 1934 | 1932 | 1934 | 1934 |
| Grand total, United States | 31,252 | 31,252 | 31,252 | 9,469 | 9,469 | 7,403 | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 |
| Engineering employment | 29,051 | 25,327 | 25,548 | 5,248 | 6,057 | 4,070 | 93.0 | 81.1 | 81.8 | 55.4 | 64.0 | 55.0 |
| Private employment | 22,456 | 18,142 | 17,378 | 3,532 | 3,926 | 2,984 | 71.9 | 58.1 | 55.7 | 37.3 | 41.5 | 40.4 |
| Private firm | 19,424 | 14,894 | 14,422 | 3,247 | 3,748 | 2,892 | 62.2 | 47.7 | 46.2 | 34.3 | 39.6 | 39.2 |
| Independent consultant | 1,303 | 1,459 | 1,243 | 50 | 25 | 17 | 4.2 | 4.7 | 4.0 | 0.5 | 0.3 | 0.2 |
| Teaching | 1,729 | 1,789 | 1,713 | 235 | 153 | 75 | 5.7 | 5.5 | 5.5 | 2.5 | 1.6 | 1.0 |
| Public employment | 6,595 | 7,185 | 8,170 | 1,716 | 2,131 | 1,086 | 21.1 | 23.0 | 26.1 | 18.1 | 22.5 | 14.6 |
| Federal | 1,647 | 2,063 | 3,149 | 531 | 1,008 | 536 | 5.3 | 6.6 | 10.1 | 5.6 | 10.6 | 7.2 |
| State and county | 2,632 | 2,884 | 2,882 | 927 | 872 | 400 | 8.4 | 9.2 | 9.2 | 9.8 | 9.2 | 5.4 |
| Municipal and other public authority | 2,316 | 2,238 | 2,139 | 258 | 251 | 150 | 7.4 | 7.2 | 6.8 | 2.7 | 2.7 | 2.0 |
| Nonengineering employment | 1,969 | 3,047 | 3,202 | 2,651 | 2,655 | 2,304 | 6.3 | 9.7 | 10.2 | 28.0 | 28.0 | 31.1 |
| Unemployment | 232 | 2,878 | 2,502 | 1,570 | 757 | 1,029 | 0.7 | 9.2 | 8.0 | 16.6 | 8.0 | 13.9 |

a. Includes both graduates and "other" engineers who were professionally active prior to 1930.
b. Includes both graduates and "other" engineers who entered the profession in the years 1930–32.
c. Includes both graduates and "other" engineers who entered the profession in the years 1933 and 1934.

county employment. There were 156 additional engineers reporting themselves as being independent consultants and 60 as engaged in teaching. Of the remaining 3,724 engineers, 2,646 were unemployed and 1,078 were engaged in work of a nonengineering nature.

The shifts noted in the period 1929–32, therefore, are indicative of 2 trends affecting engineers who had been in the profession in 1929: (1) the pronounced increase in federal employment and the decrease in private employment; and (2) the comparative stability of the remaining classes of engineering employment. These trends are accentuated further by a consideration of the shifts which occurred between December 1932 and December 1934.

In 1932–34, all categories of engineering employment, with the exception of that with federal government, decreased. Thus, an additional net total of 472 engineers graduating before 1930 were separated from private firms. The decreases in jobs in the remaining engineering classes ranged from 2 in the case of teaching to 216 for independent consultants. Incidentally, it may be noted that the proportion engaged in the latter class was only slightly less than the proportion so engaged in 1929. This would seem to indicate that the increase which did take place by December 1932 was an artificial one. Altogether, the decreases in engineering employment affected 865 engineers. Despite these decreases in many types of job opportunity, there was also a decrease of 376 in the number of engineers reporting unemployment. Only 155 found opportunities in nonengineering employment. The federal government gave engineering employment to the remaining 1,086 (87.5 per cent) of those whose status shifted from 1932 to 1934.

The net result of the changes in employment status among the older engineers was such that by December 1934 only 46.2 per cent were in the employ of private firms, whereas 62.2 per cent had been so engaged at the end of 1929. Federal employment provided for 10.1 per cent in December 1934, as against only 5.3 per cent in 1929. All other classes of engineering employment remained comparatively stable over the period 1930–34, especially if state, county, and municipal employment are considered together. In December 1934 there were 8.0 per cent unemployed, but it is obvious that had not 10.2 per cent of the older engineers found work of a nonengineering nature, the proportion unemployed would have been larger by that amount. It is also obvious that by December 1934 it was primarily the increased engineering employment by the federal government that ameliorated employment conditions for these older engineers.

Among the engineers who entered the profession during the depression, certain outstanding shifts may be noted. In the first place employment opportunities increased from the end of 1932 to the end of 1934 among those who graduated in 1930–32. Slightly more than half the 16.6 per cent of this group who had been unemployed or on work relief in 1932 found employment by 1934. Furthermore, they had found nonrelief engineering employment. There was no change in the proportion engaged in nonengineering work. The gain was almost equally divided between private employment and public employment. Fewer engineers were teaching or engaged in consulting work. The increase in employment by private firms, however, absorbed 5.3 per cent of all engineers in these classes. Similarly, there was a slight decline in the proportions employed by states and counties, but this was much more than offset by an expansion of federal engineering employment that absorbed an additional 5.0 per cent of the total number.

A comparison of the distributions of employment of 1933–34 graduates in 1934 may be made with employment in 1932 of those graduating in 1930–32 to show how conditions had changed as regards the most recent graduates. This comparison is not perfect because in the one case 3 graduating classes are considered and in the other only 2.

From 1932 to 1934 there was almost no change in the proportions of the most recent graduates who found engineering employment. Unemployment was slightly lower, primarily because 3.1 per cent more 1933–34 graduates

were in nonengineering work in 1934 than had been true of 1930–32 graduates in 1932.

While recent graduates in 1934 had as much opportunity for engineering employment as a comparable group had had in 1932, this was because of an expansion in private employment and particularly employment with private firms. In 1934, 4.9 per cent more of the 1933–34 graduates were employed by private firms and 1.8 per cent fewer were in teaching or acting as independent consultants than had been the case in 1932 among 1930–32 graduates.

The total opportunities for public employment were less in 1934 among the most recent graduates than had been true of a similar group in 1932. The federal government did employ 1.6 per cent more of them in 1934, but this could not offset the decline of employment opportunities with states, counties, and municipal authorities from 12.5 per cent of the 1930–32 graduates in 1932 to 7.4 per cent of the 1933–34 graduates in 1934.

The preceding discussion has shown the barriers that the depression threw in the way of newcomers to the profession. It now remains to examine the effect that even the partial absorption of the newcomers had upon the employment opportunities of the older engineers.

This interrelationship is best studied in 2 different phases of the employment cycle: (1) during a period of an absolute contraction in job opportunities, and (2) during a period of expansion. These conditions are represented, respectively, by the 2 periods 1929–32 and 1932–34. In the first, it may be recalled that total engineering employment for the adjusted sample decreased from 29,051 to 27,787. In the second period, it grew to 30,299 by the end of 1934. The adjusted data are presented in table VII.

By December 1932 employment with private firms had declined by 15.5 per cent. The loss of employment by private firms among older engineers was even greater than this. In absolute numbers, 4,530 were put out of work. Despite the enormous drop, even at this period of the depression no less than 1,522 of those engineers who entered the profession in the period 1930–32 found opportunities for engineering employment with private companies. Thus, approximately $^2/_3$ of the loss of employment among older engineers was due to a decrease in the total amount of private employment available; $^1/_3$ of it was due to the fact that older engineers were unable or unwilling to take employment which newcomers to the profession secured.

By the end of the second period, private-firm employment increased by 1,118 or 6.8 per cent, over that reported for December 1932. Here again there was a repetition of the condition noted for the period 1929–32. Even in this period there was a reduction in employment with private companies, affecting 472 of the older engineers. In passing, it should be noted that this decrease did not affect those who entered the profession from 1925 to 1929, but was confined to those who graduated prior to 1925. Essentially, therefore, those who entered the profession in the years 1930–34 secured all the net new employment that developed with private firms and also continued to find some openings at the expense of older engineers. Over the entire 5-year period 1930–34, although 5,002 older engineers suffered loss of employment with private firms, no less than 3,112 of the new entrants found engineering work.

A considerable number of the younger engineers were able to enter engineering activity with private firms, apparently at the expense of the older engineers. But this was probably not the result of a direct displacement on a particular job of any one group of older by younger engineers. The explanation is to be found in the relative ease with which a younger engineer found a new job as compared with an older one who had lost a job. The older engineer inevitably had a greater concern with the suitability of the employment and remuneration offered than had the man without an established position. Furthermore, the enormous influx of new entrants to the profession caused keen competition for all kinds of engineering employment, which, under the then prevailing conditions, were very definitely not of the type to suit the older engineers and which further depressed salary rates for the more elementary types of work.

The changes effected by the depression upon the engineers in the employ of state and county, and municipal and other public authorities, are in striking contrast to those which occurred among older engineers in private firms. Between 1929 and 1932 there was a 14.7 per cent increase over the total of 4,948 who were engaged by state and county and municipal and other public authorities in 1929. The increase was shared by both the older engineers and new entrants. The number of the former increased by 174, the latter by 555. By December 1934 the total so employed had increased to 5,804. But in this second period only the new entrants increased—by 228—whereas the older engineers decreased by 101, a net change in favor of the younger engineers of 127. It may be noted, however, that 73 of the net number of older engineers who entered these fields of employment by December 1932 were retained.

Clearly, the older engineers in the employ of these particular public authorities held on to their jobs tenaciously

**Table VII—Increases or Decreases in Employment of Older Engineers and Younger Engineers, by Class of Employment, 1929 to 1934**

(Figures adjusted as explained on page 525)

| Employment Class | Total Number Reporting | | | Increase or Decrease | | | |
|---|---|---|---|---|---|---|---|
| | | | | 1929 to 1932 | | 1932 to 1934 | |
| | 1929 | 1932 | 1934 | Older[a] Engineers | New[b] Entrants | Older[a] Engineers | New[c] Entrants |
| All classes | 27,988 | 28,694 | 32,735 | −2,862 | +3,568 | +668 | +3,373 |
| Private firm | 19,424 | 16,416 | 17,534 | −4,530 | +1,522 | −472 | +1,590 |
| State, county, and municipal government and other public authority | 4,948 | 5,677 | 5,804 | +174 | +555 | −101 | +228 |
| Federal government | 1,647 | 2,312 | 3,872 | +416 | +249 | +1,086 | +474 |
| Nonengineering | 1,969 | 4,289 | 5,525 | +1,078 | +1,242 | +155 | +1,081 |

a. Includes all engineers who were professionally active prior to 1930.
b. Includes all engineers who entered the profession in the years 1930 to 1932 inclusive.
c. Includes all engineers who entered the profession in the years 1933 and 1934, and also came in during this period from classes of 1930–32.

during the depression. The most marked shift as regards this type of employment was the decrease in the proportion of younger engineers who found work with such authorities. The decrease in the number of older engineers so employed by December 1934 may not have been due wholly to the increase of new entrants. Many of the older engineers may have found this employment an easier passage to federal employment, which, in the period 1932–34, required a large number of engineers as administrators and supervisors for the work-relief programs then under way. These positions may have been more in keeping with the older engineers' previous training and experience.

This last statement is substantiated by the changes which occurred in federal employment. In both periods the absolute number of older engineers who found this kind of work was greater than that for younger engineers. Thus, by the end of December 1932, federal employment increased 40.0 per cent from 1,647 to 2,312. This increase covered 665 engineers, which comprised 62.5 per cent older and only 37.5 per cent younger engineers. In the second period, the total number in the employ of the federal government increased from 2,312 to 3,872, an increase over 1932 of 68.0 per cent. The absolute increase was divided in the ratio of 70.0 per cent of the older to 30.0 per cent of the younger engineers. Over the 5-year period, the respective total absolute increases were 1,502 and 723. It was also be noted that, while in the period 1929–32 the rate of increase of older to younger engineers was 2 to 1, it increased $2^1/_2$ times for the older by the end of December 1934. From this marked preference for older engineers in federal government employment, it can only be assumed that the nature of the work did more closely meet their criteria for re-employment, at least for such opportunities as were available.

Over the 5-year period the younger engineers also had a decided advantage in securing nonengineering employment. Thus, while 1,233 older engineers were so engaged, 2,323 of the younger were able to find work of a nonengineering nature. This is made clear from an analysis of age groups of the relative increase in the number of those engaged in nonengineering to the total number displaced from engineering. The ratio of those who secured nonengineering work decreased progressively with age. Thus, 15 per cent of the displaced engineers who were over 52 years old in 1934 secured nonengineering work. The remainder were unemployed. Among those who were 28 to 32 years of age, 52 per cent secured nonengineering employment. But even the ratio of 52 for engineers entering the profession in 1925–29 was very much less than either of those for the 1930–32 and the 1933–34 engineers; for the former this was 78 and for the latter 69.

This analysis indicates that, taking all factors into consideration, between 1930 and 1934 there was a substantial net loss of employment by the engineers active before 1930, and a considerable absorption in employment of newcomers to the profession. Some of this shift may have been due to direct displacement; some of it to the securing of newly created positions by the younger men. There is no evidence bearing on the proportions affected by these 2 tendencies.

# Unemployment as of February 1937

## Reported by National Industrial Conference Board

THE TOTAL number of unemployed workers in February 1937 was 8,914,000, according to estimates of the National Industrial Conference Board made public April 19, 1937. This is a decrease of 203,000 (2.2 per cent) from the revised estimate for January 1937 and a decrease of 1,865,000 (17.3 per cent) from February 1936.

Employment in all types of enterprise in the United States in February 1937 as reported was 43,881,000 workers, an increase of 252,000 workers (0.6 per cent) over January 1937 and 2,457,000 (5.9 per cent) over February 1936. The number of workers employed in February 1937 was reported as 3,395,000 (7.2 per cent) below the average of 47,276,000 workers employed in 1929.

From January 1937 to February 1937 the increases reported in employment, by industrial groups, were: manufacturing, 233,000; service, 49,000; transportation, 29,000; construction, 20,000; trade, distribution and finance, 17,000; mining, 6,000; and public utilities, 1,000. The only decrease, amounting to 113,000, was found in agriculture.

Compared with February 1936, according to the report, employment in February 1937 increased 13.4 per cent in manufacturing; 7.7 per cent in trade, distribution and finance; 7.5 per cent in transportation; 5.7 per cent in the public utilities; 5.4 per cent in mining; 5.2 per cent in the service industries; 1.7 per cent in forestry and fishing; and 0.9 per cent in agriculture. The only decrease, amounting to 13.2 per cent, was found in construction.

The accompanying table prepared by the Conference Board shows the number of employed workers in the various industrial groups in 1929, February 1936, January 1937, and February 1937.

### Number of Employed Workers (in Thousands) Reported by National Industrial Conference Board

| Group Division | 1929 Average | February* 1936 | January* 1937 | February** 1937 |
|---|---|---|---|---|
| Agriculture | 10,650 | 10,335 | 10,542 | 10,429 |
| Forestry and fishing | 268 | 172 | 175 | 175 |
| Industry | | | | |
| Mining | 1,087 | 725 | 758 | 764 |
| Manufacturing | 11,073 | 9,518 | 10,565 | 10,798 |
| Construction, public and private | 2,841 | 1,387 | 1,184 | 1,204 |
| Transportation | 2,416 | 1,754 | 1,857 | 1,886 |
| Public utilities | 1,167 | 888 | 938 | 939 |
| Trade, distribution and finance | 7,323 | 6,751 | 7,251 | 7,268 |
| Service industries | 9,070 | 8,620 | 9,016 | 9,065 |
| Misc. industries and services | 1,381 | 1,273 | 1,345 | 1,352 |
| Total employed | 47,276 | 41,424 | 43,629 | 43,881 |

* Revised. ** Preliminary.

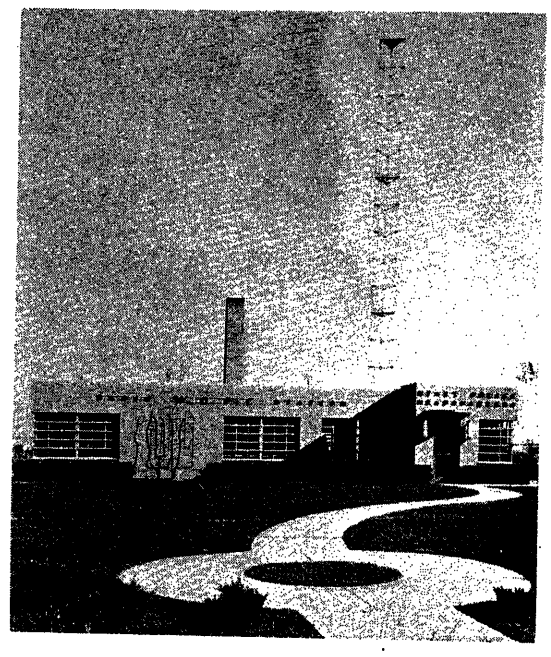
# Police Radio Communication

By EDWIN LEE WHITE  E. C. DENSTAEDT


## Synopsis

The history and development of police radiocommunication is discussed and an outline given of the federal regulations under which this type of service is rendered together with reasons therefor. The problems arising in the selection of equipment and during the installation and operation of police radio systems are discussed. The methods of operation of the various classes of police radio services are described. The various uses of radio covered by this paper are:

1. By municipalities for one-way communication to mobile units and remote police stations
2. By municipalities for 2-way communication with mobile units
3. By states in the general dispatching of state police units
4. By states and municipalities for the ratiotelegraphic exchange of police information
5. By harbor police in connection with the dispatching of harbor police boats and general policing of shipping
6. By states for emergency radiotelegraphic use in the event of interruption of the wire teletype network

Illinois state police radio station, Chicago

## History and Regulation

A GENERAL study of the history of police communication systems indicates that the police of the United States have always been progressive in adapting new communication facilities to police uses. As new systems were developed they were pressed into police service to assist in the never-ending battle with crime. We thus find the wire telegraph used by New York City Police Department in 1847. In 1878 just 2 years after its invention by Dr. Bell, the Chicago Police Department installed a police telephone system. Emergency police dispatching systems with telephones for communication were in use before the automobile had replaced the bicycle and horse as a means of transportation.

Probably the first use made by any police department of radio was on June 2, 1916, when a private coastal station was established by the New York Police Department, using the call letters KUVS (now WPY) for communication with harbor police boats and for the general policing of shipping in the New York harbor. This station is still in existence, has been modernized from time to time, and is rendering a useful service.

In 1923 the State of Pennsylvania established a system of radiotelegraph stations to provide a means of communication between important police headquarters. With the growth of wire teletype communication the necessity of these stations has been greatly reduced and at the present time they are used primarily in emergencies when wire communications have been disrupted.

As far as is known the first use of radio in the manner in which we are now familiar was by the City of Detroit. Experiments were initiated in this city in 1920 when a radio receiver was installed in a police car and tuned to the broadcast station of the *Detroit News*, the only broadcast station in the city at that time and one of the first in the country. The result warranted further investigation and in 1921 a station was established using the appropriate call KOP.

The early Detroit experiments although partially successful, did not immediately result in a radio equipped police department. The cumbersome receivers and fragile tubes available at the time resulted in unreliability and a high cost of maintenance. However, in 1924, a regular broadcast of stolen automobiles and crime reports was inaugurated, primarily for the use of outlying police departments in the Detroit area.

During the next few years sporadic tests and experiments were made along various lines with a view to determining the most suitable manner of fitting radio into police department needs. For instance, about 1924 the City of New York conducted experiments and purchased some equipment for station house use with a view to establishing a system which would permit, by the use of a suitably designed dial call system, the transmission of a message to all stations simultaneously, to an individual receiver, or to a selected group of receivers.

The early experiments were conducted on the band of

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frequencies now assigned to the broadcast service. With the growth of broadcasting it became evident that it would be necessary for a separate band of frequencies to be assigned for police activities. This situation resulted in the allocation of 8 frequencies between 1,700 and 2,500 kilocycles by the Federal Radio Commission, which were set aside for use by state and municipal police departments without distinction.

The development of the screen-grid tube and discovery of methods of reducing ignition interference simplified technical difficulties and in 1928 the first successful radio patrol was inaugurated. The remarkable success of this patrol caused the system to spread rapidly. Several cities added this equipment in 1929 and 1930. In 1931 the State of Michigan installed a 5-kw transmitter at Lansing to serve those cars of the Michigan State Police which operated over the lower Michigan peninsula.

At the time the Federal Radio Commission made its first allocation of frequencies it did not appear that specific provision of radio for state police would be a particularly serious problem. However, it quickly became apparent that the allocation of frequencies to municipalities must of necessity be carefully considered and the issuance of authorizations closely co-ordinated if radio facilities were to be made available to all municipalities throughout the country.

It was determined that any plan of allocation must meet the following conditions:

1. It must provide for the issuance of authorizations to any municipality regardless of its location within the United States, or the status with respect to radio of adjacent municipalities.

2. It must be capable of administration in congested areas, such as Philadelphia, Chicago, and New York as well as in sparsely settled districts such as Nevada.

3. Considering the number of frequencies available it must provide the maximum service with the minimum of interference.

In the consideration of the establishment of a system of allocation of frequencies the following principles were used as a basis:

1. It is not necessary that the police cars receive a high quality of service, as long as signals are sufficiently intelligible through interference to ensure accurate reception they are satisfactory.

2. There is a higher incidence of crime in densely populated areas than in sparsely settled districts. Consequently, more messages per thousand population would require transmission in large cities than in rural areas.

3. The poor transmission conditions of the congested areas and the level of electrical noise in such areas require more watts per mile than in the rural districts.

Considering these factors and after much study the United States was divided into areas, the size of the area depending upon the population to be served as well as the density of population. For instance, for all practical purposes the cities of New York and Chicago embody single frequency allocation areas while the whole state of Nevada likewise embodies a single allocation area. Under this plan all cities within a single area are required to co-operate in the use of the area frequency. The power is in general limited by the total population to be served. In order to limit interarea interference a maximum power limitation of 500 watts night, 1,000 watts day is placed on these stations.

It is desirable for adjacent municipalities to pool their radio activities. Provision was, therefore, made for the establishment of a station to serve a number of municipalities and the authorization of power necessary to serve the total area, provided that an agreement was submitted with the application for increased power showing the establishment of a metropolitan area type of system.

Referring again to the frequency-assignment problem, in 1933 as a result of a regional international conference held in Mexico City, frequencies were made available for police use by international agreement. At this time a general readjustment of municipal police area boundaries was made and in addition provision was made for the establishment of state police radio stations. A specific frequency was allocated for the use of the state police of each of the 48 states without reference as to whether the state was at the moment contemplating either the establishment of a state police or of a state police radio system.

Referring to figure 1, which gives the present allocation of frequencies to states, you will note that on an average each frequency is shared among 4 states. The frequencies allocated by the Mexico City conference have been, by agreement with Canada, further allocated as among the United States and adjacent nations. The allocation plan shown in this figure gives due weight to this situation and it is possible for Canada, Mexico, Cuba, and other countries adjacent to the United States to establish police radio stations in the recognized bands for such service and to receive the same quality of service as is rendered by these stations as established in the United States.

Figure 2 shows the existing plan of allocation of frequencies to municipal police stations. As in the case of the state police service shown in figure 1, the allocation shown in this figure also makes provision for the establishment of police stations in foreign countries.

Perhaps the most important effect of the use of radio has been in the growth of a co-operative feeling by the various police agencies of the nation. Possibly because of the necessity for co-operation in the use of radio frequencies a general feeling of co-operation has grown until at present every police officer is willing to give and anxious to receive all possible information which may be available with regard to crime in any adjacent locality.

In line with this co-operative feeling a need was felt for point-to-point communication between police departments. As a result many cities began exchanging communication at night using facilities allocated primarily for communication with mobile units. The service was found to be valuable and resulted in the rapid solution of many crimes which might otherwise have gone unsolved or have had the solution delayed for an extended period.

Approximately 2 years ago the organization "Associated Police Communication Officers" was established and practically the first action of this organization was to recommend to the Commission that steps be taken leading to the establishment of a police radiotelegraph communication system designed to meet the need of police departments for a means of exchanging information. After a

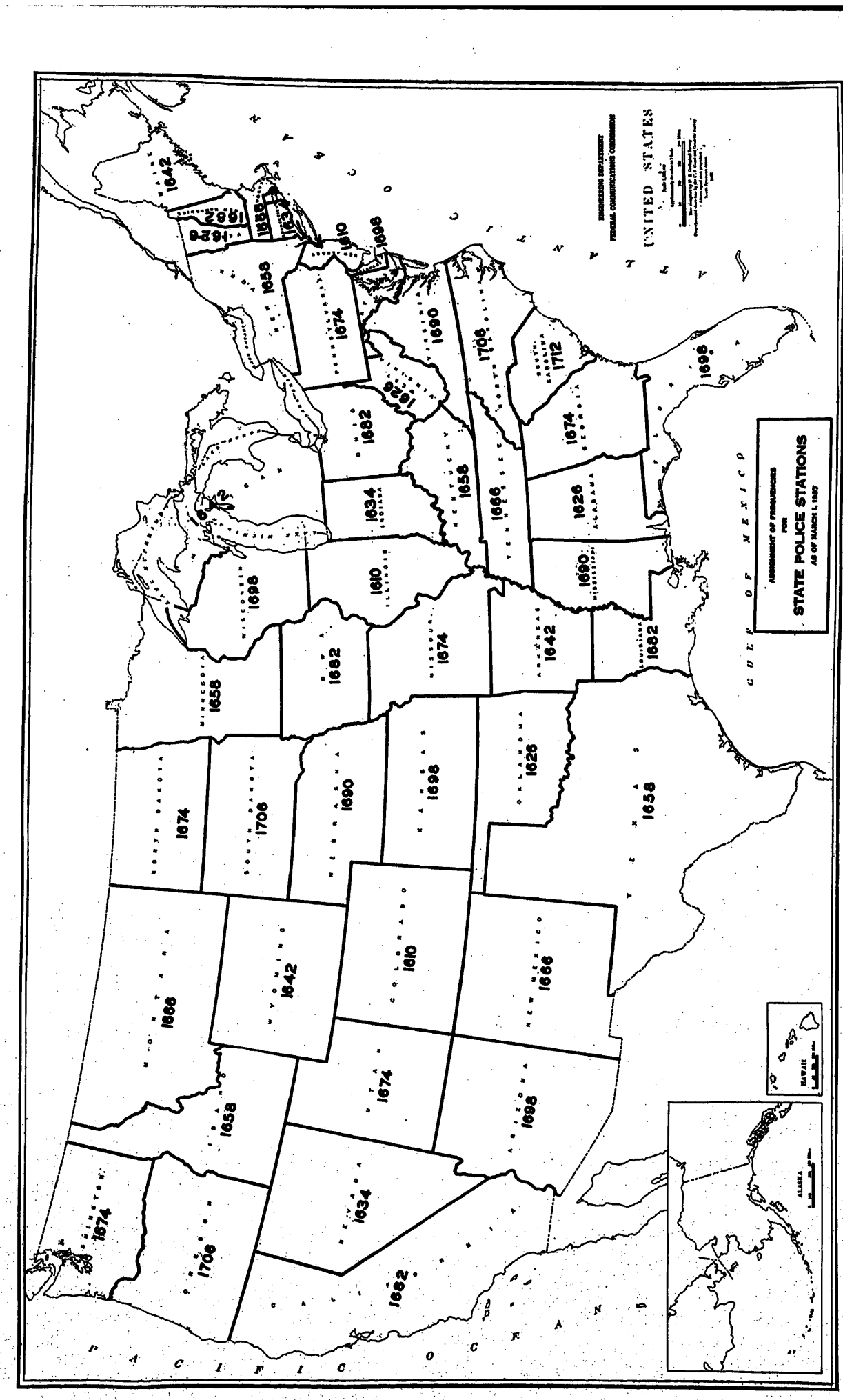



Fig. 1. State police frequency allocation plan as of March 1, 1937

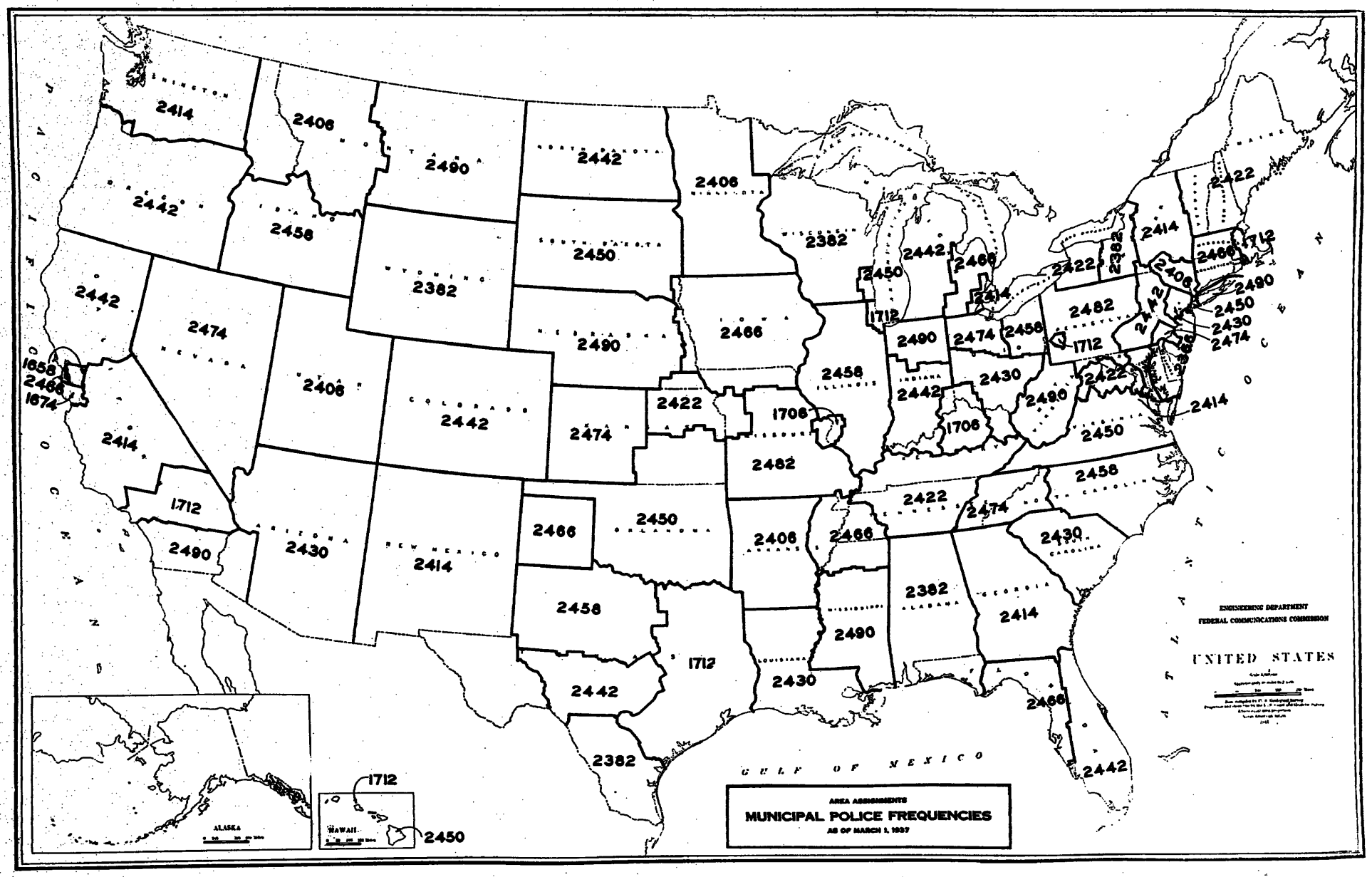



Fig. 2. Municipal police frequency allocation plan as of March 1, 1937

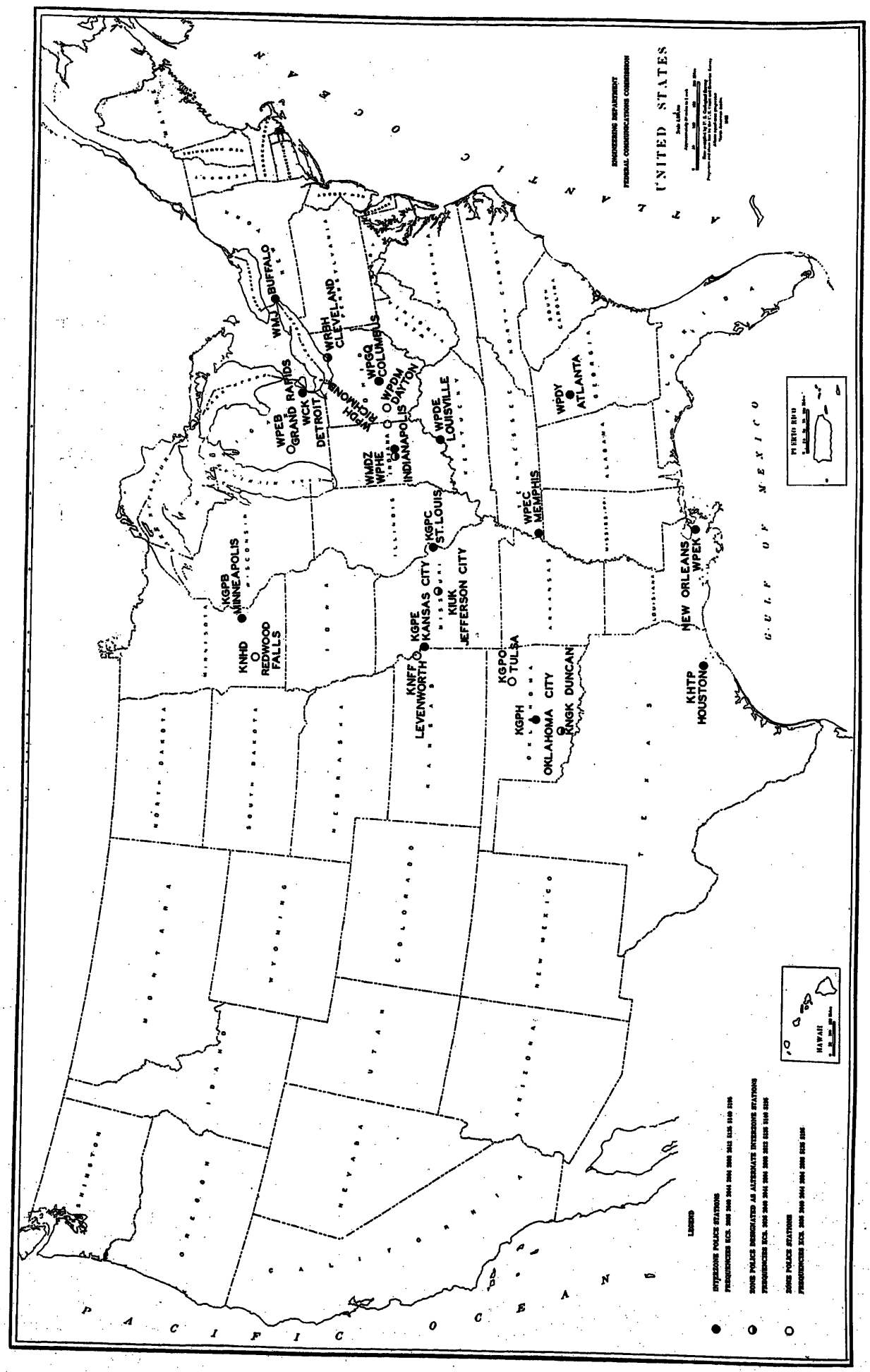
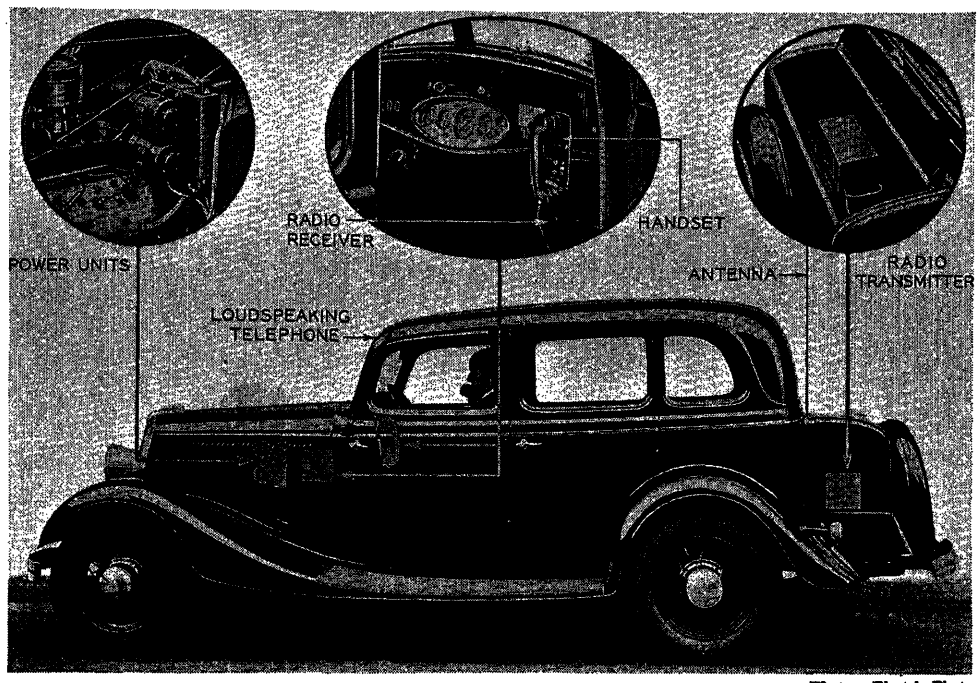



Fig. 3. Stations authorized in the intercity radiotelegraph system as of March 1, 1937

**An automobile equipped for 2-way police radio communication**

The system is operated on ultra-high-frequency channels. The transmitter weighs 20 pounds, has a power output of 5 watts, and its frequency is crystal controlled. To talk from the car, the patrolman merely lifts the telephone from the instrument board and the first sound of his voice puts the car's transmitter on the air. It switches off automatically the instant he ceases talking. The transmitter uses 4 pentodes; the receiver is a 6-tube heterodyne




Western Electric Photo

co-operative study in which not only the Communications Commission but also the police, the Army, and the Navy participated, a system has been established and is now in operation. It is based primarily upon the type of communication system employed by the military services. The same general procedure is used and the same type of control of communication is required.

Under this system the United States is divided into zones, each of which is under the jurisdiction, as far as the use of radio facilities by zone police stations is concerned, of a zone control station. In general, under the supervision of the zone control station, municipalities within the zone are permitted to exchange messages freely with each other. However, messages from zone to zone must be routed through the zone control stations involved for final dispatch. Figure 3 shows the extent to which this system had grown on March 1, 1937. A number of stations have been added since this illustration was prepared.

The Commission will continue its policy of co-operation with the using service in order that modifications may be made from time to time to best fit this new instrument to the hands of police officers.

A few years ago the frequencies above 30,000 kilocycles were deemed to be practically useless. As a result of the activity of amateurs in the band between 56,000 and 60,000 kilocycles it was demonstrated that these frequencies could be quite useful for many types of local communication. The Commission then received requests from certain police organizations for authority to establish stations for use by their police departments on frequencies in or adjacent to the amateur band. After considerable study and consultation with those interested and well informed with regard to the propagation characteristics of the frequencies above 30,000 kilocycles, the Commission authorized 4 frequencies lying between 30 and 40 megacycles which might be licensed temporarily to general experimental stations which were to be operated as municipal police stations. Although licensed experimentally, from the point of view of the police officer in the car these stations were not experimental since they were used for the regular dispatch of police officers in the same manner as if a regular license had been granted. They might perhaps be considered as units in a program of experimental research conducted by the Commission to determine the frequency in these bands best suited to police departments and to determine a number of other engineering questions such as the total number of frequencies necessary to serve the police, the mileage separation which must be maintained between assignments of identical frequencies, and the frequency separation which must be maintained between adjacent channels.

On the frequencies assigned to municipal police stations the establishment of 2-way communication between the police officer in his car and police headquarters has always been prohibited for various reasons, some of which are technical. However, the use of frequencies above 30,000 kilocycles offered an opportunity for the establishment of a 2-way communication system. Although initial installations on these high frequencies were identical in all respects to those on frequencies used by municipal police stations, very quickly a number of municipalities began the experimental use of 2-way police communication. The first authorization issued by the Commission for 2-way police radiocommunication was to the city of Bayonne, New Jersey, on December 22, 1932. On March 1, 1937, 226 cities were operating 1,367 mobile police transmitters providing for such 2-way communication. Of this number of cities 22 made new installations after January 1, 1937.

The experimental program of the Commission on frequencies above 30,000 kilocycles has practically completed one of its phases. On June 15, 1936, the Commission held an informal engineering conference at which time the needs of all the various services were discussed with particular

respect to their needs in the band of frequencies above 30,000 kilocycles. As a result of this hearing allocation plans have been studied and in the near future routine commercial licenses will be issued to various stations to replace experimental licenses outstanding.

## Installations and Equipment of Municipal Police Systems

The installation of police radio equipment in a city is essentially a radio-engineering problem but it is unusual for it to be handled upon a strictly theoretical basis, a compromise generally being made between the ideal and the most economical arrangement. A preliminary survey usually is made to determine if present city owned property or buildings are in a favorable position for a transmitter location and also contain the necessary connections to the police telephone system. Since the average police department has a number of precinct stations, all of course connected into the police wire system, it is generally possible to pick out a building that is in the proper geographical position with respect to the city boundaries and also not in too unfavorable a transmitting location. In 4 cities it has been found necessary to use more than one transmitting station to give adequate coverage. In those cases the transmitting locations cannot be decided upon by considerations of the territory each is to serve alone but also must be considered with respect to one another as well.

In some cases cities have been able to gain some of the advantages of an open location by erecting the transmitting station in a park within a few miles of the district in which a heavy field is desirable. In other cases transmitting stations have been erected in residential sections composed mainly of small homes and fairly clear of large buildings.

In the majority of the early police radio installations the equipment was of composite manufacture. At present, however, radio manufacturers are offering equipment that fits this field and the average installation today uses commercial equipment.

Police radiotelephone transmitters are in general designed for good speech reproduction, but do not need the high standards of fidelity that are built into modern broadcast transmitters. The relay and switching systems must be very sturdy, however, since some of these transmitters are turned on and off over 1,000 times in 24 hours. Standby voltages must be maintained upon the filaments and if rotating equipment is used it must run continuously, it being desirable to have those transmitters come on the air with a delay of not more than one second.

Since the transmitters are used primarily for emergency transmissions, delay in a message becomes serious and it is necessary rapidly to repair the transmitter. To avoid delay a number of cities have installed standby equipment.

The usual troubles encountered are tube, relay, or control circuit failures. Regular inspection and maintenance can reduce the relay and control circuit failures to a minimum.

Fixed receivers at stations offer no particular problems in municipal installations. Antinoise-type antennas are often necessary because of the electrical disturbances originating from call box and teletype circuits in the precinct stations. A simple doublet-type antenna with a twisted pair lead-in is usually satisfactory in such installations.

Automatic volume control may or may not be an advantage. The particular location at which the receiver is to be placed should be studied with respect to this factor. If the station is in an area having a low field strength it may be necessary to use automatic volume control in order to insure reception during periods of low signal. However, in such circumstances a carrier operated antinoise device should be embodied in the receiver in order that the occupants of the station house may not be annoyed by atmospherics and other forms of interference during the time no signal is being received.

The important thing in station receivers is to obtain equipment designed for continuous service. Most cities are using receivers designed for the job and are experiencing little trouble.

The mobile-unit receivers are, however, a different story and practically every department can furnish many woeful tales about their experiences. Troubles with mobile installations are divided between those caused by car ignition, battery, or antenna and those in the receiver itself.

Troubles in mobile police radio receivers are much more numerous than those experienced in broadcast receivers for automobiles. Police re-

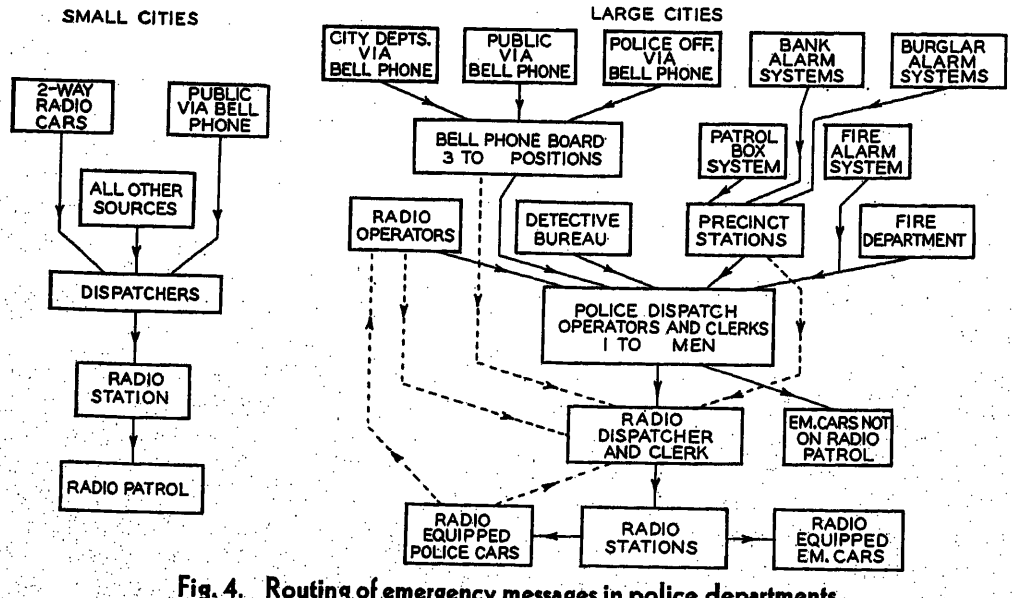



**Fig. 4. Routing of emergency messages in police departments**

ceivers operate 24 hours a day and are mounted in cars that will drive 50,000 to 75,000 miles in a year. Several attempts to modify standard broadcast auto receivers so as to be used in police cars have resulted in disappointment and today the great majority of police departments gladly pay the increased cost necessary to obtain receivers manufactured for police service.

Tube life in police mobile receiver service is now very good, particularly when the cars are equipped with voltage regulated generators.

A life of 1,000 hours is often used as a standard for tubes and vibrating equipment in radio work. While this may represent a life of over one year in ordinary passenger car service, it only represents a life of 6 weeks in police service.

The great majority of police receivers in service use dynamotors for *B* supply, a few using vibrating rectifiers. In general better life has been experienced from the dynamotor and it, in spite of its greater cost, is in greater use.

The detuning or drifting of police receivers, once the greatest single source of trouble, has been fairly well taken care of as far as municipal police work is concerned. State police organizations, however, needing greater sensitivity and selectivity in their receivers, are still experiencing

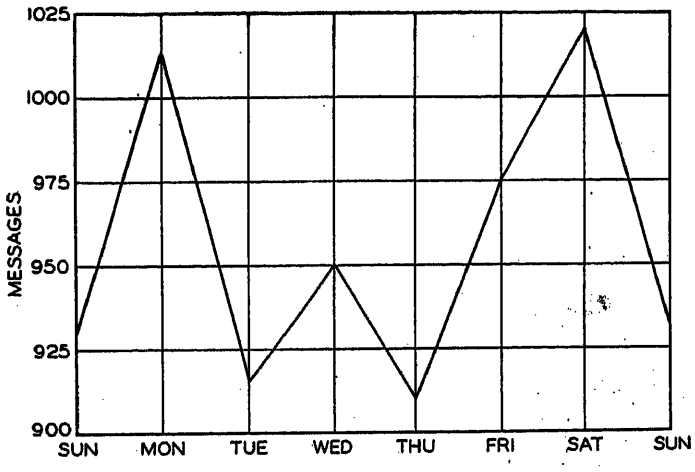



**Fig. 5. Average daily load chart of a representative municipal police radio station**

trouble. In some cases recourse has been made to the use of crystal-controlled receiving equipment.

The average police receiver draws from 4 to 7 amperes from the car storage battery. This drain when continuous and coupled with the fact that police cars cruise slowly would result in discharged car batteries unless special provision is made. Standard generator and battery equipment on automobiles has proved to be inadequate for police radio service and special voltage regulated generators are generally installed on cars for municipal police patrol.

The generator used should be able to balance the radio and ignition load on the car battery at the slowest cruising speed of the cars, usually about the slowest speed at which the engine runs evenly. This varies from 6 to 10 miles an hour. The generators should peak at a speed between 15 and 20 miles an hour and should have a peak current of

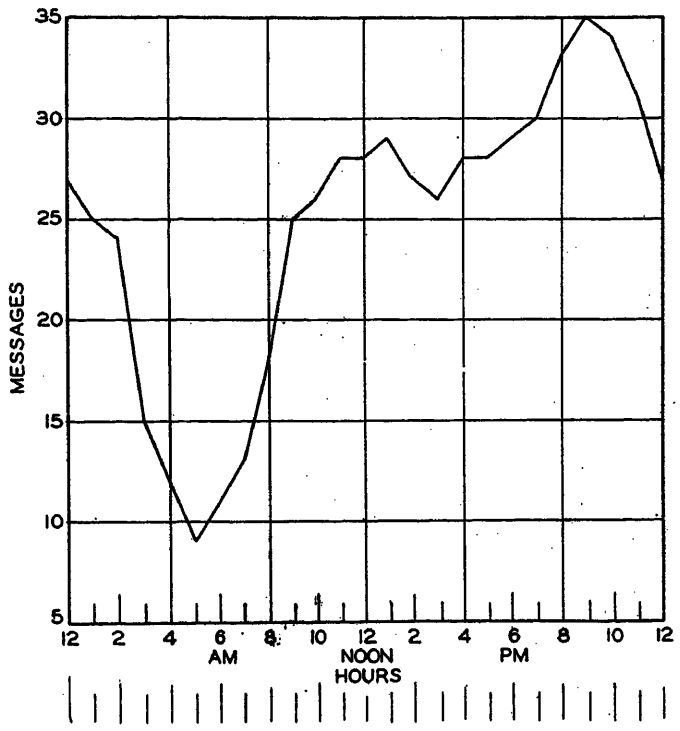



**Fig. 6. Average hourly load chart of a representative municipal police radio station**

from 18 to 25 amperes. They must be equipped with a voltage regulator. Such generators are now commercially available.

It is also considered desirable to advance the battery size in municipal patrol cars in order to carry over periods when it is necessary to leave the radio on but the motor off. Such cases happen quite frequently when car crews are "planted" to watch a car or house.

A screen antenna in the top of the car had proved to be the most satisfactory antenna for police radio work. However, with the advent of the steel top, police were forced to use various forms of undercar antennas, none of which are entirely satisfactory. A better antenna is provided by use of an insulated steel rod rising from the dash, either straight or curved back over the top. The rods, or "fish-poles," are flexible and no harm results from their hitting something.

The reduction of electrical noises set up by the ignition system is accomplished in much the same manner as is standard with broadcast receivers but, because of the higher frequencies used, it is a slightly harder job. Standard spark-plug resistors together with condensers on generators, gas, and oil gauges are used, bonding and shielding are carefully installed. If after an installation is made it is found that ignition noise remains at a high level, different things are tried until the noise is eliminated. As a general rule spark-plug resistors are kept as low in resistance as it is possible to use, since resistors of 25,000 ohms and up have caused some engine trouble.

Some police car receivers have a sensitivity control as well as an audio volume control to take care of the "carrier off" condition. If the sensitivity control is retarded sufficiently to reduce the electrical noise at points

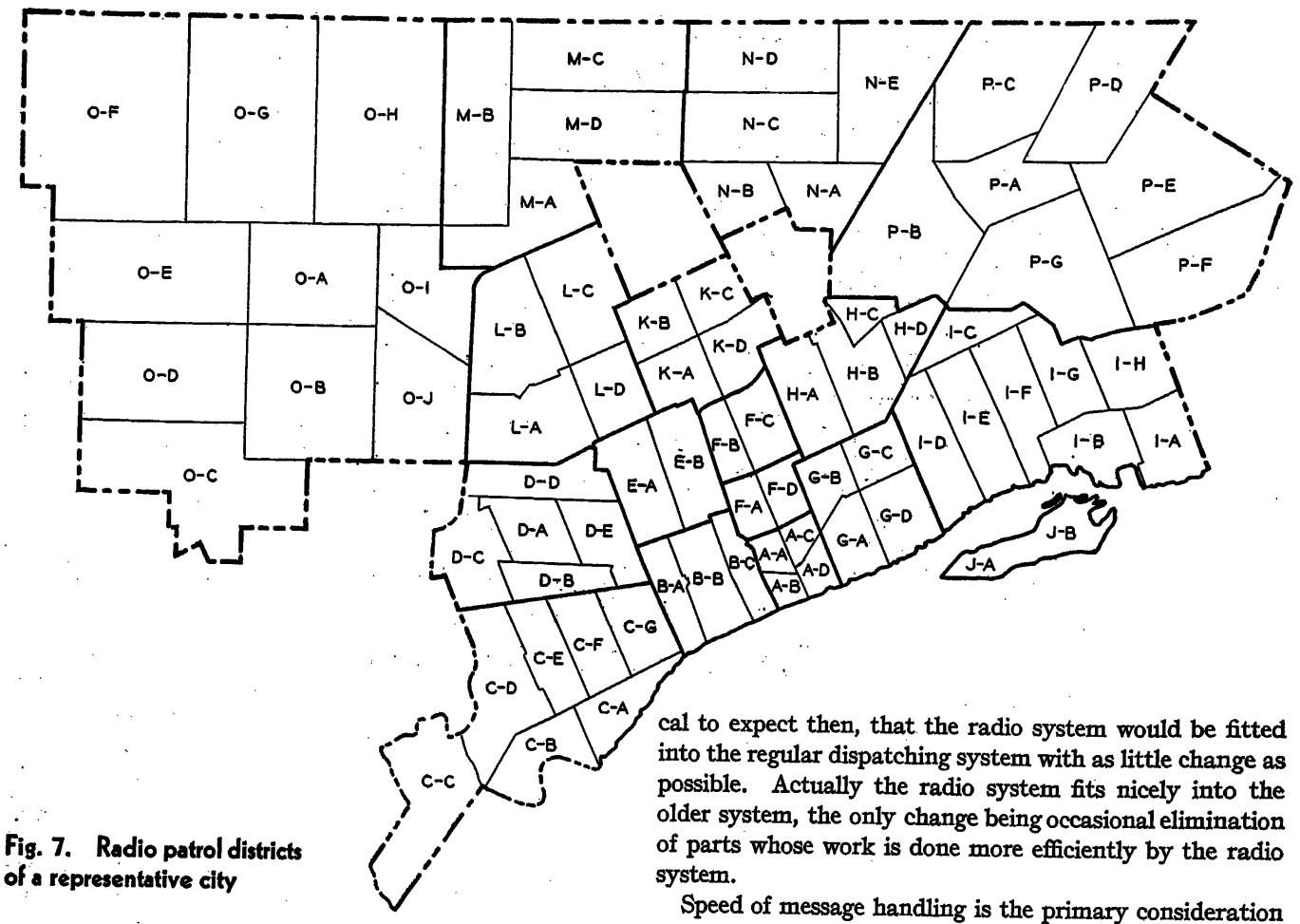



**Fig. 7. Radio patrol districts of a representative city**

in the city where electrical noise levels are high it may also automatically cut out the signal because of the relatively weak radio field from the police transmitter, a dangerous condition in police work. Antinoise circuits have aided in reducing the noise but at best police receivers in patrol cars on busy streets several miles from a transmitter, are rather noisy.

The crews of police cars shade into 2 general classes. One group who keeps the controls turned up and seem oblivious to the noise, the other who keeps the control retarded so much, that when street noises are high they have to turn up the volume to understand the broadcast. Observations indicate that this second group senses the presence of the transmitter carrier by the change of the background noises in the receiver, and, therefore, seldom miss any broadcast information due to the practice of carrying the receivers at low volume settings.

There are some types of men, usually of a nervous disposition, who should not be put on radio patrol cars. The combinations of noises, mental strain due to the presence of a receiver which at any moment may reproduce an order, and the lack of physical exercise have a bad effect on their health. In one of the larger cities the police medical division is at present quite concerned over the problem.

## Operation of Municipal Police Systems

The police radio system is simply a development and extension of previous communication systems. It is logical to expect then, that the radio system would be fitted into the regular dispatching system with as little change as possible. Actually the radio system fits nicely into the older system, the only change being occasional elimination of parts whose work is done more efficiently by the radio system.

Speed of message handling is the primary consideration involved, and of course, a system whereby the person wanting emergency police assistance could call directly to the policeman coming to his assistance would be the ideal method. Obviously this is impossible, yet in smaller towns only 2 intermediate persons are involved, one the telephone operator who makes the connection, second, the police dispatcher who sends the help, figure *4A*. In the larger cities this simple system, although just as desirable, becomes impossible because of the volume of the traffic. It becomes necessary to set up a system similar to *4B* which, while it may look complicated, is as simple as it is possible to arrange and still have a system that will operate smoothly and with rapidity during peak periods.

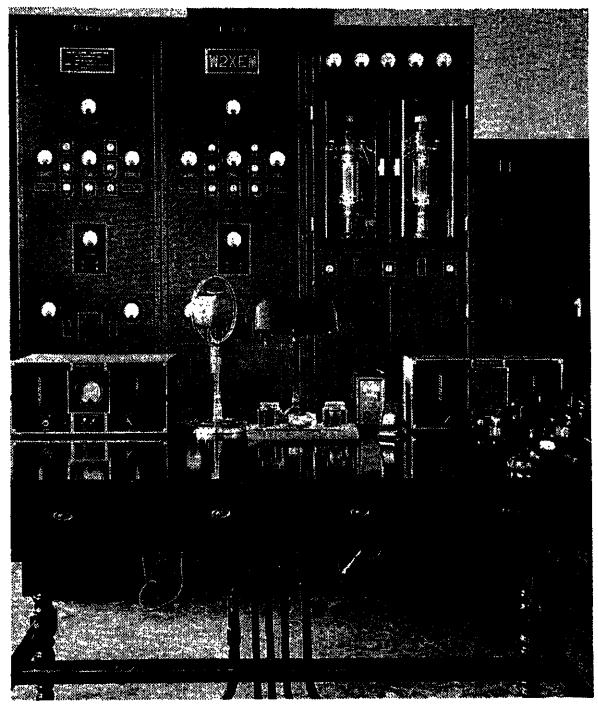
Figures 5 and 6 show the average load charts of a representative police radio station. Actually these average peaks are increased considerably upon such evenings as Hallowe'en, New Years Eve, etc.

The sources of police information of all natures are extremely numerous, however, the sources of information requiring emergency action are fewer in number. While the detective bureau is shown as a source of information in diagram *4B* the reference is to emergency cases only which are a small part of their activity.

By far the greatest number of emergency requests comes from the public over the telephone system. The incoming telephone switchboard in larger cities thus has to be used in multiple sections so as to allow any one of a number of operators to answer any incoming trunk line. In some cities all incoming calls come in on the one board, in New York, however, emergency calls and routine calls are seg-

regated by having the public call one telephone number when emergency service is desired, and another when making routine calls. Each board, of course, can handle emergency messages in cases where the public makes a mistake.

The switchboard operators handle all routine calls much as any telephone operator. They are trained, however, in proper handling of an emergency call and in how to get the most information from an excited person, and get it reliably. At best the information is none too accurate. The operators then pass this information along to the dispatchers who either broadcast the necessary order or in the largest cities pass it on to another man for broadcast.




**Transmitting equipment of the Newark, N. J., police radio system. Duplicate transmitters, one of which is a stand-by unit, are provided. The unit at the right is the power amplifier, which may be fed by either of the other sets**

The dispatcher's board besides receiving information from the general board may get information from several other points as noted in 4*B*. Bank alarm systems usually are terminated in precinct stations, sometimes in headquarters; fire-alarm systems also occasionally have a wire into the police department and policemen are dispatched simultaneously with fire equipment. Other sources of information include police, via the patrol-box system, precinct stations and substations, radio operators, and fire and other city departments.

It will be noted that the dispatcher has other facilities besides the radio patrol at his disposal. Patrol wagons and other emergency vehicles are kept at precinct stations and substations, and ambulances, pulmotors, etc., at other points. He decides as to what vehicle is to be used, dispatching it or passing the information to the person who makes the dispatch as the case may be.

The dotted lines on diagram 4*B* indicate routes taken by messages of 2 general types. First: routine unimportant traffic with which it is not desirable to load the dispatcher since the emergency dispatch is not involved; second: exceptionally important or "hot" information which must be transmitted without the slightest delay. Most systems are flexible enough to allow some deviation from regular routine in particularly important cases.

The majority of cities have centralized the dispatching authority into the dispatchers. These men and no others are responsible for the proper dispatch of policemen to the scene of a crime, fire, or disturbance. In some cities the dispatcher's word is absolute law in all precincts, and the commanding officer of a precinct cannot move a single emergency vehicle in his own precinct without permission of the dispatcher. This of course means that the dispatcher in addition to being a good police officer, must be familiar with the city, must know the territories patrolled by each car, and must have a continual accurate check upon the condition of each car. The dispatcher is often assisted by a clerk, while various check boards, maps, mechanical or electrical arrangements are used to keep track of the cars. The dispatcher must know where his cars are at all times, whether they are in or out of service, when they are on a run, and when they need radio or garage service. To the dispatcher and his assistants is delegated the job of keeping track of a large fleet of cars. This job is made harder by the fact that these cars are continually prowling about the city doing routine police work on their own initiative while waiting for emergency broadcasts or specific orders. The details involved in this position are considerable and a mistake may mean a missed run or possibly a lost life.

Messages broadcast by police radio stations fall into 4 general types:

1. Emergency dispatches: Orders to a particular car to proceed to the scene of a crime, fire, or disturbance. This is the most numerous and most important of the 4 types of messages
2. General broadcasts: Crime reports, stolen cars, missing person reports, descriptions of wanted persons, etc.
3. Station calls: Routine police work, orders to cars to call their stations, go for gasoline or repairs, take care of a detail or traffic, etc.
4. Intercity traffic: Messages of police nature transmitted to other police radio stations by radiophone

The police radio station exists primarily for broadcast of types 1 and 2. Type 3 is more or less routine and is handled if time permits, while type 4 is not handled at all by some cities. It is expected that police radiotelegraph will eventually handle most of this latter type of traffic.

An interesting point to note here is that because of the general unreliability of information coming from the public, very often a broadcast of type 1, sending a police car to the scene is made before a general broadcast of the crime (type 2). The actual descriptions, etc., are obtained by a policeman from the persons at the scene.

In municipal one-way systems the patrolmen, after having been sent on a run, call back over the police or city phone systems. The dispatcher or radio operator de-

pends entirely upon the car crew hearing the run and obeying instructions. If, however, the car crew does not report back in a specified time after the order is broadcast (from 5 to 30 minutes depending on the city), another car is dispatched.

No system is perfect and occasionally a run is missed. A follow-up is desirable on important runs, therefore, 2 or more radio cars are often sent. In some cities station cars are dispatched by telephone in addition to those dispatched by radio.

The efficiency of the radio equipment is attested by the fact that accidents, car failure, and mistakes made by the operating personnel each result in as high a percentage of runs missed as does failure of radio. Radio failure as a cause of missing runs is of course eliminated by the use of a 2-way system and most larger cities are now experimenting with 2-way equipment. In a 2-way system if the dispatcher does not get an immediate "OK" from the car crew dispatched, he dispatches another car.

As the radio system follows the plan of the precinct signal systems, so are the territories of the radio patrol cars influenced by the precinct boundaries. Each precinct is broken up into patrol territories and a radio patrol car assigned to each. In addition there may be other cars, usually better equipped and carrying a larger crew, who patrol through the whole precinct or through several territories and still other crews and cars that work more or less free lance or on special police problems. Each territory and car are assigned a number and this number alone is used in dispatching. Often individuals are assigned numbers to permit their being called without mention of names.

Figure 7 is a representative layout of the city of Detroit (neither correctly numbered nor accurate) that shows how cars may be arranged in a large city. In this case the actual car numbers are replaced by letters that have no significance.

The patrol districts are chosen systematically with the following factors in mind:

1. Density of population
2. The crime record of the territory under consideration
3. The traffic problem, in which account is taken of the density of traffic, of possible congested points, and of impediments such as railroads, canals, etc. The traffic problem affects the speed of police cars, and therefore, the time required to respond to a call
4. Other police protection. (Such as detectives, traffic officers, etc., in the business sections)
5. Records of the radio station as to the frequency and number of runs originating in the territory considered

By this mehod the available cars are placed where they will result in the most effective patrol.

## Two-Way Police Radio Systems

It seems unnecessary to justify the additional expense of the 2-way system, yet a number of departments have been hampered in obtaining funds for installation of 2-way equipment because of the fact that they have a one-way system in successful operation.



**A view of the equipment at station WRDP, of the Michigan state police, located at Paw Paw**

Certain types of crimes can be solved in many cases if rapid efficient communication can be maintained between the police dispatcher, or radio operator and a crew on the scene. This refers only in part to continuous pursuits, where other cars can be used to block off escape. These are spectacular and have attracted press notice but more important are the cases where information immediately furnished by the car crew on the scene results in a broadcast and a capture by another car crew before a clean getaway can be made. In hit-and-run cases it is often possible to obtain a hit-and-run license number from a crew on the scene, check registration and have another car waiting at the driver's home when he gets there. Since only a few minutes are available, by eliminating the time required for the patrolman to get to a phone and get a connection to the dispatcher or radio operator, 2-way often means the difference between success and failure. Seconds count in police work.

Two-way radio makes the patrol force more efficient. The efficiency of a police department depends considerably upon attention to details. Routine and uninteresting though they may be, they are important. As an example, a patrol car crew passes a parked car, something about it makes them slightly suspicious, if the patrol car is equipped with 2-way communication, in such a case they would call for a check on the license and sometimes find their suspicions are correct. Only once in 100 times possibly, but that once may be extremely important.

Consider now, that the cost of a 2-way system is but a fraction of the yearly salary cost of the patrolmen assigned to radio cars and we see why 2-way growth has been rapid.

Two-way radio systems divide into 2 types, one using ultrahigh frequencies exclusively, the other using a medium high-frequency station transmitter. Cities which are making an initial installation of a complete system now usually install the first type. The second type exists in those cases where cities already equipped with a one-way system add ultrahigh-frequency transmitters to their mobile equipment. There are also certain situations in which

installations of the second type are made due to the fact that the municipality involved has assumed responsibility for the rendition of service to surrounding areas, such as the county, which lie beyond the range of any ultrahigh-frequency transmitter which could be considered.

The method of operation of 2-way systems also varies and can be classified as follows:

1. Simplex operation: One frequency is used for both station and car transmitters. Only one can be on the air at a time, direct car-to-car communication, when the cars are not separated too far, is possible

2. Duplex operation: The station transmitter is on one frequency, the cars on another. Both can talk at once if necessary and operation is similar to ordinary telephone conversation. Car-to-car communications not possible except by rebroadcast through the fixed station (sometimes called triplex)

3. Voice break-in operation: A system using voice operated relays that control transmitter and receiver. In this case one station can break in on the other during pauses in speech. Direct car-to-car communication is also possible in this method under the same conditions as specified in the first case.

In its actual operation the 2-way system does not differ greatly from the one-way system. Calls are received and handled as noted in figure 4. The difference is that return calls from the car crews are made by radio instead of wire. The dotted lines in figure 4*B* from patrol car to dispatcher or radio operator indicates this communication channel. The only possible addition is direct car-to-car communication, which is not shown in the figure.

## State-Wide Radio Systems

The last few years have seen increasing interest in statewide radiotelephone systems and, while state-operated systems are not as yet in operation in the majority of states, the time is not far away when they will be. In some states teletype systems are used while in others a state patrol force does not exist. Parts of states are sometimes given the benefit of radio coverage by arranging with municipalities having transmitters for broadcast of necessary messages, all of which tends to delay state police installation.

The engineering problem involved in the installation of a statewide police radio system differs considerably from that in the municipal police system. Electrical noises, shadows of steel buildings, and high noise levels at certain points provide the major problems in the selection of a site for a municipal police station. However, the problem involved in a state police system is primarily the size of the area to be covered and the average conductivity of the ground within that area. The problem is so involved that it is doubted the selection of the most economic facilities can be based on anything less accurate than actual field strength surveys.

It is characteristic of the frequencies used by state police radio systems that at a more or less definite distance from the transmitter, depending upon the conductivity of the ground pronounced fading occurs which is usually sufficient to make the signals practically useless. Increase in power will not obviate this difficulty The distance at which this so-called fading wall appears is dependent upon the conductivity of the ground and the type of antenna in use. On the basis of a field-strength survey the location of the fading wall can be quite accurately determined, as can the amount of power necessary to place the minimum useful signal at the inner edge of the fading wall. The use of any power beyond this figure is wasteful. Thus some states have found from 3 to 7 transmitters necessary. Figure 8 illustrates the arrangement of the stations in the state of Illinois. This arrangement was determined on the basis of a field strength survey. The circles shown indicate the 100-microvolt contour which was estimated to be the inside boundary of the fading wall or the maximum range at which satisfactory service might be expected. At the present time it is possible to operate the cars at a considerable distance beyond this range.

In selecting transmitting locations for municipal police stations it is the usual practice, as stated above, to select city-owned property as a site for the transmitting station. However, in a state system it is often found economical to purchase new property, erect new buildings, and move existing state police headquarters to the location best

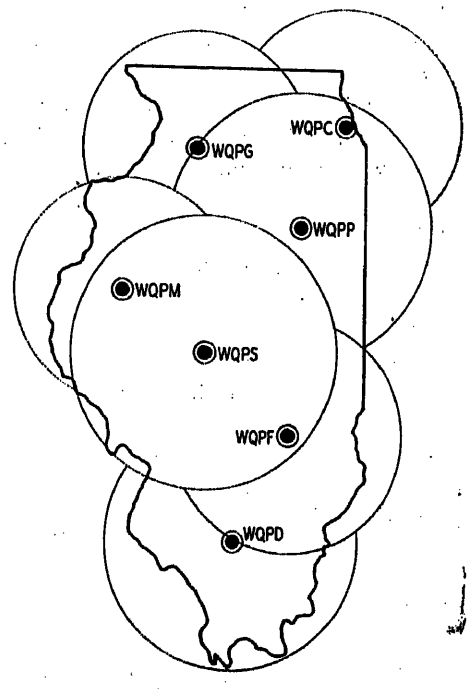



**Fig. 8. Arrangement of state police radio stations in the state of Illinois, showing coverage of each station**

suited for radio transmission. In selecting this location the primary factors to be considered are:

1. The most suitable location for statewide coverage with the minimum number of stations

2. The location of the property as nearly as possible to a highway network center

3. Availability of commercial power and wire communication circuits

The use of a number of transmitters for state police service has an advantage in addition to that of pure economics. Many of the situations that arise requiring the transmission of a message over state police radio stations are of restricted interest and may be handled by the local station. Each of these stations then becomes a unit in a statewide

system and each has its own sphere of activity. This feature results in a strengthening of the patrol, since in major crimes or statewide man hunts all departments act together, usually under the direction of one of the state stations. It may also provide a local police radio service to the county sheriff's officers, or the small communities that would of necessity be unable to afford a system.

Many states are providing, in addition to stations at fixed locations, state police stations located in trucks that can be moved to scenes of disturbance or disaster to operate with a temporary state police headquarters in order that the greatest facility may be had in handling the situation. The utility of this type of installation was amply demonstrated during the recent flood, in which the State of Ohio operated 4 such installations and the State of Indiana 13.

It is necessary where communications are exchanged for each state police station to monitor not only the transmission of the other state police stations within the same state but also those of adjacent states and of municipal police stations in the vicinity in order that in an emergency there may be a facility available for the most rapid distribution of crime information. As an illustration in certain police stations nine radio channels are continuously observed.

Figure 9 illustrates the importance of a state radio system in a communication network. This figure shows the extensive police communication system that has been built up in and around the state of Ohio. Columbus, the control station of the Ohio State Highway Patrol, is the focal point and radio circuits extend from there in all directions.

This figure shows all the various systems of police communication that are in use for intercommunication, including teletype, radiotelephone, and radiotelegraph. Long-distance telephone and wire telegraph are used in emergencies and as extensions of this system. Since ultra-high-frequency stations do not enter this network such installations are omitted as are receiving points not equipped with transmitters. These latter points are very numerous as sheriffs' offices and the majority of cities monitor the transmissions of the state system. There are additional city-to-city circuits in existence within this territory which are not shown since they do not clear messages through Columbus.

The use of radio to set up blockades so as to isolate an area in which a serious crime has occurred is a valuable point in a statewide radio system. The co-operative system in use by Michigan, Ohio, and Indiana is a splendid example; these 3 states have a planned system laid out on maps with which the dispatchers are familiar. Each police car, police post, sheriff, and municipal organization has a part to play in setting up a blockade and knows its duties in advance. Main highways and strategic points such as bridges, etc., are closed immediately, the border between states is sealed by cars and then the hunt in the territory begins. In the case above mentioned the 3 states act in unison whenever a crime is committed near the border, the cars of one state watching certain points while those of the other states watch others. Police organizations of

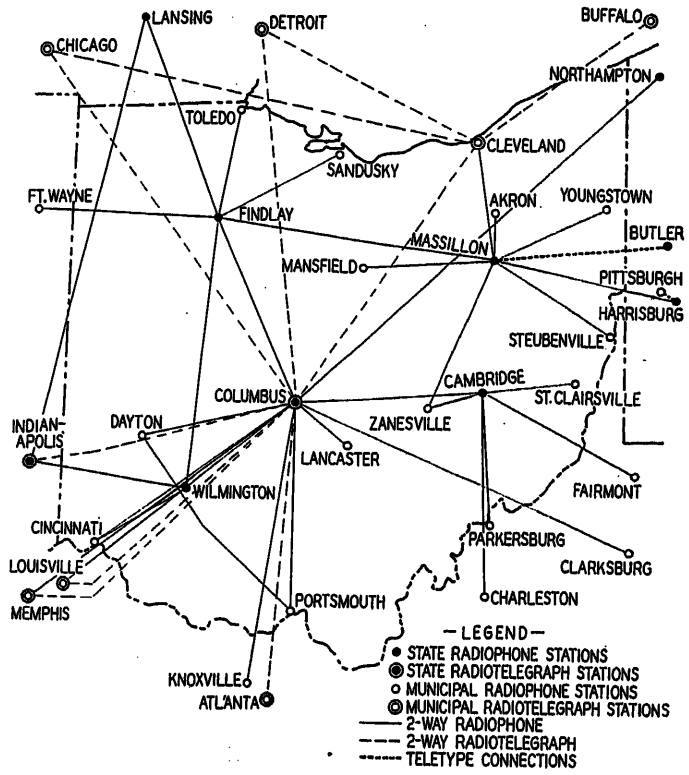



**Fig. 9. Police communication channels in and around the state of Ohio**

these states, numerous counties, and a score of cities participated in a recent successful man hunt and blockade.

As a general rule the state police radio system acts as a clearing house for information regarding automobile-license data and stolen- or wanted-car records. The cities having police transmitters depend upon the state police system to collect and maintain these records as well as to provide access to auto records of the state licensing authority.

In addition, it is generally considered the duty of the state police system to keep a crossfile on criminals working in the state and to advise individual departments of criminals' activities elsewhere.

Summarizing it may be stated that the police departments are using radio for 6 purposes:

1. By municipalities for one-way communication to mobile units and remote police stations
2. By municipalities for 2-way communication with mobile units
3. By states in the general dispatching of state police units
4. By states and municipalities for the radiotelegraphic exchange of police information
5. By harbor police in connection with the dispatching of harbor police boats and general policing of shipping
6. By states for emergency radiotelegraphic use in the event of interruption of the wire teletype network

All of these systems have their peculiar problems and uses. Therefore, no police radio installation should be made until adequate study has been given to the problem, in order that the equipment purchased and installed may suit the situation.

# A New Approach to the Industrial Lighting Problem
## Specific Lighting for Different Services

By H. B. DATES
FELLOW AIEE

Comprehensive surveys have shown the general inadequacy of artificial lighting in industry. The rapid increase of scientific knowledge on the relations of light and seeing has opened a new approach to the specification of lighting for industrial processes involving critical studies of the visual tasks, and the quality and quantity of the illumination needed. Results of the application of this new method are described in this paper.

## Introduction

FOR PERHAPS thousands of years manufacturing was a home industry, pursued only in daytime, and to a considerable extent out-of-doors—the forge under a tree; the loom in front of the cottage.

Learning was the special business for the few; the mass of the human race ignorant and poor, engaged in homely, coarse occupations.

Even after the art of printing was invented and books and periodicals became cheap and abundant, artificial light was costly and scarce.

In the evolution of industry, the change from home to group production in factories, manufacturing, in the absence of any but the most primitive of light sources, was of necessity a daytime occupation but carried on indoors under a tiny fraction of the light out-of-doors. Gains in learning and the supplying of material manufactured necessities were at the heavy cost of impaired eyesight—a large capital expenditure.

## Daylight

It is not generally appreciated, even today, how inadequate, in most cases, natural lighting is for indoor work requiring close, visual applications.

Daylight varies through an enormous range of brightness values. On a June day from as high as 10,000 foot-candles in the sunlight to 200 foot-candles or more just inside the window of a room. It also varies according to the time of day, the season of the year, and the state of the weather. But indoors, 25 feet back from the window, the light may be but $1/40$ or $1/100$ of that on the window sill. In interiors daylight decreases surprisingly fast as distance from the windows increases.

Consider then the conditions for seeing fine details, under natural light, in literally thousands of factories with but moderate window area, wide floors, and often with adjacent buildings shutting out the sky. It is not a question of needing artificial light only at night, but of needing it in most of the work places throughout the day.

## Development of the Lighting Art

The incandescent lamp for the first time in the history of illuminants opened possibilities for a safe, convenient, and inexpensive light.

The excessive brightness of the bare bulbs, with its accompanying discomfort, and fatigue, led to the shielding of the filament from the eye by crude shades which developed into open bottom, inverted glass bowls, metal reflectors, and enclosing glass globes.

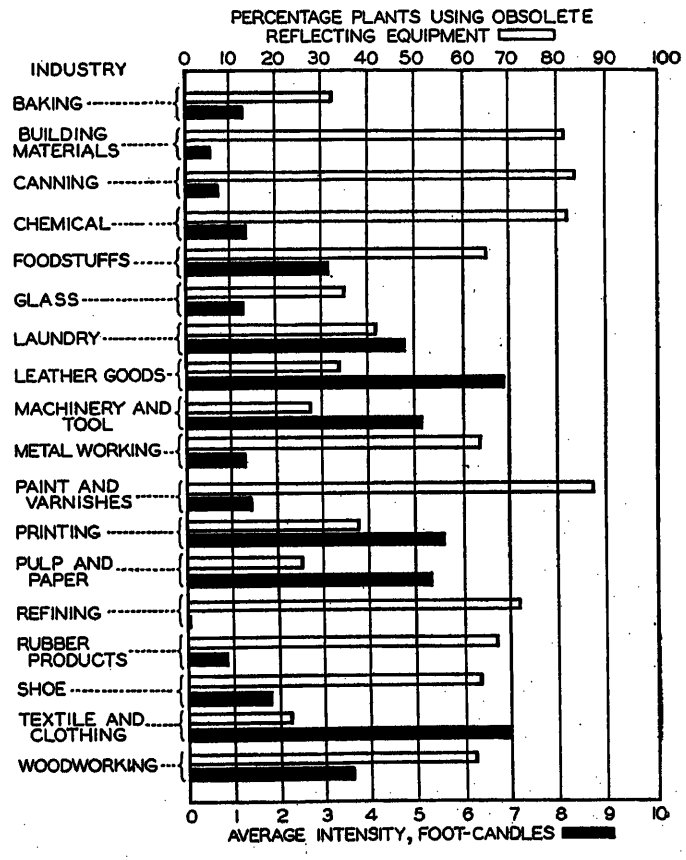



Fig. 1

Gradually as lamps improved and their use enlarged, the art of lighting developed and with it a large variety of fixtures and reflectors adapted to industrial applications.

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Progress was made in lighting practice as a result of studies on the effect of better lighting on quality and quantity of output, on the prevention of accidents, and the efficiency of workers. However, lighting remained largely an *empirical art* rather than a practice resting on a scientific basis. Lighting specifications were formulated mainly from experience and opinions and tended to emphasize foot-candles, size, and spacing of lighting units, rather than lighting for the best seeing conditions for the visual tasks involved.

## Seeing

The physiology and pathology of the eye have been studied intensively by the medical profession over a long period of years. The correction of refractive errors of the eye has long been on a scientific basis, but only in relatively recent years has serious attention been given to the problems of seeing and the relation of seeing and illumination.

The act of seeing involves many factors; the recognition of outline; of size; of form and detail; the perception of light and shade; quickness of seeing as involved in the observation of rapidly moving objects; the brightness contrast of the object viewed with that of its immediate background and more distant surroundings; color and glare. In addition psychological reactions must not be overlooked.

The influence of illumination on each of these factors must be studied separately; the fundamental laws determined, and methods of measurement and of evaluation developed.

This science of the relations between light and sight has made large strides and while admittedly still incomplete, knowledge has so greatly increased during the last decade that many of the physical, physiological, and psychological factors comprising the complex process called seeing can be appraised and measured; thus there is building up a truly scientific background for the lighting art.

As has been the case in every important scientific advance, so in this field there is a reluctance to abandon old empirical methods. However, the last few years have witnessed a tremendous public awakening to the importance of eyesight and a rapidly growing recognition that the primary objective of light and lighting is to promote the most accurate, comfortable, and easiest seeing and that the production and control of light are but means to this end.

## Prevailing Industrial Lighting Conditions

Of the need for comprehensive studies in industrial lighting there is no question. During the years 1933 and 1934 extensive surveys were conducted throughout the United States to determine the lighting conditions in various industries as well as the average conditions in industry as a whole. In figure 1 and table I are summarized some of the findings of the surveys.

The Federal Census of 1930 listed 220,670 industrial plants in the United States.

It will be noted that as of October first, 1934, 54 per cent of the lighting equipment used in industry was of obsolete types. The average age of the lighting equipment, 8.74 years, and the average level of illumination in the work areas, 2.85 foot-candles.

However, it must not be inferred that all industrial lighting is inadequate. Much good lighting is in use providing excellent seeing conditions, though as yet it represents far too small a percentage.

The surveys further pointed out that there is a lack of proper standards for the satisfactory solution of specific lighting problems; that comparatively few industrial lighting problems have been solved to the mutual satisfaction of illuminating engineers and industrial executives, and indicated the need of fundamental studies to determine the illumination values adequate for all types of industrial processes and the best methods for supplying these values. These

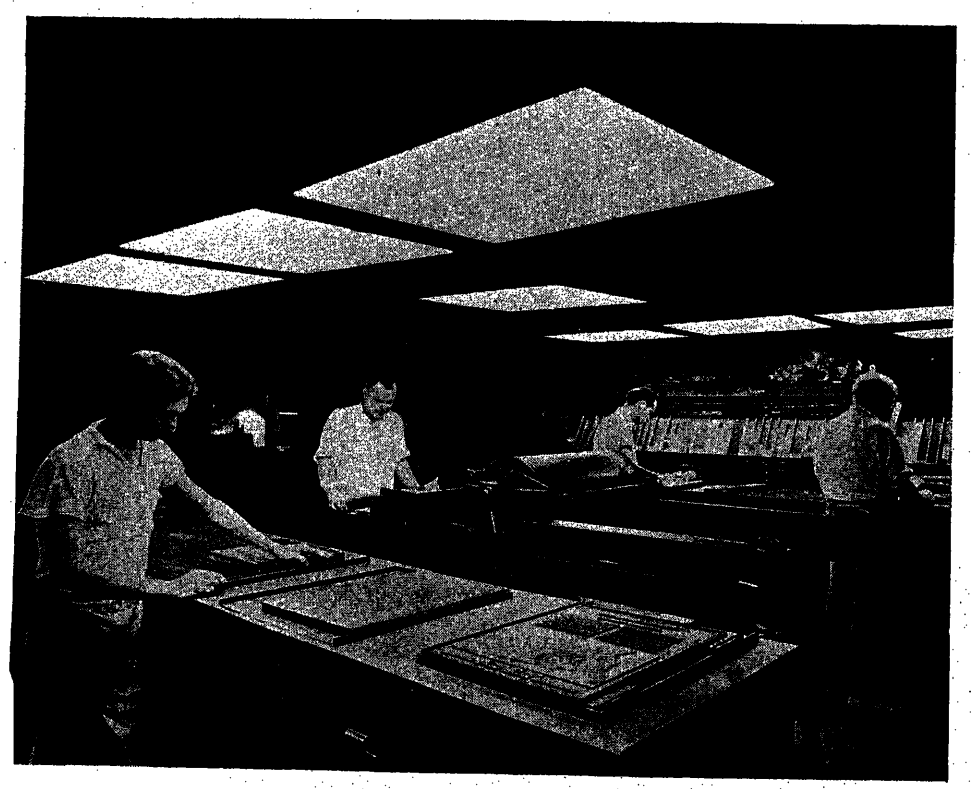


Fig. 2

studies definitely show that good lighting saves eyesight, minimizes accident hazards, reacts favorably on the morale of the workers, decreases spoilage and waste of materials, and is generally effective in improving the quality of finished products.

## New Approach to Industrial Lighting

Thirty years ago industrial plants if provided with any artificial illumination had a drop lamp over each machine or workplace. Sometimes reflectors were used, often lamps were bare and glaring. In those days if general illumination was used at all, there were a few high-powered arc lamps or clusters of carbon incandescent lamps under flat reflectors.



Fig. 3

This was followed by a more or less universal adoption of general illumination methods where medium and large size tungsten filament lamps in scientifically designed reflectors were symmetrically spaced throughout the working area and various levels of more or less uniform general illumination were supplied. Many times these levels were of a decidedly low order and on some occasions reasonably satisfactory for most types of work.

What then is this new approach to industrial lighting? It is to study for each manufacturing process in an industry the visual task; to appraise this task in terms of the fundamental factors of seeing: size, contrast, glare, etc.; to determine the quality of the lighting and the quantity of light needed to perform this visual task accurately and quickly with comfort and ease, and without abuse to the eyes or the frequent results of eye strain noticed as headaches, irritability, and general fatigue; thus is developed as a result—a lighting specification for the process in question, and there then remains the determination of light sources and equipment to produce the specified results.

## Researches in Industrial Lighting

To these ends the industrial and school lighting committee of the Illuminating Engineering Society, 2 years ago, initiated a series of comprehensive studies to determine adequate lighting solutions for industrial seeing tasks. It is the hope that as a result there may eventually be formulated, on as scientific a basis as present knowledge permits, lighting specifications for all of the important industrial operations.

To date studies have been made on:

1. Lighting in the printing industry

Table I

| Classification of Manufacture | Federal Census—Number of Plants of This Type | Average Age of Present Lighting Equipment in Years | Average Foot-Candle Intensity | Per Cent Increase in Light Necessary for Good Illumination | Per Cent of Plants Using Obsolete Reflecting Equipment |
|---|---|---|---|---|---|
| Baking | 15,684 | 7.5 | 1.24 | 195.0 | 32.1 |
| Building materials | 14,792 | 8.1 | 0.5 | 1500.0 | 82.0 |
| Canning | 2,917 | 11.7 | 0.6 | 1150.0 | 83.4 |
| Chemical manufacturing | 8,871 | 9.3 | 1.3 | 208.0 | 81.7 |
| Foodstuffs, candy, dairy | 46,113 | 8.9 | 3.1 | 271.0 | 65.2 |
| Glass | 8,478 | 5.6 | 1.2 | 460.0 | 35.0 |
| Laundry | 21,926 | 5.5 | 4.75 | 139.0 | 41.3 |
| Leather goods | 4,796 | 6.5 | 6.88 | 62.5 | 33.7 |
| Machinery and tool manufacturing | 11,807 | 6.57 | 5.1 | 106.5 | 27.3 |
| Metal working | 12,021 | 9.57 | 1.3 | 562.3 | 63.7 |
| Paints and varnishes | 923 | 17.1 | 1.4 | 494.0 | 87.3 |
| Printing | 22,725 | 5.4 | 5.5 | 109.8 | 37.6 |
| Pulp and paper manufacturing | 3,783 | 10.0 | 5.29 | 193.0 | 25.0 |
| Refining | 2,906 | 6.8 | 0.02 | 592.5 | 72.0 |
| Rubber products | 498 | 7.2 | 0.8 | 496.0 | 67.3 |
| Shoe manufacturing | 1,460 | 4.3 | 1.8 | 263.0 | 63.4 |
| Textiles and clothing | 24,443 | 5.3 | 7.0 | 115.2 | 21.3 |
| Woodworking | 16,527 | 4.0 | 3.6 | 367.0 | 62.4 |
| Totals and averages | 220,670 | 8.74 | 2.85 | 404.7 | 54.0 |

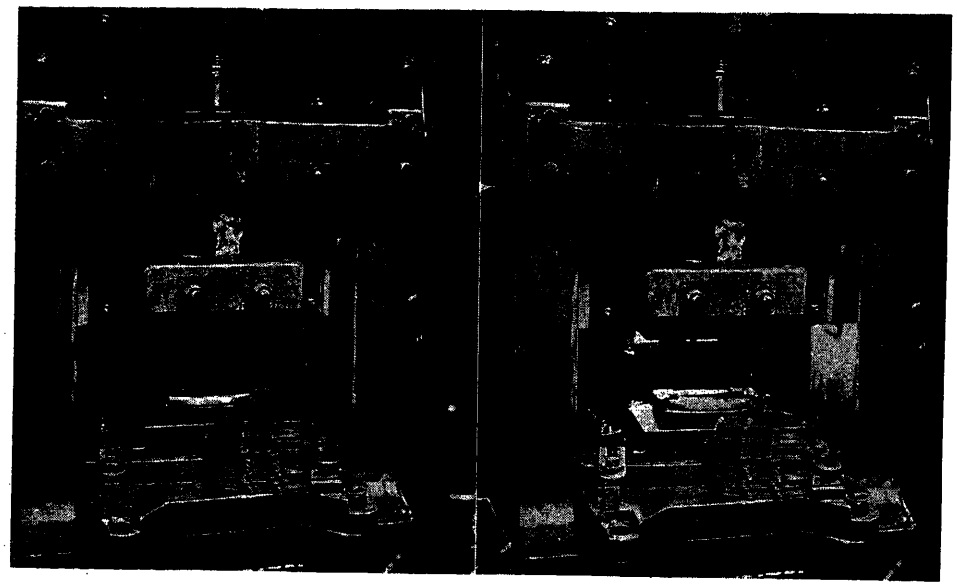


Fig. 4



Fig. 5

2. Lighting in the shoe manufacturing industry
3. Lighting in the textile industry (grey goods and denim)
4. Lighting in the candy manufacturing industry
5. Lighting for radio assembly and inspection and small parts manufacturing

According to the complexity of the industry, these studies represent from 8 months to 2 years critical and painstaking study by very competent groups of engineers. It is not claimed that they are completely exhaustive for any one industry, but as more are completed, investigations of the processes in one industry begin to overlap into other industries and progress becomes more rapid —the coverage more complete.

The projects which have been completed have been exceedingly valuable to that particular industry. In each of the completed studies it has been found that by providing proper quality of lighting and quantity of light, the ease and speed of production have been enhanced. The better morale of the workers and their lack of eye fatigue have been manifested in the amount of work accomplished. The value of this method of approach is further evidenced by the rapidly growing application of these methods by competent, progressive lighting engineers, to the large number of industrial and other lighting problems which they are called upon to solve in their daily work.

In providing good quality lighting at adequate levels of illumination, it has often been necessary, for economic reasons, to supplement general lighting by localized installations. The status of the art at the present time indicates that where more than about 50 foot-candles are needed, it is often more practical and economical to secure and control the higher level of illumination needed for good vision, by the use of supplementary lighting for the relatively small work areas involved. However, where such supplementary lighting is used, seeing conditions are impaired rather than improved if the brightness of the area being illuminated by the supplementary units exceeds too greatly the brightness of the surroundings. The absolute permissible brightness ratio is still a subject of investigation, but current practice tends not to exceed a ratio of 10 to 1.

In making recommendations for lighting specific processes, instances occasionally arise where existing equipment is not adequate or adaptable to meet the lighting requirements. Equipment designed for a particularly difficult task often is found highly suitable for other applications not previously realized.

It is obviously impractical here, due to space limitations, to quote in detail from the Illuminating Engineering subcommittee reports. It is the author's principal desire to give the AIEE members a general picture of how the specialist or the illuminating engineer now tends to approach the problem. Lighting is a specialized branch of electrical engineering and much valuable data on the subject is to be found in the *Transactions* of the Illuminating Engineering Society. It is recommended, therefore, that the electrical engineer who is not a specialist in lighting refer to these *Transactions* when he wishes specific and detailed information on particular subjects. In the references are given some of the most recent and vital presentations along specific lines.

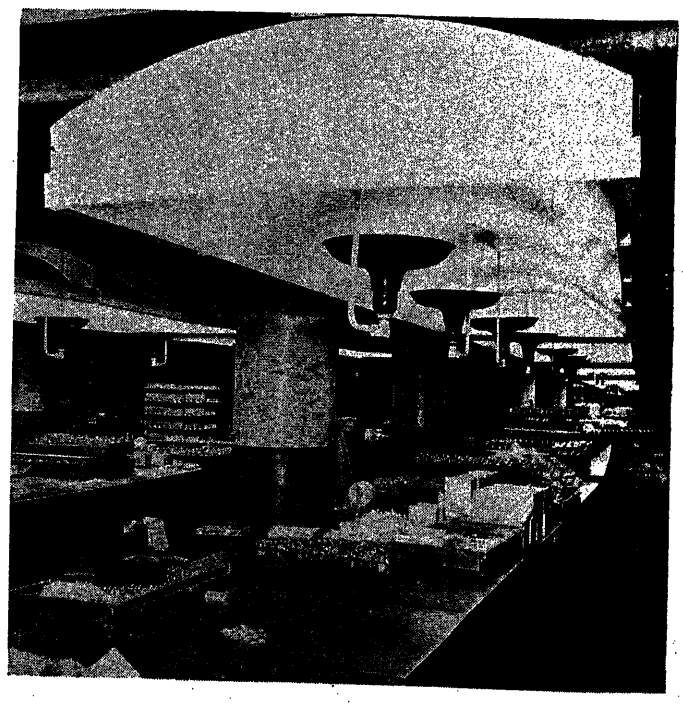


Fig. 6

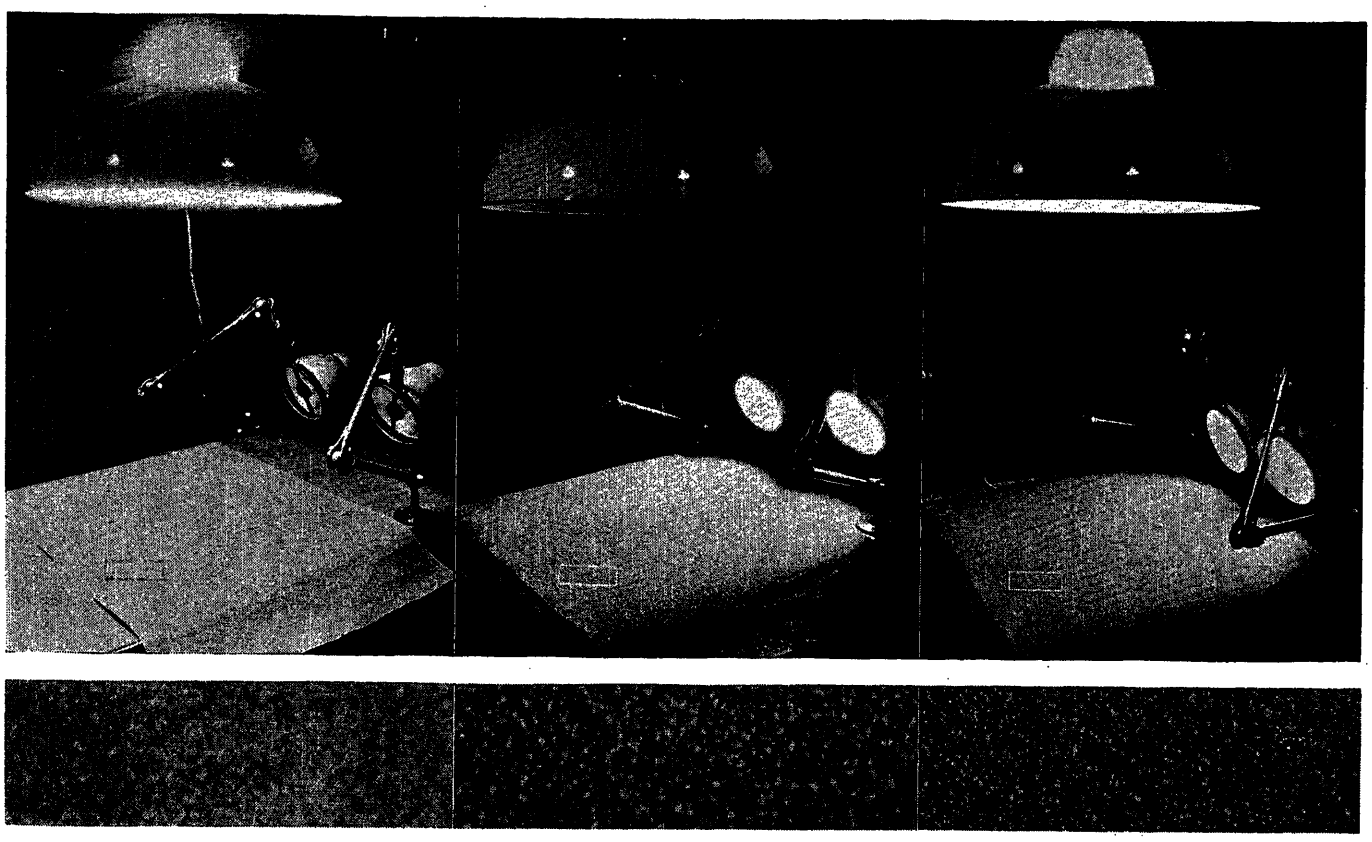


**Fig. 7A. Diffused quality of light, even though of 100 foot-candles intensity, does not show defects but washes out detail**

Diffused lighting, 100 foot-candles

**Fig. 7B. Directional light from an oblique angle and from one direction plainly reveals the wrinkle defects**

Oblique lighting, 13–15 foot-candles

**Fig. 7C. Combination general and oblique lighting. With considerable diffused lighting to approximate general daylight conditions in factory, defects still show up plainly under sufficient oblique component**

Diffused—30 foot-candles
Oblique—15 foot-candles

An appreciation of the value of this new approach may be enhanced by a few examples of its application to the solution of fairly difficult visual tasks.

In the printing industry critical studies of seeing type indicated that the ideal lighting should be from a large area, low brightness light source, giving a highly diffused light with an illumination of the order of 50 foot-candles. Figure 2 shows an application of this quality of lighting to the lighting of type cases, proof press, and page form, composing stones in a large newspaper plant, while figure 3 illustrates how a large light source of low brightness is effective in reducing the reflections from the surfaces of highly polished cylinders upon which are etched the various illustrations and type matter which will appear in a printed rotogravure page.

In the cotton textile industry, the weaving of grey goods presents difficult seeing tasks due to lack of contrast between the thread and the warp and finished cloth. The operator must locate and repair broken ends and see the finished cloth exceptionally well so as to locate defects and determine if all the factors contributing to the production of first-class cloth are functioning properly. Shadows on the work area are particularly annoying. The position of the lighting unit, and the quality of the emitted light have a tremendous effect on the clarity with which details are revealed.

Good general lighting is not always sufficient in itself to provide adequate seeing conditions where most needed and supplementary lighting must be supplied. Figures 4 and 5 illustrated the improvement in punch-press lighting by the addition of local lighting to the general lighting.

Inspection processes frequently present difficult lighting problems. For example: It was necessary to detect small defects such as scratches and buffed-through places on small chromium plated parts. To detect the defects rapidly it was found necessary to have the light highly diffused, with a minimum of glare and an illumination of the order of 50 to 60 foot-candles. The problem was further complicated by the large areas involved. The solution adopted is shown in figure 6.

A manufacturer of abrasives had a very difficult inspection problem, inability to detect defects in the finished product causing expense in rectifying mistakes and a considerable loss of business. In spite of rigid inspection of all the grades of sandpaper passing over inspection tables at a slow rate of speed, and being constantly watched by expert observers, the defects were slipping by, and not showing up until the eventual customer had installed this abrasive sheet upon his automatic machinery. Then an uneven abrasion appeared on the veneer or other

surfaces and caused no end of trouble in attempting to turn out a uniform product. This always produced a retroactive effect on the abrasive manufacturer by causing an expense in adjustment as well as a loss of good will. Many times, it meant an abrupt termination of a contract. Under the general conditions of factory lighting with a good daylight component, these defects were unable to be detected.

The problem consisted of seeing the small wrinkles in the abrasive sheet, which cannot be seen under ordinary general lighting. The wrinkles occur during the process of putting the abrasive on the cloth or paper background. Since the abrasive consists of small jagged particles, which have specular surfaces, general lighting, with its components of light from every direction, causes a multitude of reflections toward the eye, so that the net effect is to see a mass of abrasive surface without seeing any minute detail. Since the light penetrates into the slight hollows as well as on to the high spots, the reflections are uniform from the depressions as well as from the rest of the surface, so that the depressions or wrinkles cannot be distinguished. However, with very oblique lighting, with the rays of light just grazing the surface, the light impinges upon the higher surface, but completely misses the depressed wrinkles. This causes a shadow in the depressions, so that the wrinkles can readily be seen.

The 3 photographs (figures 7*A*, *B*, and *C*) illustrate 3 steps showing the procedure in solution of the lighting problem.

Figure 7*A* shows that even with a high intensity diffused quality of light, the defects did not show up, but on the contrary were obliterated.

Figure 7*B* demonstrates the fact that directional light from an oblique angle, and from one direction, plainly revealed the wrinkle defects.

Figure 7*C* illustrates the typical conditions under which the abrasive sheet will be seen under the proper lighting. It shows a combination of general lighting of a diffused nature, of about 25 foot-candles and an oblique component of light, of approximately 15 foot-candles. There is sufficient quantity of oblique light to still plainly show the defects, despite the tendency of the general lighting to fade them out.

If progress in industrial lighting has, in the past, been relatively slow, it may be attributed in part to a lack of proper standards for the satisfactory solution of lighting problems, and in part to the lack of appreciation of the value of good lighting not merely from the standpoint of production, but of its effect on human efficiency, human welfare, and eyesight conservation.

Much real progress is being made and the next few years will undoubtedly witness greater progress in industrial lighting than has resulted during the last 20 years.

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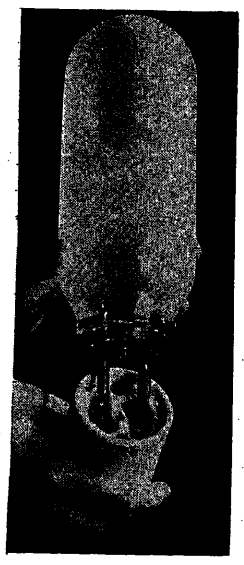
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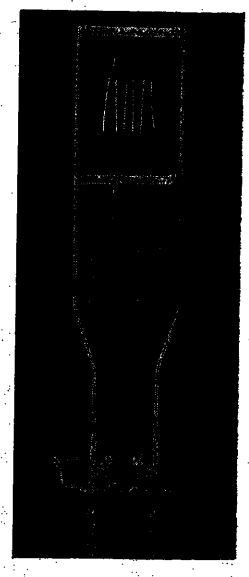
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## New 1,000-Watt Bipost-Base Lamp

A rugged 1,000-watt general service lamp, equipped with a medium bipost base and an inside-frosted tubular bulb, recently was developed. The bulb is made of special heat-resisting hard glass which resists shock; and because of an extremely low coefficient of thermal expansion, such temperature changes as result from rain, snow, and sleet have been found in tests to cause no breakage. The bipost base offers the advantages of more accurate focusing of the filament, a simplified socket, and more dependable electrical contact; production also is simplified. The comparatively small size of the lamp makes possible the design of luminaires of relatively high efficiency and small size. Two screens or grids mounted above the filament within the lamp collect much of the normal blackening which in usual lamps is deposited on the bulb; the lamp shown in the illustrations, of course, is designed to be burned base up. The simplified production is said to result in reasonable cost.



# Expulsion Protective Gaps

By W. J. RUDGE, JR. ASSOCIATE AIEE  E. J. WADE ASSOCIATE AIEE

EXPERIENCE with the expulsion protective gap since 1932, when the first commercial installation was made, has demonstrated the efficacy of this device as a means of improving service by preventing lightning outages on overhead transmission lines.

The expulsion protective gap (figure 1) consists of a weather-resisting "textolite"-wrapped fiber tube, whose ends are fitted with metal electrodes. The lower electrode has an opening through which the gases generated by the power arc are expelled. The breakdown voltage through the tube is less than that of the insulator which is in parallel, hence the lightning discharge is kept within the tube. This prevents damage to the insulator, either from the lightning or the power arc, which would result if the tube were not present. The lightning arc through the tube establishes a path for the power current which flows until the next normal current zero, at which time the expulsion action in the tube prevents further flow of current. The tube is isolated from the line by a series air gap which prevents full line-to-ground voltage being applied under continuous operation.

Expulsion gaps are particularly applicable on grounded-neutral circuits. Their ability to prevent lightning flashovers of insulators and the resulting outages and possible damage to the insulators is not dependent upon tower-footing resistance. They are equally applicable on low- and high-voltage lines. To date they have been applied on circuits ranging from 13.8 kv to 138 kv (figure 2). Experience is being obtained with installations on a 230-kv line.

Several of the major applications have been made on 138-kv systems which already had overhead ground wires and insulation consisting of 10 disk insulators. In these cases, the lines passed through areas where it was difficult to obtain the low tower-footing resistances, which are essential for proper operation of the ground wire, without considerable expense. Expulsion gaps were placed on each tower as a means of preventing insulator flashovers and subsequent experience has proved the application to operate as expected. They have also been applied to circuits varying from 13.8 kv upward, both on lines with and without overhead ground wires. Economic considerations show that in many cases they can be applied to each insulator string at a lower cost than that of lowering the tower-footing resistances by addition of counterpoises, ground rods, etc.

Expulsion protective gaps have been found particularly valuable as a means of protecting pole-top switches and river crossings. Often pole-top switches have a lower line-to-line and line-to-ground flashover than the adjacent structures on the line, making them a susceptible point to lightning flashovers. Also, pole-top switches are often used as emergency ties operated normally in an open position, which means that they are located at a reflection point and therefore subjected to higher voltages. River crossings frequently have taller structures and longer spans than normal, which means greater exposure to lightning. On several river crossings the use of expulsion gaps has not only eliminated circuit outages but has prevented damage to the insulators as well.

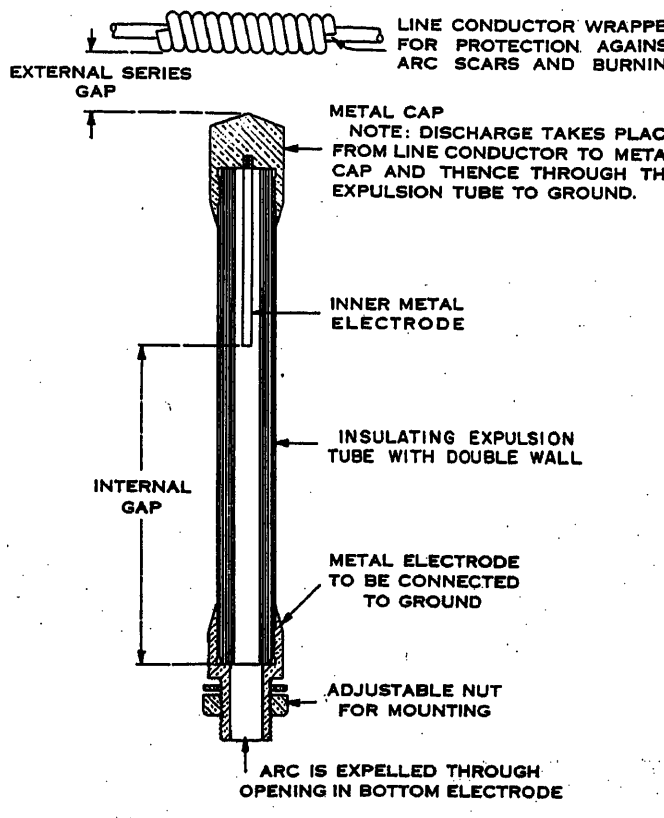



**Fig. 1. Construction of expulsion protective gap**

Where it is found necessary or desirable to obtain the best available lightning protection in important stations, expulsion gaps used at the line end of the shielded zone (approximately 2,500 feet long) adjacent to the station, serve to limit the magnitude of the surge voltage which can be transmitted over the conductors to the station lightning arresters. In some cases it is difficult to install an effective shielded zone for the distance of 2,500 feet from the station. Expulsion gaps installed on all structures out

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1. For all numbered references see list at end of paper.

from the station for a distance of approximately one-half mile will provide parallel paths to ground for the lightning currents and will reduce the severity of the stroke currents which must be handled by the station arresters. By using this means of discharging a part of the direct stroke currents to ground the voltage wave will be chopped and its length greatly reduced, so that protection will be secured for strokes which might otherwise result in damage to the station equipment. The gain which can be obtained in either of the above cases is greatest for lines with unusually high line insulation, such as wood pole lines having large spacings, and no guy wires.

Expulsion gaps give the best lightning protection when installed on every structure. However, in several instances it has been found that a material reduction in outages can be realized by equipping only the guyed poles. In other cases it has been found economical to equip a particular section of line or a feeder where lightning troubles have occurred frequently. When they are not installed on all structures, it is essential that the expulsion gaps have low-resistance grounds, to gain maximum effectiveness in reducing stress on the adjacent unprotected structures.

## Volt-Time Flashover Characteristics

Expulsion protective gaps have a somewhat flatter volt-time flashover characteristic than plain rod gaps or disk insulators. The volt-time characteristic of a 115-kv expulsion gap is compared with that of a rod gap in figure 3. It may be noted that the expulsion gap is equivalent to a rod gap having a 34-inch spacing on the full $1^1/_2 \times 40$ positive wave. However, when tested on a wave rising to flashover at the rate of 1,000 kv per microsecond, the expulsion gap is equivalent to a 22-inch rod gap. A similar situation exists with regard to disk insulators. When tested in parallel with a string of 6 disk insulators, the expulsion gap was found to give protection on the full $1^1/_2 \times 40$ positive wave. However, when tested on a wave rising at the rate of 1,000 kv per

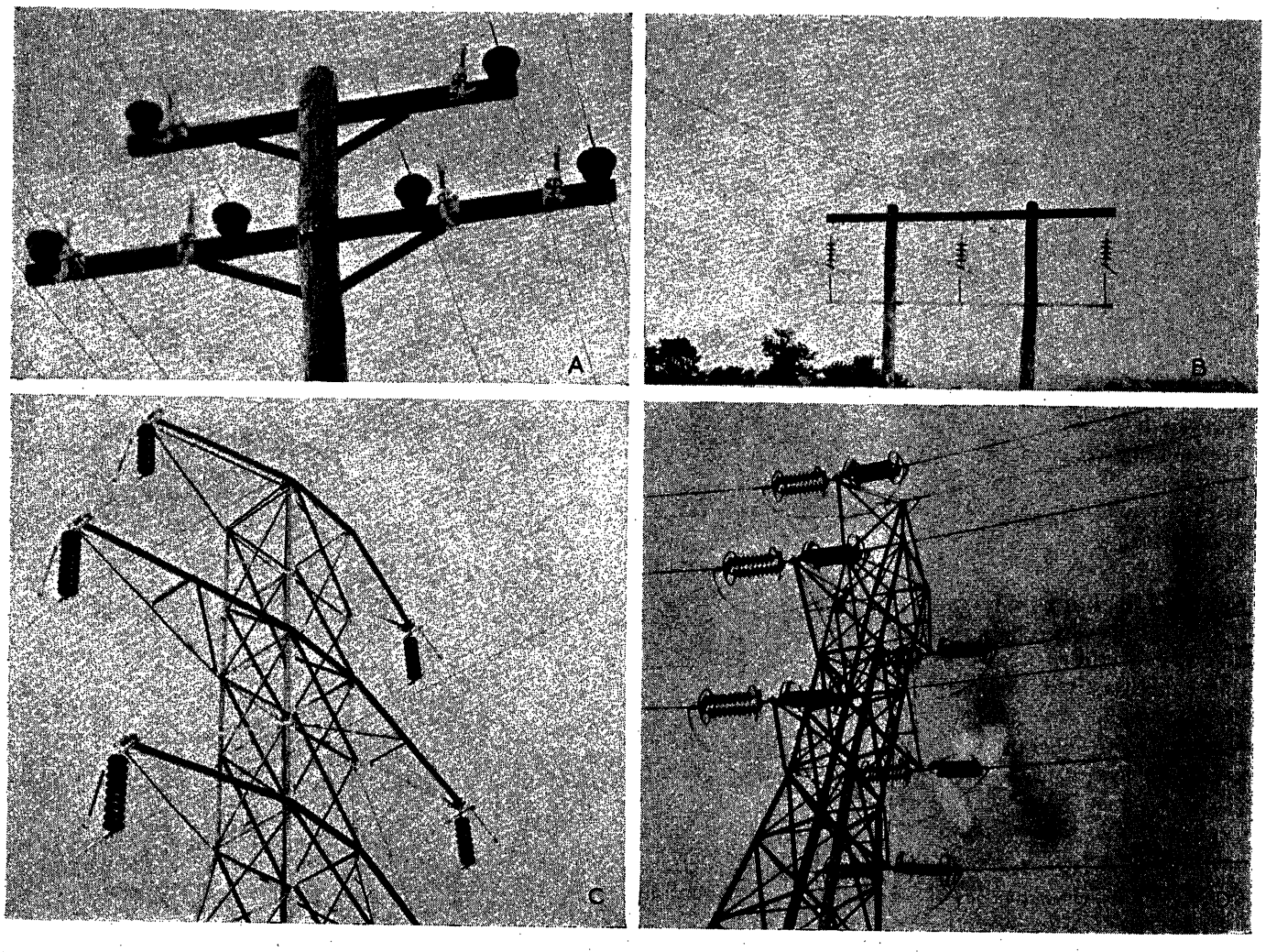



**Fig. 2. Typical installation of expulsion protective gaps**

*A*—13.8-kv system *B, C*—69-kv system *D*—138-kv system, gap on one phase during tests

second, the expulsion gap protects 5 disk insulators which have been made on various combinations of sion gaps and disk, pin, and pedestal insulators, te that where protection is obtained on the $1^1/_2$ x 1 positive wave, protection will also be obtained for ive waves and waves rising in shorter times. Wave ty has little effect on the flashover voltage of the sion protective gap.

e expulsion gap does not have a sufficiently flat ime characteristic to make it suitable for protecting ormer insulation. Comparative tests between the ver characteristics and the breakdown strength of tion pads such as used in transformers, show that ash over of the expulsion gap rises more rapidly than reakdown voltage of insulation pads, as the time to ver becomes less.

en installing expulsion gaps, it is necessary to allow iable tolerances in the settings of the series air Obviously, increasing the series gap raises the ver voltage. Figure 4 shows how the protection of a 115-kv expulsion gap is increased as the series s raised from 11 inches (the standard setting) to ches. To estimate the increase in flashover voltage, from a rod-gap curve, the spacing corresponding to expulsion-gap voltage ($1^1/_2$ x 40 positive wave). o this spacing the number of inches by which the gap is to be increased. From the rod-gap curve the voltage corresponding to the larger rod-gap ig. This will be a close approximation for the tion level of the expulsion gap with increased gap spacing.

## ulse Discharge Characteristics

view of the increased amount of data on direct e currents, it is of interest to speculate as to the bility of an expulsion gap tube being burst by direct e currents. Laboratory tests have shown that its in excess of 100,000 amperes are required to burst the tubes. Lewis and Foust have shown that only one per cent of the 358 strokes measured have tower currents exceeding 100,000 amperes. A similar investigation in Germany, in which 224 strokes were reported, showed a maximum tower current of 70,000 amperes. It appears, therefore, from these data that the probability of an expulsion gap being burst from lightning is very small. Furthermore, field experience with many thousand expulsion gaps over the past 4 years has yielded only $^1/_{40}$ of one per cent where the evidence indicated that the lightning current was great enough to cause bursting.

## Operating Characteristics of Expulsion Protective Gaps

In addition to providing a discharge path for lightning to earth, the expulsion gaps must be capable of interrupting the power current which flows after the lightning discharge. The maximum power current which they will safely interrupt depends upon the pressure generated in the fiber tube by the arc current. An extensive series of tests has established the relation governing the pressure generated as a function of the particular design, the physical dimensions of the fiber tube and the crest current. This makes possible the determination of the tube dimensions for any particular current (figure 5).

Since the test data is of necessity taken and correlated against crest current, it becomes necessary to convert the current values to corresponding symmetrical root-mean-square values when applying expulsion gaps to a given system. When making the conversion from crest current to the equivalent symmetrical root-mean-square value, it is necessary to apply a factor which takes into account the transient d-c component and the wave form occurring in the first half cycle of current flow. If the resistance of the circuit is zero, and the current

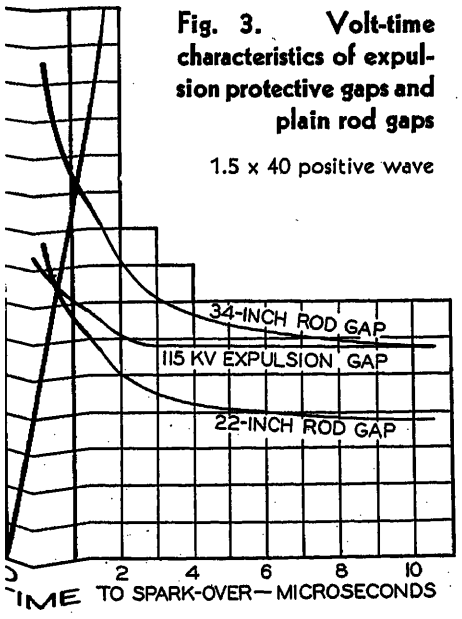



**Fig. 3. Volt-time characteristics of expulsion protective gaps and plain rod gaps**

1.5 x 40 positive wave

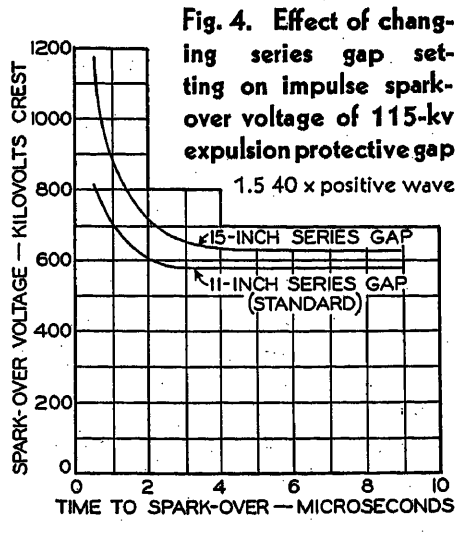
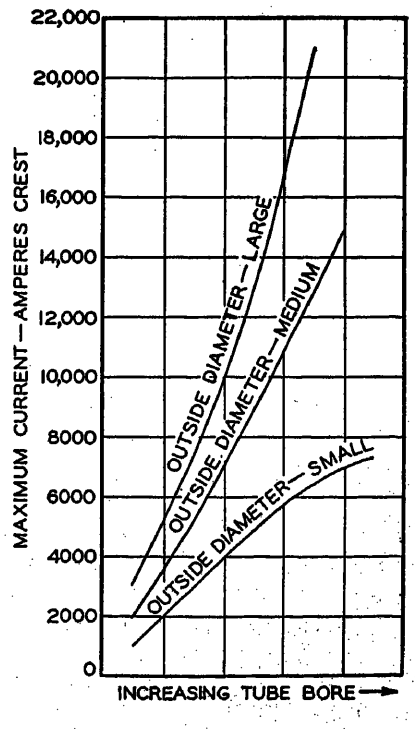



**Fig. 4. Effect of changing series gap setting on impulse sparkover voltage of 115-kv expulsion protective gap**

1.5 40 x positive wave

**Fig. 5 (right). Maximum currents for expulsion protective gaps**



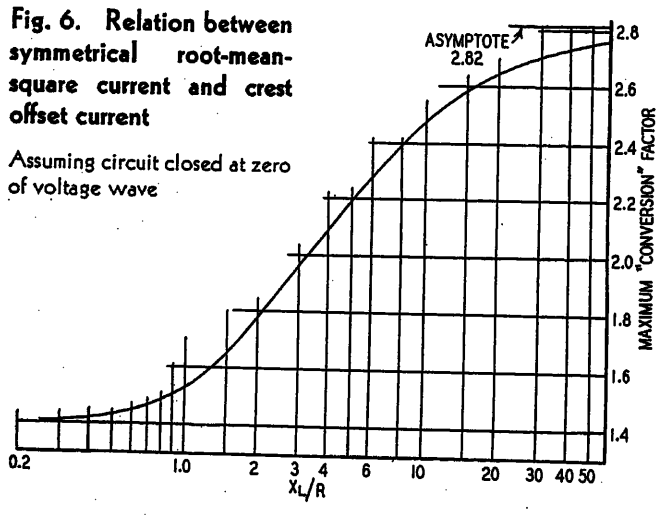
flow starts at the zero of the voltage wave, this conversion factor has a value of 2.82. However, the resistance always has a finite value and if the lightning occurs exactly at the zero of the voltage wave, follow current will not be started. Therefore, this maximum conversion factor will never be obtained. The available data from systems on which short-circuit tests have been conducted indicates that the maximum conversion factor in service does not exceed 2.4 which corresponds to a ratio $x/R$ of 8.2 (figure 6). The ratio of $x/R$ is the relation between the inductive reactance (i.e., the transient reactance or that reactance which is effective during the first cycle of current flow) and the resistance of the circuit. The curve shown in figure 6 gives the maximum conversion factor in a single phase circuit where the current is assumed to start at the voltage zero.

It should be noted that measurements of short-circuit currents having a duration of $^1/_2$ cycle, using bushing-type current transformers whose ratings are satisfactory for metering and relaying are likely to be in error due to core saturation as the result of residual magnetism and overloading. Staged tests made where a special current transformer was used in series with a standard bushing current transformer showed differences greater than 400 per cent. This does not mean that differences of this order will exist in all cases, but it does indicate the necessity of eliminating this source of error when determining the current which is the basis for selecting the expulsion gap.

It is always advantageous to select the expulsion gap whose rated maximum current is only slightly above the maximum available system current, as by so doing the minimum or required clearing current can be kept to its lowest values, thereby extending the range of system conditions for which the expulsion gap is applicable. The advantages are twofold. First, the expulsion gap selected can be used in locations where the available short circuit current is lower, i.e., on structures having higher tower footing resistance, or systems with greater neutral resistance. Second, the expulsion gaps will be capable of a greater number of operations before erosion of the fiber raises the minimum or required clearing current beyond the point of successful operation.

**Fig. 6. Relation between symmetrical root-mean-square current and crest offset current**

Assuming circuit closed at zero of voltage wave




In a given circuit there are 3 factors which determine whether or not a particular expulsion gap will extinguish the arc in one cycle:

1. The current
2. The crest value of the (recovery) voltage which appears immediately following the power current zero
3. The rate of rise of the recovery voltage

Figure 7 shows the relation between the recovery voltage which an expulsion gap can withstand and the current during the preceding half cycle. It is apparent from these relations that the minimum current or the current required to clear depends upon the circuit characteristics. The application problem, therefore, becomes one of determining the short-circuit current and the recovery voltage of the particular circuit being considered.

## Circuit Characteristics

A number of papers dealing with the recovery voltage characteristics of circuits have been presented before the Institute.[1–6] However, most of these papers have dealt with this problem in connection with oil circuit breakers, in which very high rates of recovery voltage were encountered. In the case of expulsion gaps, the recovery rates obtained in service are much lower than those for breakers. This is true because the capacitance of the line or line to earth is always in parallel with the gap. In the case of simple 3-phase circuits a fair determination of the recovery voltage can be made by calculation, however, with an extensive interconnected network, the calculation of recovery voltage becomes very complicated. Much less effort and time are required to determine the recovery voltages by test. Furthermore greater confidence can be placed in the test results, as they do not involve any assumptions. Extensive tests on a number of systems form a background of knowledge for applying expulsion gaps. Therefore tests are not necessary in every case to insure a successful application.

## Field Tests

To facilitate the determination of recovery voltages on power systems, and to obtain other fundamental data on operating systems, a truck has been equipped with the apparatus suitable for field testing.

The truck is equipped with the following:

1. An automatic 3-element cathode-ray oscillograph shown at left on figure 8 which may be used to measure current or voltage on three phases of a system. The oscillograph utilizes a rotating drum type film holder, the speed of which can be varied, and a thyratron-controlled circuit which may be adjusted for different exposures. Records can be obtained from a high film speed corresponding to 25 microseconds per millimeter down to speeds which can be successfully recorded by the magnetic oscillograph.

The oscillograms are obtained by photographing the phenomena on the fluorescent screen of the cathode-ray tube using $f$ 2.0 lenses

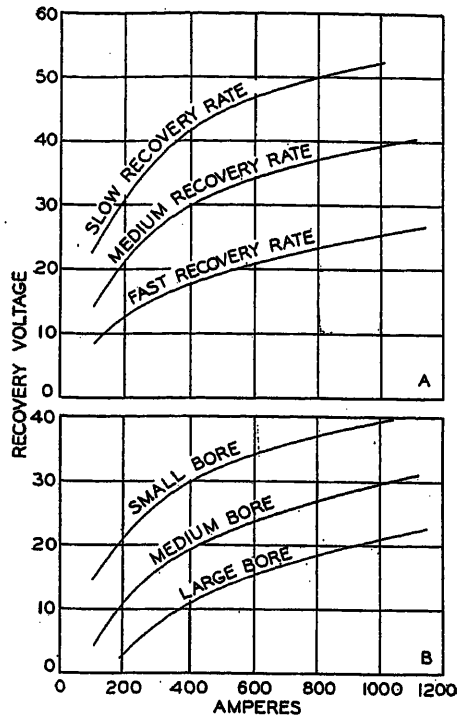



**Fig. 7. Effect of bore and recovery rate on clearing current**

*A*—Varying recovery rate—bore constant
*B*—Varying bore—recovery rate constant

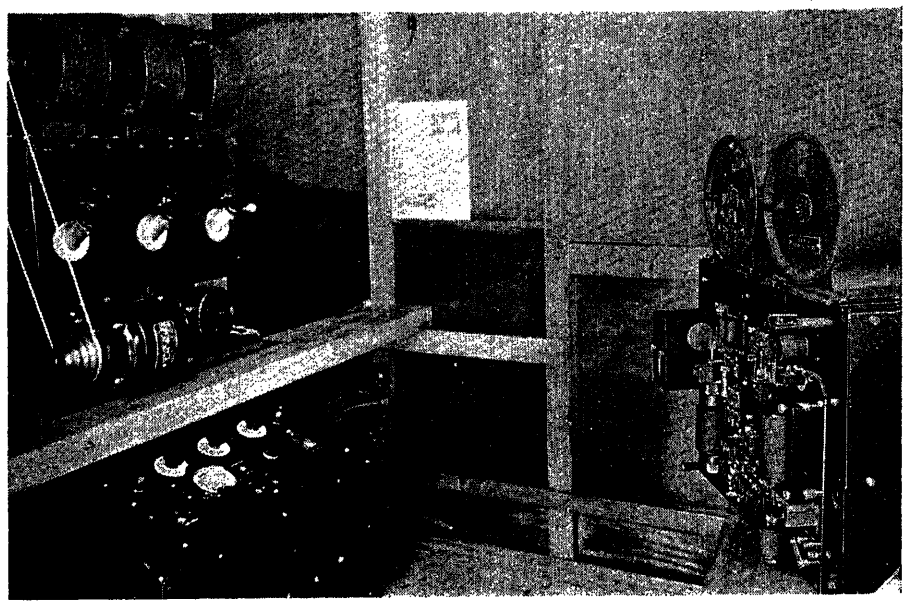


**Fig. 8. Interior of truck for making field tests. View showing 3-element cathode-ray oscillograph and 6-element magnetic oscillograph**

and 35-millimeter "cine" film. The magazine film drums hold 100 feet of film, and means are provided for cutting off the exposed portions after each test.

Porcelain-housed coupling capacitors are used as voltage dividers for the cathode ray oscillograph.

2. An automatic 6-element oscillograph is used for current and pressure measurements. This oscillograph is equipped with a mirror to provide the initial sweep motion, and a motor which brings the recording paper up to speed before the mirror reaches the end of its travel.

3. A pressure recorder is used for measuring the pressures developed in the expulsion protective gap and recoil forces developed during its operation. The pressure record is automatically recorded by the 6-element oscillograph during the test.

4. A ground resistance meter.

5. A dark room which enables film to be developed and examined in less than 5 minutes after the measurement.

6. A portable 110-volt power supply for operating the equipment where no such supply is available.

The equipment described above is so versatile that the effect of all circuit conditions on recovery voltage can be determined.

Figure 9 shows both the cathode-ray oscillograph and magnetic oscillograms obtained during a staged 3-phase test on a 26.4-kv system utilizing a 75-ohm neutral ground. It may be noted that the expulsion gap on phase 3 opened the circuit ahead of phases 1 and 2. The expulsion gaps on phases 1 and 2 opened simultaneously on phase-to-phase current as this current was much greater than the ground current. Had the system neutral been solidly grounded, the two last to clear would have operated on ground current at their respective current zeros.

## Mountings

Proper mounting arrangements are vital to successful operation of expulsion gaps. The series gap must be controlled to prevent its becoming either too great or too small. Where the series gap becomes too small, a greater percentage of line voltage is applied continuously to the tubing, which results in corona tracking and damage to the fiber. The limits for the series gap setting are determined by 2 factors:

1. The minimum setting allowable is that which prevents excessive continuous voltage being applied to the tube, or an unnecessary number of operations.

2. The maximum setting is that beyond which protection will not be obtained for the insulators in parallel.

It is preferable to have the series gap setting as large as possible and still protect the insulation as it reduces the normal operating voltage on the fiber tube and is in the direction to keep the number of gap operations at a minimum. The ionized gases must be properly directed, to avoid flashovers due to their conductivity. Figure 10 shows the length of the flame path as a function of the power current through the flashover protector. Obviously the circuit voltage and the expulsion gap dimensions should enter in such a relation. However, the curve can be used to estimate the safe distance for objects in the direction of the flame having a different potential from that of the discharge gases. Sufficient clearance should be provided between the expulsion gap and the structure to which it is attached to assure that lightning flashovers will be confined within the expulsion gap.

Recoil forces must be considered when designing the mounting hardware. The magnitude of the recoil force is a function of the velocity and pressure of the discharge

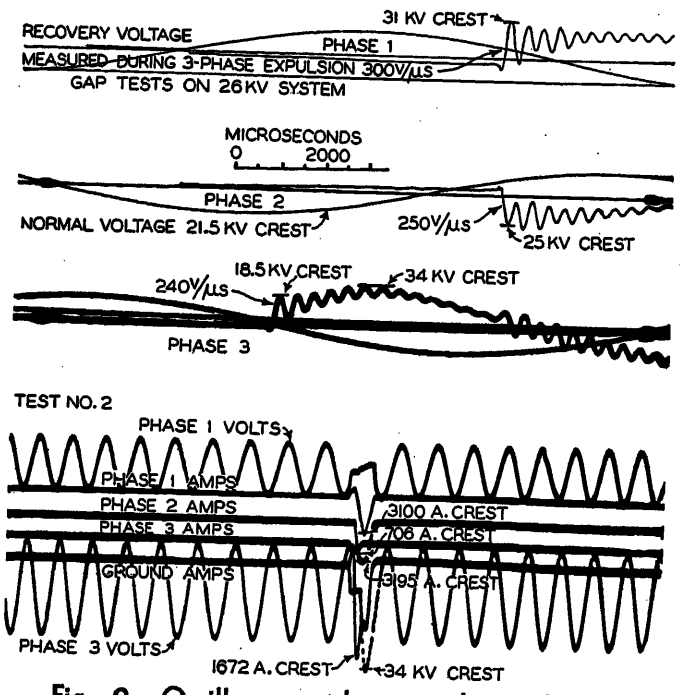



**Fig. 9. Oscillograms taken on the 3-element cathode-ray oscillograph and automatic magnetic oscillograph during staged tests on expulsion protective gap for a 26.4-kv system**

gases and the shape of the opening at the end of the expulsion gap. Tests have been made on flexible mountings which show that the recoil force is a function of the current and the design. The relation between these factors has been determined by an extensive series of tests and is taken into account in the finished designs. The pressure-time relation of the recoil force is of nearly the same shape as the current, although slightly lagging. While the recoil force may reach values in the order of 3,000 pounds, the time is so short that the expulsion gap and its mounting hardware does not move appreciably until the pressure has ceased. The acceleration imparted to the expulsion gap during this short period results in further movement and an oscillation whose frequency is determined by the mass of the expulsion-gap assembly and the rigidity of its mounting. The greater the mass of the assembly, the less the energy imparted by the discharge. The greater the rigidity of the mounting, the greater the stress in the mounting.

It is of utmost importance that the mounting hardware be designed to facilitate ease of installation. This results in a direct saving to the operator and broadens the field of application.

## Weathering

It is felt that insufficient time has elapsed to form any definite opinion as to the ultimate life expectancy of expulsion gaps. Past experience with plain fiber tubes for expulsion gaps as well as in other applications has indicated the real necessity of providing a weather resistant covering to avoid deterioration of the fiber and warpage.

While experience to date has shown the textolite-covered tubes to have excellent weathering characteristics, and to be free from warpage, organic materials cannot be expected to have a life comparable with inorganic materials such as porcelain. Periodic refinishing of the tubes with a weather-resistant paint, will increase the weather resistance, although examination of expulsion gaps from both service and accelerated life tests, have indicated that the textolite wrapping retains its dielectric and mechanical properties when subject to the weather under normal conditions, and that refinishing of tubes is not essential. There is a slight discoloration of the outer layer of the laminated paper after the original finish disappears. However, a careful checkup has shown this condition to have had no harmful effect on either the operating characteristics or life. The electrodes and all metal parts are of selected weather resisting alloys.

## Operating Experience With Expulsion Gaps

Operating experience where records have been obtained on expulsion protective gaps installed since 1933 is given in table I. It may be noted that they have been equally successful in overcoming the lightning outages for both low- and high- voltage systems. Care should be exercised, however, when interpreting the data regarding operations. The discharge indicator consists of a strip of soft copper bent across the open end of the tube. The escaping gases cause the strip to be moved from its position. Obviously this indicator does not count the actual number of operations. Usually the line is patrolled at intervals of from 1 to 2 weeks or only after lightning storms. Therefore a blown indicator can only be taken to mean that an operation has occurred since the last inspection of the line. Whether there has been one or more operations such as might occur with multiple lightning strokes will not be disclosed. It should be noted that every blown indicator does not necessarily mean a separate stroke to the line, as a severe lightning stroke may not only cause operation of all expulsion gaps on the structure nearest the point struck, but may cause operations on the adjacent structures as well. At present there is not sufficient data available to arrive at a factor which will permit determination of the number of strokes to the line in terms of indicator operations; however, it is expected that the number of strokes to the line will be somewhat less neglecting multiple strokes.

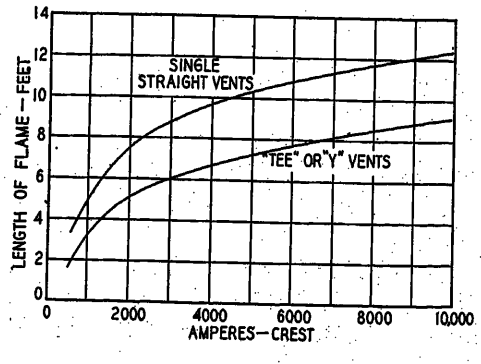



**Fig. 10. Maximum flame lengths for expulsion protective gaps**

## Table I—Expulsion Protective Gap Operation

| Year | Line | Notes | Company | Length Line | No. Gaps | No. Structures | Structure With Gaps | Tube Operation | Tube Flashover or Failed | Tripouts |
|---|---|---|---|---|---|---|---|---|---|---|
| **13.8-Kv Lines** | | | | | | | | | | |
| 1935 | 13,862 | | Consolidated Gas Electric Light & Power Company | 0.62 | 240 Ph. 40 Gr. | 120 | 40 | 25 Ph. 2 Gr. | 1† | |
| | 13,863 | 2–4 | | 0.62 | 240 Ph. 40 Gr. | 120 | 40 | 13 Ph. 6 Gr. | | 0 |
| 1935 | 87 | | | 3.38 | 213 Ph. 71 Gr. | 142 | 71 | 33 Ph. 6 Gr. | 1† | 0 |
| | 88 | 3–4 | | 3.38 | 213 Ph. 71 Gr. | 142 | 71 | 66 Ph. 9 Gr. | 0 | 0 |
| 1936 | 87 | | | | | | | | | |
| | 88 | 3–4 | | 3.46 | 240 Ph. 40 Gr. | 160 | 40 | 37 Ph. 5 Gr. | 1† | |
| 1936 | 60 | | | | | | | | | |
| | 61 | 1–4 | | | | | | | | |
| **69-Kv Lines** | | | | | | | | | | |
| 1935 | Holtwood** Engleside | | Pennsylvania Water & Power | 15.6 | 648 | 108 | 108 | 78 | 4† | 16* |
| 1936 | Holtwood** Engleside | | | 15.6 | 648 | 108 | 108 | 83 | 0 | 5 |
| 1934 | Safe Harbor Donegal | | Pennsylvania Power & Light Company | 13.4 | 390 | 130 | 130 | 28 | 0 | 0 |
| 1935 | Safe Harbor Donegal | | | 13.4 | 390 | 130 | 130 | 140 | 0 | 0 |
| 1936 | Safe Harbor Donegal | | | 13.4 | 390 | 130 | 130 | 166 | 0 | 0 |
| 1935 | Donegal Harrisburg | | | 17.5 | 550 | 175 | 175 | 65 | 0 | 0 |
| 1936 | Donegal Harrisburg | | | 17.5 | 550 | 175 | 175 | 138 | 0 | 0 |
| **110-Kv Lines** | | | | | | | | | | |
| 1934 | Laurinburg to Lumberton | | Carolina Power & Light Company (Steel tower)‡ | 25.5 | 648 | 216 | 216 | 150 | 1 | 1 |
| 1935 | Laurinburg to Lumberton | | | 25.5 | 648 | 216 | 216 | 37 | 0 | 5§ |
| 1936 | Laurinburg to Lumberton | | | 25.5 | 648 | 216 | 216 | 19# | 2 | 5§ |
| 1934 | Lumberton to Abbotsburg | | Carolina Power & Light Company (Wood H-frame)‡ | 18.7 | 491 | 167 | 167 | 23 | 0 | 0 |
| 1935 | Lumberton to Abbotsburg | | | 18.7 | 491 | 167 | 167 | 7 | 0 | 0 |
| 1934 | Abbotsburg to Wilmington | | Tidewater Power Company (H-frame)‡ | 48.6 | 1230 | 410 | 410 | 12 | 2 | 0 |
| 1935 | Abbotsburg to Wilmington | | | 48.6 | 1230 | 410 | 410 | 17 | 1 | 4§ |
| 1936 | Abbotsburg to Wilmington | | | 48.6 | 1230 | 410 | 410 | 16 | 1 | 1 |
| **132-Kv Lines** | | | | | | | | | | |
| 1933 | Glenlyn Roanoke | | Appalachian Electric Power Company | 65 | 816 | 292 | 292 | 16 | | |
| 1934 | Glenlyn Roanoke | | | 65 | 816 | 292 | 292 | 87 | 12† | 9 |
| 1934 | Roanoke-Fieldale | | | 68 | 921 | 301 | 301 | 156 | 3† | 2 |

1. Gaps on every fourth structure.
2. Gaps on every third structure.
3. Gaps on every second structure.
4. Gaps on each circuit of structures equipped (double circuit lines). Multiplex connection neutral tube common to both circuits.

† The cause for these flashovers has been determined and remedied.
* Twelve operations due to improper relay settings.
** Double-circuit steel-tower line.
‡These records are incomplete.
#Operations for only one patrol of line.
§Part of tripouts due to towers being knocked down and other causes than lightning.

Field experience has indicated to date that the average number of times an expulsion gap will be called upon to operate will not cause sufficient erosion of the fiber tube to constitute a factor in its life. From table I the number of operations per year has been worked out for the 3 circuit voltages for which records are available: 13.8, 69, and 138 kv, for which the years elapsing between operations of a given expulsion gap are, respectively, 6.7, 5.12, and 9.75.

While the present data indicate that operations occur on the lower voltage circuits more frequently than on the higher voltage circuits, further experience may show otherwise. In general this appears logical as the flashover voltage is lower and less stroke current is required to cause operation.

The operating records which have been obtained over the past 5 years with many thousand expulsion protective gaps are in themselves proof that line tripouts and outages caused by lightning can be practically eliminated. Thus, expulsion gaps increase the reliability of the system, improve the system stability, and reduce maintenance by preventing damage to the line insulators.

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# Empirical Method of Calculating Corona Loss From High-Voltage Transmission Lines

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## Synopsis

It is difficult to find a mathematical formula which will fully agree with observed data on corona loss under all conditions. Therefore, a purely empirical method of corona loss calculation has been developed, based on analysis and co-ordination of the experimental data which have been accumulated at Stanford University.

## Introduction

THERE IS great need for a method whereby the corona loss which will occur on a transmission line of any given description can be predetermined with a fair degree of accuracy. It is difficult to find a mathematical formula which will fully agree with observed data under all conditions. For this reason it has been thought desirable to develop a purely empirical method of corona loss calculation, based on analysis and co-ordination of the experimental data which have been accumulated at Stanford University over a number of years. These data are useful for such a purpose because they were obtained with considerable accuracy on sections of line erected out-of-doors in 3-phase configuration on actual insulator strings, and corresponding with present-day high voltage transmission practice in regard to the size, height, and spacing of the conductors.

The method developed is based on the experimental observation that the shape of the curve of corona loss versus voltage for cables of sizes used in high voltage transmission is virtually constant, and that the effect of variation in such factors as spacing, diameter, altitude, etc., is simply to shift this fundamental curve parallel to itself along the voltage axis. Having established the characteristic curve shape, the problem reduces to developing empirical rules for determining its location under any given set of conditions.

## Basic Data for Study

The results of the experimental work at Stanford University have been incorporated in a series of papers[1,2,3,4,5,6] which will be used as the basic material for the present study. The effect of incomplete removal of die grease was not at first fully appreciated, and puzzling inconsistencies resulted in some cases. Hence only certain curves of the references cited are suitable for use in the present analysis, and these with due qualification for the degree of cleanliness of the conductor surface. This matter is discussed in greater detail in appendix I.

The curves selected for use are assembled in figure 1, having been replotted to semilogarithmic co-ordinates from the original test points. It is readily seen that the relative positions of the curves, when considered with respect to conductor diameter, are somewhat inconsistent with one another. These apparent inconsistencies are largely due to differences in spacing, air density, and surface condition. It is the purpose of this paper to analyze the effect of these factors and properly co-ordinate the curves.

## Characteristic Shape of Corona Curve

The essential similarity in shape of the corona curves is apparent from figure 1. For calculations of ordinary accuracy any one of the curves (except that for the rope-lay cable) could be selected as typical with good results. However, close analysis shows divergencies which may possibly be of significance if very fine comparisons are being drawn or if the curves are to be extrapolated very far. Apparently the loss level at which the transition to the steeper slope occurs becomes higher as the diameter is increased. Apparently, also, the curves for the smooth segmental surface are slightly steeper than those for the stranded surface. In 2 cases the curves for stranded aluminum appear to be a little steeper than those for stranded copper, but this is believed to be largely a matter of experimental conditions. The curve for weathered stranded cable drops faster in the lower region, than does that for the same cable unweathered.

The curve for the rope-lay cable has a distinctive shape which should not be regarded as typical for any other cable. The corona characteristics of the rope-lay cable are notably poor.

For the convenience of the reader a few curves are assembled in figure 2 which are believed to be reasonably typical for various cases noted. For purposes of reproduction the numerical co-ordinates of several points on each curve are listed in table I. If any fine distinctions are to be drawn or comparisons made between the merits of different types of construction, however, the curves of figure 2 should by no means be accepted as basic, but the reader should go directly to figure 1 and use his own judgment as to what typical shape or shapes to select.

Turning to figure 3, the solid line represents the shape of a composite corona-loss curve for a cable $^1/_2$ inch to 2

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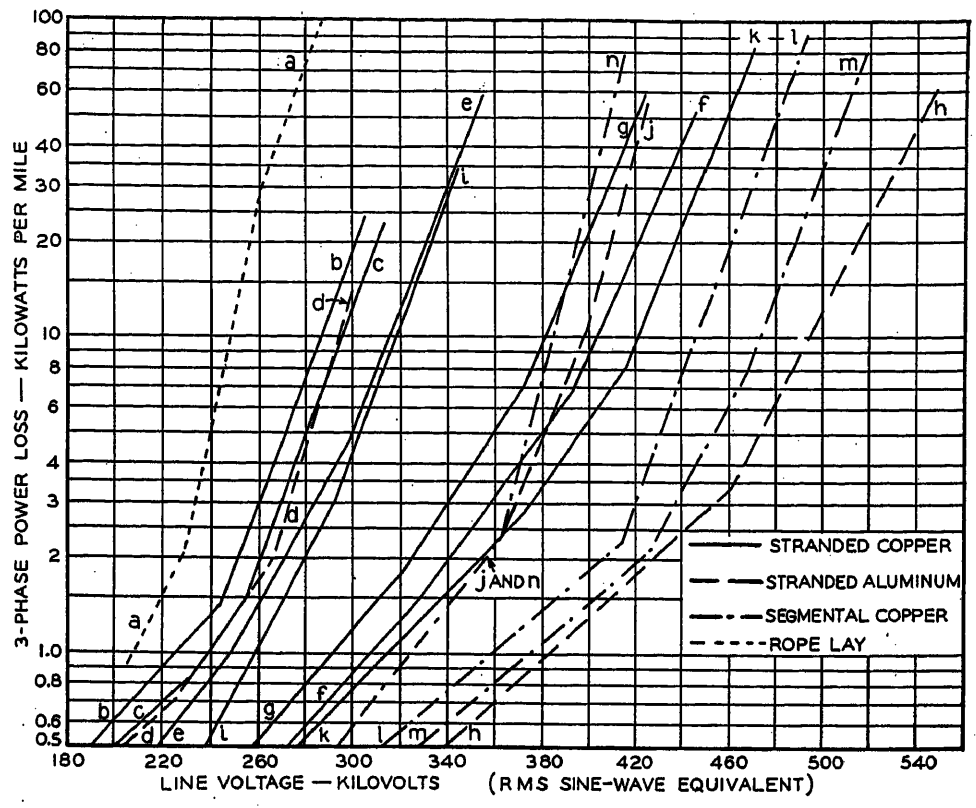
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**Fig. 1. Curves taken from references**

See table I for detailed description of conductors

| Curve Symbol | From Reference Number | Figure Number in Reference | Curve Number in Reference Figure |
|---|---|---|---|
| *a* | 1 | 11 | 2 |
| *b* | 1 | 11 | 3 |
| *c* | 1 | 11 | 4 |
| *d* | 1 | 11 | 5* |
| *e* | 3 | 7 | 2 |
| *e* | 3 | 5 | 5 |
| *f* | 3 | 7 | 4 |
| *g* | 3 | 7 | 5 |
| *h* | 3 | 7 | 7 |
| *i* | 3 | 5 | 4 |
| *j* | 4 | 12 | 3 |
| *k* | 4 | 12 | 4 |
| *l* | 4 | 12 | 6 |
| *m* | 4 | 12 | 8 |
| *n* | 5 | 2 | 1 |

* Caption in original paper should have read "unused."




inches in diameter, based on figure 2 but plotted in the more familiar rectangular co-ordinate form. The location with respect to the voltage scale is selected at random. If this curve is arbitrarily projected downward from a point $A$ corresponding to about 4 kw loss, it intercepts the voltage axis at a point $e_1$. The shape of this curve $e_1 AB$ then closely resembles that of the curve for a small highly polished wire ($^1/_4$ inch diameter or less), although the latter would of course be located farther to the left on the voltage axis. For the small polished wire, corona is of a fairly uniform character and begins at a definite voltage $e_1$ which in general is a function of the electrostatic gradient at the surface for a given impressed voltage, the nature and condition of the surface, and the air density. On the large cable, localized brushes of an unstable nature begin to occur at a relatively low voltage and cause the curve below point $A$ to diverge from the small-wire form. However, the upper part of the curve $AB$, corresponding to general corona, is the controlling element and fixes the location of the entire curve. Hence it is this upper portion or its projection $e_1$ on the voltage axis, which should be given consideration in analyzing the relative locations of various corona curves.

Analysis of many test curves for large cables shows that if the upper part $AB$ is projected to find $e_1$ the latter falls approximately at the voltage corresponding to one kw loss. This is a purely empirical observation of curve shape, but is very convenient for general use. Individual curves may deviate slightly from this general rule; but even so, the error resulting from such deviation is of second order magnitude. This is because in performing shifting operations $e_1$ is used merely as a basis for calculating the kilovolts shift corresponding to a certain percentage shift of the curve position. If the value of $e_1$ selected is, let us say, 10 per cent in error and the shift to be applied is 5 per cent, the curve after being shifted will be within one-half of one per cent of its correct position.

The curves plotted on semilogarithmic co-ordinates, figures 1 and 2, show a distinct "break" or increase of slope at about 2 to 9 kw loss. This break no doubt corresponds to the transition from the unstable brush pattern region to the region of general corona. The curves apparently follow the law $y = a^x$ fairly closely, with one or more changes in the value of $a$.

## Shift for Air Density

Air density is given by the expression

$$\delta = \frac{17.9\,b}{459 + t}$$

where $b$ is barometric pressure in inches of mercury, $t$ is temperature in degrees Fahrenheit. The denominator $459 + t$ represents absolute temperature.

With lowered density the air breaks down at a reduced gradient and $e_1$ is decreased, shifting curves to the left. Hegy and Dunlap[6] conducted experiments at Stanford University using number 2 B and S gauge copper wire in a tank which could be evacuated to simulate various barometric pressures. The curves for different pressures were found to be parallel, furnishing a striking demonstration of the constancy of curve shape. Owing to the small size of the wires there was virtually no brush-pattern region, but the wires went almost directly into regular corona. Hence it was easy to locate their intercepts on the voltage axis. These intercepts were found to be spaced in propor-

tion to a function somewhat under the first power of the pressure. Other tests have substantiated this conclusion.

The Hegy and Dunlap results also show that when the absolute temperature of the ambient air changes, producing an inverse change in the value of $\delta$, the intercepts follow the first power of $\delta$. However, studies made by Nuttall[7] indicate that when the cable temperature is higher than that of the ambient air, $\delta$ should be calculated on the basis of a temperature corresponding to the ambient plus $^2/_3$ the rise above ambient.

Although the Hegy and Dunlap tests were made on small-size conductor, they actually concern not so much the conductor itself as the mobility of the ions in the air around it. Therefore, the results should apply equally well to any conductor in full corona. Hence, if the upper or general-corona portion of a curve for large-size cable be projected onto the voltage axis, its intercept $e_1$ should vary with air density by a law similar to that demonstrated by Hegy and Dunlap for small-size conductor.

It will be convenient to reduce all the curves of figure 1 to terms of the normal barometric pressure at sea level (29.9 inches) and 76 degrees Fahrenheit, which makes $\delta = 1.00$. Since the tests were all made close to sea level the pressure changes involved are very small, and it will be sufficiently accurate to assume that the projected intercept $e_1$ varies as the first power of the pressure. As the intercept also varies inversely as the absolute temperature, this means that the intercept can be taken as varying in direct proportion to $\delta$.

In table II the air densities for each curve of figure 1 are computed, using in each case a temperature equal to the ambient plus $^2/_3$ the cable rise above ambient. These values of $\delta$ are reproduced in column 4 of table III. Column 5 of the latter table shows the kilovolts for one kw loss for each curve, which is taken as representing $e_1$. Then in column 6 the kilovolts for one kw loss is multiplied by $1.00/\delta$ to give a shifted position of $e_1$ for standard air density $\delta = 1.00$.

## Shift for Spacing

Curves (*f*) and (*g*), figure 1, are both for 1.49-inch copper conductor with stranded surface. The former is at 30-foot spacing, the latter at 22-foot. The curves appear quite parallel, with possibly a slight divergence at the higher losses. Column 6 of table III shows that the kilovolts for one kw loss on the 2 curves are respectively 307 and 295, after the shift to $\delta = 1.00$ has been applied. The curve for the smaller spacing is therefore to the left of that for the larger spacing. The reason for this is that with the smaller spacing the electrostatic capacitance between the wires is greater, and hence the concentration of stress at the conductor surface is greater with the same applied voltage. Since the amount of charging current is an index of the concentration of stress, we might expect the variation in charging current to be an inverse index of the variation in $e_1$.

The ratio of voltages, 30-foot spacing to 22-foot spacing, at the one-kw loss level is $307/295 = 1.04$. Charging currents at the 2 spacings, calculated by the method given in Pender's Handbook,[8] show an inverse ratio of 1.052 for the center conductor, and 1.037 for either outer conductor. These values agree with the actual observed values of charging current. Apparently the outer conductor charging current is the more accurate index of the variation in $e_1$.

Of course, the mere fact that the $e_1$ ratio checks the charging current ratio for one experimental point does not prove that the charging current is necessarily a correct index of $e_1$ for all other variations in spacing. It is merely the best hypothesis that is available in the light of present knowledge. It should be applied with caution, especially where the range covered is very different from that represented by the change from 22-foot to 30-foot spacing. Fortunately the curves in figure 1 are all at spacings of 20, 22, or 30 feet, and so in reducing them all to terms of a common spacing—say 22 feet—no correction need be applied greater than that of 1.04 already experimentally established for the change from 22 to 30 feet. For the small change from 20 to 22 feet an interpolation, direct or logarithmic, should be sufficiently accurate, giving in either case a correction factor of 1.01.

**Fig. 2. Typical corona curves for weathered cable**

Voltages above and below voltage for 4-kw loss

Curve 1—Concentric strand 0.9- to 1.0-inch diameter

Curve 2—Concentric strand 1.4- to 1.5-inch diameter

Curve 3—Smooth segmental 1.1-inch diameter

Curve 4—Smooth segmental 1.4-inch diameter

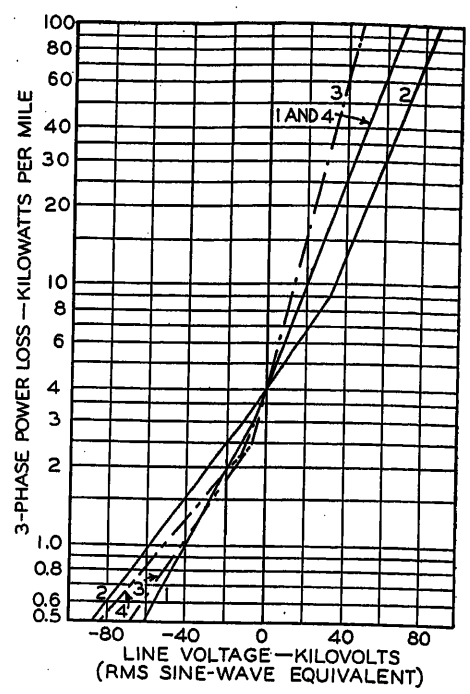



**Table I—Points for Typical Corona Curves of Figure 2**

| 3-Phase Kilowatts Loss Per Mile | Line Voltage—Kilovolts Above or Below Kilovolts for 4-Kw Loss | | | |
|---|---|---|---|---|
| | Curve 1 | Curve 2 | Curve 3 | Curve 4 |
| 0.5 | −61 | −87 | −69 | −84 |
| 1.0 | −40 | −59 | −42 | −51 |
| 2.0 | −19 | −29 | −15 | −19 |
| 2.2 | | | | −12 (break) |
| 2.4 | | | − 9 (break) | |
| 2,8 | | −14 (break) | | |
| 3.0 | − 7 (break) | | | |
| 4.0 | 0 | 0 | 0 | 0 |
| 6.0 | + 9 | +15 | + 6 | + 9 |
| 9.0 | | +32 (break) | | |
| 10.0 | +20 | +34 | +13 | +20 |
| 20.0 | +35 | +55 | +24 | +35 |
| 40.0 | +50 | +66 | +34 | +50 |
| 100.0 | +70 | +88 | +48 | +70 |

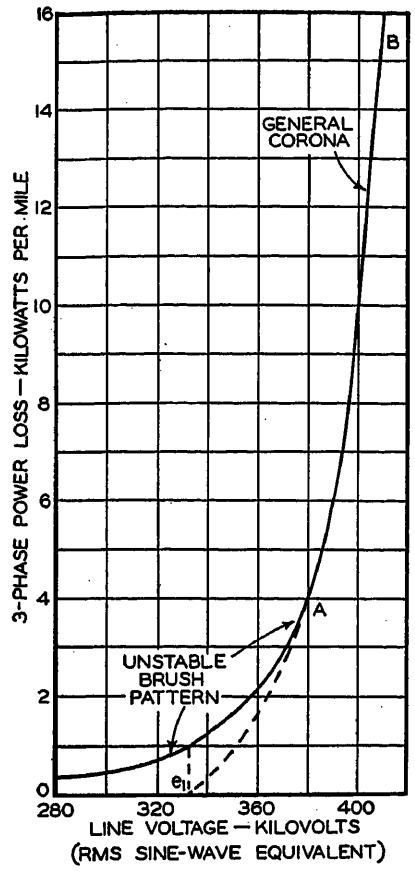



**Fig. 3. Composite corona curve for cables 1/2 to 2 inches diameter based on typical curves of figure 2, converted to rectangular-co-ordinate form**

If the transition from one spacing to another occurs with a conductor size different from the 1.49-inch diameter applicable to curves (*f*) and (*g*), the correction factor would not be expected to be affected much, as a study of capacitance tables indicates that the ratio of charging currents for two different spacings varies only slightly with conductor diameter in the range 1/2 to 2 inches.

In column 7 of table III are listed the factors for correcting each curve to terms of 22-foot spacing. Applying these factors to the kilovolts for one kw at $\delta = 1.00$ given in column 6, there are obtained the values of column 8. The latter represent the kilovolts at one kw for $\delta = 1.00$, 22-foot spacing. Comparing these figures with the corresponding points from the original curves, column 5, the difference (column 9) represents the net kilovolt shift to cover the corrections to standard air density and spacing. Since it has been established that changes in air density and spacing produce virtually parallel shifts of the curves, then the kilovolts shift at any other loss level will be the same as the kilovolts shift at the one-kw loss level. For instance, column 10 of table III gives the kilovolts for 4-kw loss on the original curves of figure 1, and column 11 gives the same figures with the kilovolt shift of column 9 added or subtracted as the case may be. Thus column 11 represents the kilovolts for 4 kw loss at 22-foot spacing, $\delta = 1.00$.

## Shift for Weathering

Curves (*e*) and (*i*) of figure 1 show the effect of weathering on a new 1.125-inch copper stranded cable after it had been dragged in loose gravel on level ground. In the original record (figure 5, Carroll and Cozzens[3]) the intermediate stages are also shown. It is there seen that the dragging moved the corona curve very sharply to the left, compared to its position just after the gasoline, soap and water wash of the new cable; but that almost at once, the curve started to move back to the right due to weathering. After 4 months it had returned approximately to its original location. In fact, in figure 5 of Carroll and Cozzens (and also in figure 1 of the present paper, where the initial and final curves are reproduced), the final curve lies actually to the right of the initial curve. However, the temperature was higher, and the barometric pressure lower, at the time the final curve was taken; hence the air density was appreciably less. When the curves are both placed on an equal footing of standard air density, as is done in table III, column 8, it is found that they become virtually coincident at the one-kw point. Observation showed that after the 4-month weathering period no further appreciable change occurred.

The weathered and unweathered curves differ in shape in the lower or brush-pattern region. Hence their true relationship is shown more clearly by focussing attention on a higher level of loss—say 4 kw, where the general corona region is entered and the 2 curves become nearly parallel. At this level column 11 of table III shows that under standard air density conditions the curve (*i*) for dragged and weathered conductor lies at 291 kv and the curve (*e*) for new conductor at 296 kv. This represents a correction factor of 291/296 = 0.983 to be applied to the kilovolts for 4-kw loss of any curve taken just after a gasoline, soap and water wash of the degree of thoroughness which prevailed in the experiments for the Carroll and Cozzens paper,[3] to represent the effect of dragging and weathering as described in the same paper.

It may be said at this point that despite the divergence in shape, the use of the kilovolts for one kw loss to represent $e_1$ in applying the spacing and air-density shifts to the curve for dragged and weathered cable introduced no ap-

**Table II—Values of Air Density for Curves of Figure 1**

| Figure 1 Curve Symbol | Barometric Pressure in Inches Mercury | Ambient Temperature, Degrees Fahrenheit | Cable Temperature, Degrees Fahrenheit | Rise Degrees Fahrenheit | Ambient + 2/3 Rise Degrees Fahrenheit | Air Density Based on Preceding Column |
|---|---|---|---|---|---|---|
| *a* | 29.90 | 67.5 | 76.5* | 9* | 73.5 | 1.006 |
| *b* | 29.87 | 64 | 73* | 9* | 70 | 1.011 |
| *c* | 29.90 | 68 | 77* | 9* | 74 | 1.006 |
| *d* | 29.94 | 80 | 89* | 9* | 86 | 0.985 |
| *e* | 29.84 | 77 | 86* | 9* | 83 | 0.987 |
| *f* | 30.05 | 71 | 80 | 9 | 77 | 1.002 |
| *g* | 29.85 | 80 | 82 | 2 | 81 | 0.990 |
| *h* | 30.05 | 66 | 80 | 14 | 76 | 1.007 |
| *i* | 30.17 | 60 | 68 | 8 | 66 | 1.030 |
| *j* | 29.75 | 93 | 102 | 9 | 99 | 0.956 |
| *k* | 29.92 | 71 | 80* | 9* | 77 | 1.000 |
| *l* | 29.91 | 76 | 88 | 12 | 84 | 0.986 |
| *m* | 29.57 | 82 | 94 | 12 | 90 | 0.966 |
| *n* | 30.16 | 60.5 | 68 | 7.5 | 65.5 | 1.032 |

* Estimated

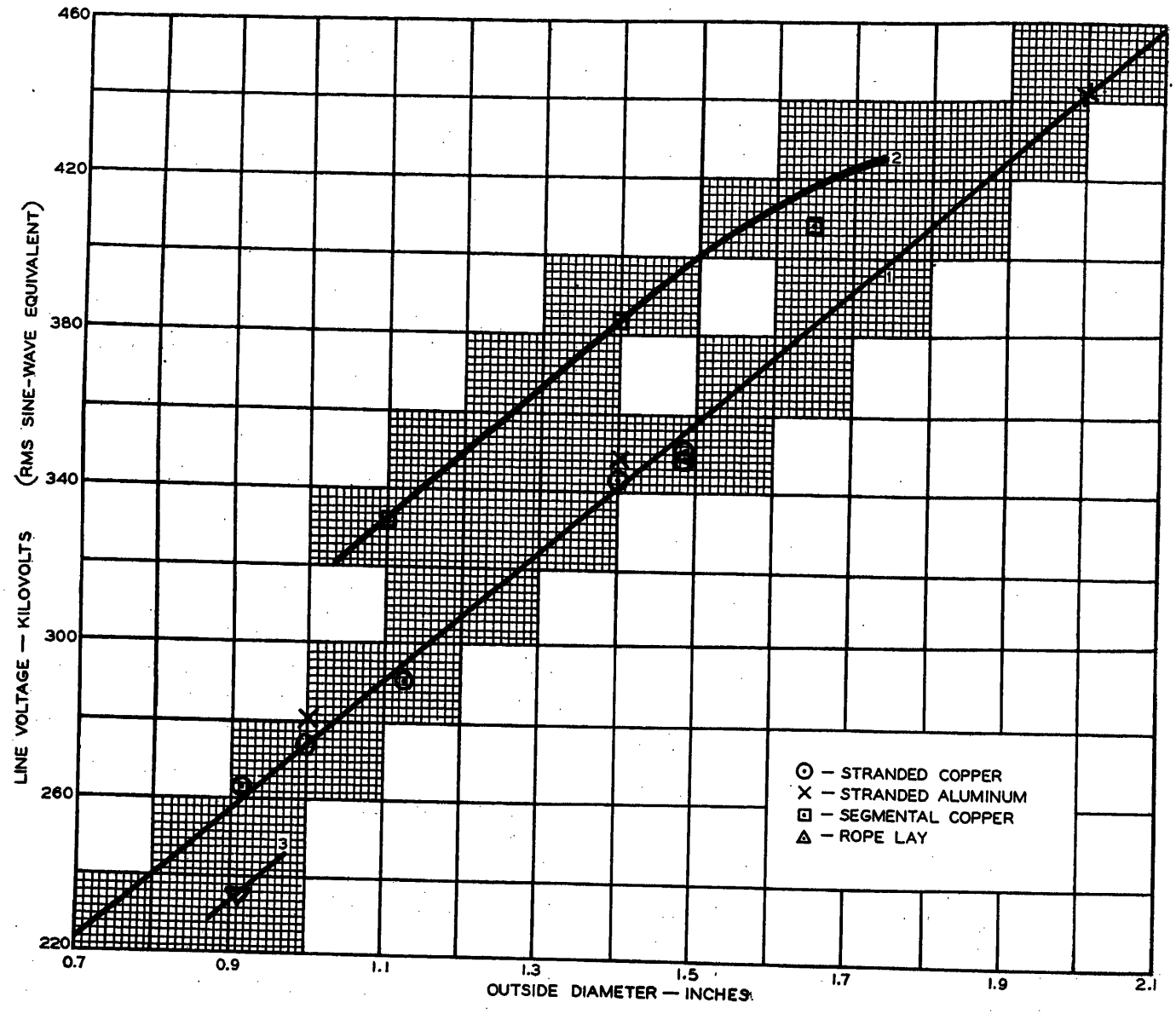



**Fig. 4. Co-ordination curves**

Kilovolts for 4-kw 3-phase corona loss per mile. Dragged and weathered conductor; 22-foot flat spacing; sea level; air density = 1.00; 60 cycles per second; Curve 1—Concentric strand; Curve 2—Smooth segmental; Curve 3—Rope lay

preciable error, because in that case the relation of a weathered to an unweathered curve was not under analysis. The one-kw point might have been a few kilovolts in error in representing the true $e_1$ of the dragged and weathered curve, but this would have a negligible effect on the amount of the shift obtained by applying the correction factors for air density and spacing.

It has been stated that the correction factor for weathering as determined from curves (*e*) and (*i*) applies only when the initial condition is similar to that just after a gasoline, soap and water wash of about the degree of thoroughness which prevailed in the experiments for the Carroll and Cozzens paper.[3] This covers only curves (*e*) to (*i*), figure 1. Curves (*j*) to (*n*) inclusive, which were taken from the Carroll, Cozzens, and Blakeslee paper[4] and the Carroll and Simmons paper,[5] represent a somewhat more thorough type of cleaning than do the curves of the earlier papers, and hence may be expected to lie relatively a little farther to the right than do the earlier curves. Hence it would not be reasonable to expect the weathering process to be able to return the cable, after dragging, to a condition having a curve as close to the initial one, as was true in the earlier cases. A weathering factor of 0.92 might be estimated for the later curves (*j*) to (*n*). Conversely, the very early curves (*a*) to (*d*), taken from figure 11 of Carroll, Brown, and Dinapoli[1] were not quite so well cleaned as the Carroll and Cozzens curves, and so would have a weathering factor of perhaps about 0.99.

It is recognized that the estimates of weathering factor, other than that for the curves of the Carroll and Cozzens paper where a definite experimental tie exists, are more or less empirical. However, they are believed to be quite

reasonable, because when the kilovolts for 4-kw loss under standard conditions given in column 11 of table III are corrected for weathering according to the factors derived above and the resulting voltages (column 13) are plotted as functions of conductor diameter, the points fall in such a way as to define a set of smooth curves (see figure 4).

## Co-ordination Curves

The curves of figure 4 represent the kilovolts for 4-kw loss for a group of conductors of various diameters and structures all reduced, so far as is possible in the light of present knowledge, to terms of the same air density, conductor spacing, handling, and weathering. As such they constitute a co-ordination of existing data and furnish a convenient means of interpolation for determining losses on conductors not covered by published corona-loss curves.

The points fall naturally into 2 groups—one for the smooth segmental cable (type *C* of the Carroll, Cozzens, and Blakeslee paper[4]) and the other for stranded cable. In addition there is a lone point for rope-lay cable which falls far below the curve for concentric strand. This rope-lay cable has an extremely irregular surface, as it consists of 7 large strands twisted together, each of these large strands being composed of 7 wires, 0.101 inch in diameter. Hence it is not surprising that its corona characteristics should be notably poor.

At the other extreme of surface smoothness lies the segmental cable, the 3 points for which lie well above the curve for stranded cable and appear to define a curve of their own. The authors have ventured to apply a curve shape for this cable which misses the point for 1.65 inch diameter, because the sample of the latter which was tested was of foreign manufacture and had been handled much more than the other cables.

That the curve for smooth segmental cable actually belongs above that for stranded cable is brought out especially well by the 3 points for 1.4 inch diameter. These were all taken from the curves of the Carroll, Cozzens, and Blakeslee group and hence the cleaning conditions were similar.

The transition from rope-lay to smooth segmental cable represents a variation between the extremes of very large strand size and zero strand size. Between these extremes lie the points for the ordinary concentrically stranded cable; and as already noted, these points all fall very close to a representative straight line. This is despite the fact that the strand sizes in the individual cables vary considerably. However, it is probable that the ratio of strand size to diameter is the really significant factor, because this is a measure of the degree of irregularity of the cable. In this respect the cables classed as "stranded" varied from a ratio of 0.065 to a ratio of 0.11. Attempts to find any reliable evidence of variation in loss with strand size ratio within this range were unavailing, and it is apparent that the differences, if they exist, are so small as to be masked by slight differences in surface cleanliness, etc.

The points for stranded aluminum might possibly be thought to define a curve of slightly different location than that for stranded copper; but it is believed that this is merely a matter of slight variations in experimental conditions and that no true distinction exists. Many attempts to establish a difference between the characteristics of the copper and aluminum surfaces have led to the conclusion that there is none. (See for example, Weidlein's paper.[2])

## Effect of Conductor Height

Nothing has been said as yet of the effect of conductor height above the ground. This can be neglected in most cases, because the height of the experimental lines at Stanford corresponded fairly well with general transmission-line practice. The minimum clearance to the earth was 30 feet, and the maximum 46 feet. No difference in the corona on the upper and lower parts of the catenary could be observed. A mean conductor height of 35 feet gave a

**Table III—Reduction of Curves of Figure 1 to Standard Conditions**

| Column | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | Kilovolts for One Kw Loss | | | | | Kilovolts for 4-Kilowatts Loss | | | |
| Curve Symbol | Outside Diameter, Inches | Conductor | Flat Spacing, (Feet) | Air Density $\delta$ | Original Curve | Times 1.00/$\delta$ | Correction to 22-Foot Spacing | Corrected Curve, 22-Foot Spacing $\delta$ = 1.00 | Net Kilovolt Shift | Original Curve | Corrected Curve, 22-Foot Spacing $\delta$ = 1.00 (Column 10 + Column 9) | Further Correction for Weathering | Weathered Curve, 22-Foot Spacing $\delta$ = 1.00 |
| *a* | 0.91 | Rope Lay | 20 | 1.006 | 208 | 207 | 1.01 | 209 | + 1 | 237 | 238 | 0.99 | 236 |
| *b* | 0.91 | Stranded copper | 20 | 1.011 | 227 | 224 | 1.01 | 227 | 0 | 267 | 267 | 0.99 | 264 |
| *c* | 1.0 | Stranded copper | 20 | 1.006 | 239 | 238 | 1.01 | 240 | + 1 | 276 | 277 | 0.99 | 274 |
| *d* | 1.0 | Stranded aluminum | 20 | 0.985 | 239 | 243 | 1.01 | 245 | + 6 | 278 | 284 | 0.99 | 281 |
| *e* | 1.125 | Stranded copper | 22 | 0.987 | 249 | 252 | 1.00 | 252 | + 3 | 293 | 296 | 0.983 | 291 |
| *f* | 1.49 | Stranded copper | 30 | 1.002 | 308 | 307 | 1/1.04 | 295 | −13 | 370 | 357 | 0.983 | 351 |
| *g* | 1.49 | Stranded copper | 22 | 0.990 | 292 | 295 | 1.00 | 295 | + 3 | 352 | 355 | 0.983 | 349 |
| *h* | 2.0 | Stranded aluminum | 30 | 1.007 | 383 | 381 | 1/1.04 | 366 | −17 | 467 | 450 | 0.983 | 442 |
| *i* | 1.125 | Stranded copper* | 22 | 1.030 | 259 | 251 | 1.00 | 251 | − 8 | 299 | 291 | 1.00 | 291 |
| *j* | 1.4 | Stranded aluminum | 30 | 0.956 | 325 | 340 | 1/1.04 | 327 | + 2 | 376 | 378 | 0.92 | 348 |
| *k* | 1.4 | Stranded copper | 30 | 1.000 | 315 | 315 | 1/1.04 | 303 | −12 | 385 | 373 | 0.92 | 343 |
| *l* | 1.4 | Segmental copper | 30 | 0.986 | 360 | 365 | 1/1.04 | 351 | − 9 | 427 | 418 | 0.92 | 384 |
| *m* | 1.65 | Segmental copper | 30 | 0.966 | 376 | 389 | 1/1.04 | 374 | − 2 | 447 | 445 | 0.92 | 409 |
| *n* | 1.1 | Segmental copper | 22 | 1.032 | 325 | 315 | 1.00 | 315 | −10 | 371 | 361 | 0.92 | 332 |

* Dragged and weathered; all other curves immediately after gasoline, soap and water wash

calculated value of charging current which checked well with observed values. In these calculations the ground plane was assumed to be at the surface of the earth, which appears to be true electrostatically for the normal balanced condition even where it is not true from the standpoint of return flow of ground fault currents. Thus the element of variation of ground plane level below the earth's surface is eliminated from corona calculations, and hence different transmission lines will not vary greatly in mean conductor height. Any correction that is to be applied will be quite small, as it enters logarithmically from the inverse charging-current calculation.

## Effect of Frequency

The curves of figure 1 were all made at 60 cycles. For other frequencies there will be no horizontal shift of the curves, but all ordinates should be multiplied by a correction factor. For frequencies not far different from 60 cycles this factor is given closely enough by $f/60$.

## Effect of Atmospheric Conditions

Humidity will have practically no effect on the corona loss if the conductor is absolutely clean. When the cable is dirty or greasy, however, increase in humidity tends to increase the loss.

A rainstorm increases the corona loss temporarily, due to the formation of brushes from the drops of water which adhere to the surface of the conductor. The same is true of a deposit of fog droplets or dew upon the surface.

Abundance of rain may be expected to accelerate the weathering process somewhat, especially if grease removal is involved.

## Summary—Determination of Corona Loss Under Any Given Conditions

To determine the corona loss to be expected from any conductor under any set of conditions, the procedure is as follows:

1. Read from figure 4 the root-mean-square kilovolts corresponding to 4-kw 3-phase loss per mile for the conductor in question. If the ratio of strand size to diameter is much above 0.11, interpolate a new curve between that for "concentric strand" and that for "rope lay."

2. Figure 4 represents the ultimate condition of a cable dragged over crushed rock in the manner described in the Carroll and Cozzens paper[3] and subsequently weathered for several months. If any departure from this condition is anticipated an appropriate correction should be applied to the kilovolts for 4-kw loss, as follows:

(*a*). It does not matter much whether the cable was originally clean or greasy, except that in the latter case it may take longer for the condition of figure 4 to be attained.

(*b*). If the cable is dragged very severely over jagged rocks which actually abrade the surface, it can never be expected to return to the condition represented by figure 4.

(*c*). If the cable is installed with no dragging at all the weathering process should gradually return it, even if it was originally greasy, nearly to the condition of a new clean cable. See (*d*). Much progress beyond this point seems unlikely.

(*d*). For a new cable thoroughly cleaned by the technique of the Carroll, Cozzens, and Blakeslee paper[4] the kilovolts for 4-kw loss will exceed the values of figure 4 by about 8 per cent (representing division by the factor 0.92).

3. Plot the kilovolts for 4-kw loss, corrected as above, on semilogarithmic co-ordinates representing loss vertically and voltage horizontally.

4. Draw through the point so plotted, a corona curve of appropriate shape. As a short cut this may be based on the "typical curves" of figure 2, though if any fine distinctions between different types of cable are to be drawn, it is recommended that the reader use his own judgment based directly on the experimental curves of figure 1. If a new clean cable is to be considered, the slope of the lower portion of the curve should be made a little less steep than is indicated by figure 2.

5. After the curve is drawn, it should be shifted at the one-kw loss point to correct for air density and conductor spacing. For the spacing shift use the following table:

22 to 30 feet—multiply kilovolts by 1.04
22 to 20 feet—divide kilovolts bo 1.01

Interpolate logarithmically. For extrapolations of any great range, correct in inverse proportion to the charging current on the outer wire. This method of extrapolation has not been completely verified, however, and should be used with caution.

For the air density shift, since the values of figure 4 are based on a density of 1.00, multiply the kilovolts for one kw by the anticipated air density, using a temperature equal to the ambient plus $^2/_3$ the cable rise. This will be sufficiently accurate where the change in barometric pressure is not very great. If a wide range is to be covered, as by going to a high altitude, the shift should probably be made more nearly in proportion to the $^2/_3$ power of the barometric pressure. Until experimental work can be carried out at high altitudes it is impossible to be completely certain of this rule, as it now rests largely on laboratory evidence.

A convenient way to perform the shift at the one-kw point is to compute the total net shift and determine the new kilovolts for one kw. Then make a movable voltage scale and slide it sidewise until this new voltage is directly under the one-kw loss point of the curve. Securing the movable scale in this location it is then possible to read off the loss at any desired voltage, as for example 230 kv. This method is especially helpful if a number of different conditions of altitude, temperature, etc., are to be investigated for a given line.

A numerical example of the loss calculation is worked out in appendix II.

## Conclusions

1. Experimental evidence shows that the shape of the curve of corona loss versus voltage for cables of sizes used in high voltage transmission is virtually constant

2. The major effect of variations in diameter, spacing, altitude, temperature, surface structure, and surface condition is to shift the

characteristic curve parallel to itself along the voltage axis

3. The amount of the shift which will result from any given change in conditions can be determined empirically on the basis of experimental data. Thus the characteristic curve can be placed in a location corresponding to any given set of conditions and the loss for any voltage determined

4. By this means corona-loss calculations for large conductors are placed on a foundation of carefully co-ordinated experimental evidence.

## Appendix I—Selection of Curves From References

The paper by Carroll, Brown, and Dinapoli[1] is the earliest of the references to be considered, and in this paper the importance of thorough cleaning was just beginning to be understood. Though some washing of conductors was carried on, it is now known that by later-day standards this cleaning was imperfect in many cases, leaving some die grease between the strands which kept oozing out, collecting dust, and giving erratic results. It is believed, however, that the curves of figure 11 may be accepted for comparison with later data, having been taken immediately after a fairly good gasoline, soap and water wash. Curve 1 of figure 11 is to be rejected, however, because the conductor had surface irregularities which resulted in abnormally poor corona characteristics.

The paper by Weidlein,[2] next in order of publication, contains no curves taken with conductor sizes and spacings used in high-voltage transmission lines, but is important in pointing out the effect of surface conditions and in showing that "corona losses from copper and aluminum conductors are the same after weathering."

In the next paper, that by Carroll and Cozzens,[3] the washing methods were fairly good. Curves 2, 4, 5, and 7 of figure 7, namely, those which are marked "washed," may be accepted for use in the present analysis. Those marked "new" cannot be used due to the grease present on the surfaces. Figure 5 of this reference is also very important because it shows clearly the relation between corona loss on a washed new cable and that to be expected after the cable has been dragged on crushed rock and then erected and allowed to weather for several months. Figures 4 and 6 are not particularly pertinent in the present study as they have to do with cable which has been buffed, scratch-brushed, etc.

In the paper by Carroll, Cozzens, and Blakeslee,[4] improvement was made in cleaning methods, as it had been learned that all grease must be removed from between the strands and inside the cable to avoid any traces of oozing afterward. All the earlier curves of this paper are summarized in figures 12 and 13. Figure 12 is for the cables after gasoline, soap and water wash; figure 13, after a clear water wash. The latter gets the cables a little cleaner for the moment but the results do not last any length of time at all, so that comparative measurements are most difficult. The gasoline, soap and water wash, however, leaves the conductor surface in a quite stable condition which is satisfactory for comparisons and which is modified only very gradually as weathering occurs. Furthermore, it is important to stick to the "gasoline, soap and water wash" curves to preserve the important tie-in between loss under this condition and that occurring after dragging and weathering, given by figure 5 of Carroll and Cozzens.

In figure 12 of Carroll, Cozzens, and Blakeslee, curves 5 and 9 are reproductions of curves 4 and 7, figure 7, Carroll and Cozzens. Curve 1 is to be eliminated due to incomplete grease removal and difficulty in obtaining smooth stranding with the multiple I-beam construction. Curve 2 is also eliminated because it was calculated from single-phase measurements and because the cleaning is believed to have been incomplete. Curve 7 is eliminated because it was made on a sample of cable produced before manufacturing methods had been perfected, resulting in surface irregularities. This leaves curves 3, 4, 6, and 8 of figure 12 as the only ones furnishing data pertinent to the present study.

In the Carroll and Simmons paper[5] the washing methods were of the best and curve 1 of figure 2 can well be utilized in the present study.

## Appendix II—Numerical Example

### Problem

Determine the corona loss to be expected on a 50-mile section of line located at 1,250 feet elevation, temperature 100 degrees Fahrenheit. The line is to be built of 0.95-inch concentric-strand cable and operated at 230 kv. The conductors will be arranged in a flat horizontal configuration with 25-foot spacing. They will be rendered reasonably free from grease at the factory.

### Solution

From figure 4, curve 1, the kilovolts for 4 kw = 267.

In the absence of any information to the contrary it is a fair assumption that the dragging and weathering conditions will be similar to those applying in figure 4 (except for the first few months when residual grease may be present to increase the loss). Hence the kilovolts for 4 kw read from figure 4 can be used directly with no correction applied.

Curve 1 of figure 2 may be used as a short cut to indicate the typical curve shape. The zero of the voltage scale then represents 267 kv. The curve passes through one-kw loss at minus 40 kv, which would then represent 267 − 40 = 227 kv. This can be taken as the approximate value of $e_1$.

The spacing is to be changed from 22 feet in figure 4, to 25 feet in the actual case. A change from 22 feet to 30 feet, or 8/22, gives a correction factor of 1.04. The change contemplated is from 22 feet to 25 feet, or 3/22.

By logarithmic interpolation the new correction factor would be:

$$c_s = 1.00 + \left[\frac{\log (3/22)}{\log (8/22)} \times (1.04 - 1.00)\right] = 1.00 + \left[\frac{\log 3}{\log 8} \times 0.04\right] = 1.00 + \left[\frac{0.4771}{0.9031} \times 0.04\right] = 1.02$$

The barometric pressure at 1,250 feet is approximately 28.5 inches of mercury. Hence

$$\delta = \frac{17.9 \times 28.5}{459 + 100} = 0.913$$

Hence net correction factor for $e_1$ is $0.913 \times 1.02 = 0.931$

Corrected $e_1 = 0.931 \times 227 = 211$ kv at one kw.

If curve 1 of figure 2 is considered to be so located that its one-kw loss is at the new $e_1$, or 211 kv, then −40 on the scale represents 211 kv. 230 kv will be 19 kv farther to the right or at (−40 + 19) = −21 kv. The loss for this point on the scale is seen to be about 1.9 kw per mile. Hence the loss for the 50-mile section of line will be $50 \times 1.9 = 95$ kw.

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# Properties of Saturants for Paper-Insulated Cables

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## Synopsis

The results of tests made on 9 viscous mineral oils of various types and on mixtures of these oils with 8 resins are presented. The physical and electrical properties, stability to oxidation, and stability to gaseous ionization are correlated with the viscosity index and chemical composition of the oils and resins. The catalytic effects of metals on oil oxidation are studied. Gaseous ionization in insulation voids is found to exert a physical pressure and to accelerate saturant oxidation.

## Introduction

IT is generally agreed that the selection of saturating compounds for impregnated paper insulation is a problem of great importance and one which requires considerable investigation. This problem has been reviewed in the past by Riley and Scott[1] and others. The saturants must meet a number of requirements concerning their physical properties such as viscosity, set point, coefficient of expansion, and surface tension. These are particularly important for materials used in solid-type, paper-insulated cables (the type commonly used at 66 kv and lower voltages). Here, correct physical properties are necessary to minimize migration of the saturant and consequent void formation caused by the combined action of gravity heads and cable operating temperature cycles. In addition, the saturants must meet certain requirements concerning electrical and stability properties, the most important of which are the following:

1. A reasonably low power factor.
2. A high oxidation stability (as measured by power factor change) so that the power factors of cables may be uniform notwithstanding unavoidable chances for oxidation in manufacturing operations, and so that possible exposure of the cable insulation to oxygen will not result in greatly increased power factor.
3. A low susceptibility to contamination (as affecting the power factor) so that possible exposure of the saturant to impurities both before and after it is absorbed by the paper will not result in greatly increased power factor.
4. A high stability to gaseous ionization (resistance to wax formation and gas evolution) caused by electrical stress in voids which may form in the insulation with use so that the amount of gaseous ionization will not increase cumulatively.

It is sometimes stated that it is better to expend effort in reducing the possibilities of oxidation and contamination than to mitigate them in other ways. Higher impregnating tank vacuums, inert gas flushing, and improved technique in both manufacturing and installing cables are steps in this direction. The users of cables, however, have obtained considerable evidence that the power factors of the most carefully made cables increase with time, even when the cables are stored. It is therefore still considered advisable to choose saturants which are resistant to oxidation and contamination, provided other properties are not sacrificed.

Cable saturants usually consist of mineral oils and mixtures of these oils with resinous materials. Materials of these classes have recently been considerably improved in certain respects. In this paper are presented the results of an extended research in which both the older and more recently developed materials have been investigated to determine their suitability as saturants for solid-type, paper-insulated cables. Much of it is also applicable to impregnated paper and insulating oils in general.

The general procedure followed in this investigation was to subject various prospective materials to a series of chemical, physical, electrical, and stability tests in order to determine how well they meet the requirements. The advantages of this procedure are several: (1) a great many materials may be investigated at comparatively small expense, leaving only the most promising materials to be tried out on the larger scale of fabricating test lengths of cable and subjecting them to load cycle life-tests; (2) small scale tests are subject to closer control than large scale tests; (3) the exact points of strength or weakness of a material are indicated and not merely the fact that it is good or poor; (4) the physical, electrical, and stability properties may be correlated with fundamental chemical properties. This last information can be used to indicate directions in which to look for better materials.

## Experimental Method

Measurements of power factor and dielectric constant were made on the materials at 60 cycles by means of a modified Schering bridge. The detector circuit of the bridge consisted of a 4-stage resistance-capacity coupled amplifier, 60-cycle band-pass filter, and an ordinary copper-oxide voltmeter which was not affected by mechanical vibrations. Magnetic pick-up was eliminated by connecting the amplifier directly to the detector terminals of the bridge, the entire detector circuit being shielded at guard potential. The power factor sensitivity was 0.00001 with 2,000 volts applied.

The electrical properties of the saturants were measured at 25, 45, 65, and 85 degrees centigrade at a stress of 15 volts per mil. The test cell was of nickel and glass construction, of the type described by Balsbaugh, Kenney,

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1. For all numbered references see list at end of paper.

and Herzenberg,[2] but of larger dimensions so that the air capacity was 89 micromicrofarads.

The electrical properties of cable paper impregnated with the saturants were also measured at 25, 45, 65, and 85 degrees centigrade. The test cell pictured in figure 1 was used, the method of preparing the samples being as follows. Several sheets of paper were placed between the disk electrodes and subjected to a mechanical pressure of 15 pounds per square inch by means of the springs in order to ensure good contact between paper and electrodes. The paper was dried at 110 degrees centigrade and 1 millimeter mercury absolute pressure for several hours and the saturant was simultaneously degassed under the same conditions. The saturant was then admitted to the cell and allowed to impregnate the paper for 2 hours. After this period the specimen was cooled to 85 degrees centigrade and an inert gas was admitted until one-half atmospheric pressure was attained. With this procedure the moisture content of the impregnated paper was less than 0.2 per cent when measured by the ASTM method *D*95-24 using xylol. Variations in moisture content below 0.2 per cent were found to have no measurable effects on the power factor of the impregnated paper. That the procedure yielded a thorough impregnation was shown by the fact that the ionization factor (increase in power factor on raising the stress from 25 to 125 volts per mil at room temperature) was less than 0.00003.

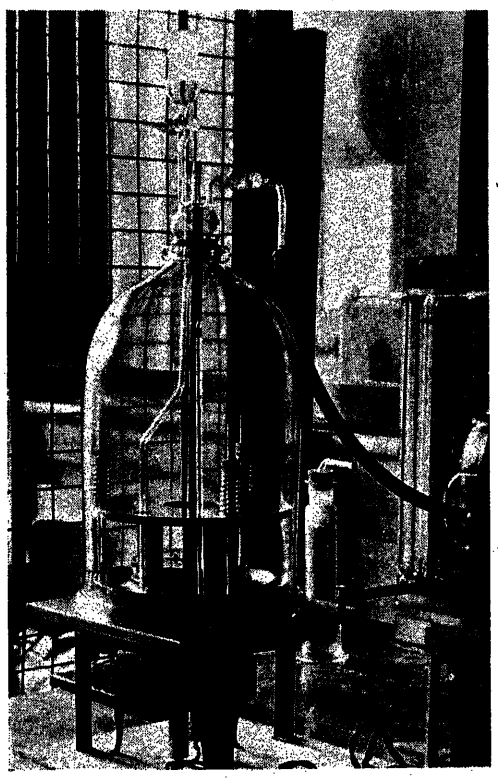


**Fig. 1. Cell for testing impregnated paper**

The relative oxidation stabilities of the saturants were determined by means of aging tests. Porcelain beakers containing samples of the materials were placed in an oven held at 120 degrees centigrade. The beakers were provided with loose fitting covers which kept dust out of the samples, but which did not prevent free access of air. The samples were removed at intervals for electrical measurements. This was accomplished with a minimum disturbance to the sample by immersing the measuring cell in the beaker, cooling them to 85 degrees centigrade, and placing them in a temperature-controlled box. After testing, the beaker and cell were removed from the box and heated to 120 degrees centigrade, the cell then removed, and the beaker placed in the oven for further aging. Oxidation tests made at various temperatures indicated that the rate of oxidation increased by 7 per cent per degree centigrade. The aging temperature was therefore maintained to within 0.5 degree centigrade of 120 degrees centigrade in order to minimize errors in oxidation stability results. Also, it was found that the rate of aging depended on the amount of the sample in the beaker, i.e., on the surface-to-volume ratio. A sample with a surface-to-volume ratio of 0.182 centimeter$^{-1}$ aged 1.60 times as rapidly as one with a ratio of 0.066 centimeter$^{-1}$. (This may mean that the rate of removal of dissolved oxygen by combination with the oil was comparable with the rate of diffusion and convection of the oxygen through the oil, resulting in a lower concentration of dissolved oxygen in the lower portion of the sample.) By close control of aging temperature and surface-to-volume ratio (at 0.066 centimeter$^{-1}$), it was possible to duplicate beaker oxidation test results to within 3 or 4 per cent.

The stability of the saturants to gaseous ionization was determined by applying an electric stress of 85 volts per per mil to saturated paper sheets in the cell shown in figure 1. In the preparation of the sheets, holes were punched in some of them and connecting slits cut between the holes and the edges of one of the sheets, so that artificial voids of known size were created in the sample after drainage of the excess saturant. (This scheme is similar to that developed at the Detroit Edison laboratory.) The cell was evacuated and a certain amount of inert gas was admitted so that the voids became filled with this gas. Carbon dioxide at 20 centimeters mercury absolute pressure was used in most of the tests, as this gas is extensively employed in flushing cables prior to saturation. The gas in the voids was ionized by the electric stress, the ionization factor of the sample being 0.04. After 96 hours exposure to ionization the sheets were removed and examined for wax formation. This was facilitated by extracting the saturant from the sheets and dyeing some of them as described by Robinson.[3]

## Materials Investigated

Results obtained for 9 mineral oils and 8 resins are presented in this paper. Descriptions of these materials and data concerning their chemical composition are given below.

### The Oils

The oils are the most viscous cylinder stocks made for commercial use by a number of different refiners. They were selected so that the principal fields of crude supply and types of refining procedures are represented. See table I.

In order to obtain information concerning the composition of the oils, various methods of analysis were used. One method was that of viscosity index developed by Dean and Davis.[4] In this method, an extreme Pennsylvania-type (paraffin base) oil having a relatively flat viscosity-temperature curve is assigned a viscosity index of 100, while an extreme California-type (asphalt base) oil having a relatively steep viscosity-temperature curve is assigned a viscosity index of 0. The viscosity indices of the 9 oils were calculated from their respective viscosity-temperature curves, and are included in table I.

**Table I—Description of Mineral Oils**

| Oil | Viscosity Index | Proportions of Basic Constituents | | |
|---|---|---|---|---|
| | | Paraffinic | Naphthenic | Residual |
| *O*-1 | −1 | 0 | 70 | 30 |
| *O*-2 | 4 | 0 | 65 | 35 |
| *O*-3 | 65 | 35 | 30 | 35 |
| *O*-4 | 84 | 55 | 35 | 10 |
| *O*-5 | 90 | 60 | 30 | 10 |
| *O*-6 | 96 | 55 | 35 | 10 |
| *O*-7 | 96 | 65 | 30 | 5 |
| *O*-8 | 100 | 65 | 30 | 5 |
| *O*-9 | 104 | 85 | 10 | 5 |

*O*-1 to *O*-3 Gulf Coast and East Texas crudes
*O*-4 to *O*-9 Midcontinent and Pennsylvania crudes
*O*-1 to *O*-4 Acid refined
*O*-5 to *O*-9 Solvent, fuller's earth or aluminum chloride refined

Further information on the composition of the oils was obtained by subjecting samples to selective solvent extraction processes. With the processes used, it was possible to separate an oil into 3 classes of constituents: (1) paraffinic, (2) naphthenic, and (3) residual. (These terms, commonly used in petroleum technology, will be defined on the basis of molecular structure in the discussion.) In this way the relative proportions of the basic constituents in the oils given in table I were obtained. It is seen that the oils of high viscosity index are rich in paraffinic constituents; these oils are hereafter called paraffinic oils. The oils of low viscosity index are rich in naphthenic constituents; they are hereafter called naphthenic oils.

**Table II—Description of Resins**

| Resin | Color | Acid Number | Saponification Number | Oxidized Resin Content |
|---|---|---|---|---|
| *R*-1 | Black | | | Large |
| *R*-2 | Red | 155 | 164 | Medium |
| *R*-3 | Yellow | 189 | 193 | Small |
| *R*-4 | Yellow | 174 | 185 | Small |
| *R*-5 | White | 186 | 186 | None |
| *R*-6 | Red | 15 | | Medium |
| *R*-7 | Yellow | 12 | | Small |
| *R*-8 | Yellow | 87 | 93 | Small |

### The Resins

A tabulation of the resins and their descriptive and chemical properties is given in table II. The resins *R*-1, *R*-2, *R*-3 are various grades of commercial wood rosin containing appreciable proportions of oxidized constituents (oxyabietic acids, aldehydes, ketones) and of nearly neutral oils. Resin *R*-4 was obtained by treating *R*-2 with solvents which removed most of the oxidized constituents and oils, while *R*-5 was obtained from *R*-4 by a further treatment which yielded a white crystalline form of pure abietic acid. By causing rosin to react with alcohols under special conditions, the resin esters *R*-6 and *R*-7 of low acid number were obtained. Resin *R*-8 was produced by a polymerizing reaction which also removed a large proportion of oxidized constituents.

## Solubility of Resins in Oils

When a resin is mixed with heated oil, a certain amount may fail to dissolve. Part of the insoluble matter settles to the bottom of the mixing container as a sludge, while part remains suspended in the oil. Data are given in table III. Resins *R*-1, *R*-2, *R*-6, which contain large percentages of oxidized constituents (table II) are highest in insoluble matter. Oils having a high content of certain types of residual constituents, such as *O*-3, dissolve much of the oxidized resin, while oils which are low in these constituents, such as the paraffinic oil *O*-9 or the naphthenic oil *O*-2, dissolve little of the oxidized resin.

The resins *R*-3, *R*-4, *R*-5, *R*-7, *R*-8 are practically entirely soluble in all the oils. When some of these oil-resin mixtures are allowed to stand at room temperature over a period of weeks, however, a gradual crystallizing out of some of the resin occurs. This behavior has also been observed by Kirch and Riebel.[5] It indicates that a certain amount of impurities is necessary in the resins in order that they may stay in solution in the oils. In the present work it was found that the optimum purity of the resin depends on the oil used. For example, resin *R*-4 is of greater than optimum purity for use in highly paraffinic oils *O*-7, *O*-8, *O*-9, as it crystallizes out when mixed with them, but this same resin mixed with oils containing more naphthenic or residual constituents, such as *O*-1, *O*-2, *O*-3, stays in solution perfectly, even when cooled to −10 degrees centigrade. *R*-5 is of greater than optimum purity for all the oils.

When oil-resin mixtures are oxidized, many of them form a resinous sludge. This is disadvantageous mainly in cable manufacturing as the impregnating tanks and pipe lines may become coated with sludge, and also the entrainment of suspended sludge on the outer layers of the cable insulation may hinder impregnation. The laboratory aging tests indicated that the sludge formation was large in mixtures made with resins which originally contained much oxidized material. Mixtures made with the purer forms of resin sludged somewhat when the oils used were predominantly paraffinic, but did not sludge in the other oils.

## Physical Properties

The principal requirements concerning the physical properties of saturants for solid-type cables are the follow-

ing. The surface tension must be fairly high to enable the saturant to be drawn into and held by the paper capillaries. The viscosity at the impregnating temperature (105 to 115 degrees centigrade) must be fairly low in order to obtain a thorough and economical impregnation. Throughout the temperature range in which cables may be installed or operated (−10 degrees to 80 degrees centigrade) the viscosity must be high to minimize saturant migration and, in case of injury to the lead sheath, bleeding of the saturant, yet the saturant must possess sufficient lubricating value to enable the cable to be bent. The coefficient of expansion should be low in order to minimize void formation caused by expansion and contraction of the saturant arising from temperature changes in service.

Data on the physical properties of the oils and oil-resin mixtures are given below.

## Viscosity

The viscosities of the oils at 100 degrees Fahrenheit are from 1,800 to 6,000 Saybolt seconds, and at 210 degrees Fahrenheit are from 100 to 180 Saybolt seconds. While discussing viscosity it is valuable to introduce the term *viscosity ratio*, which may be defined as the ratio of the viscosity at 100 degrees Fahrenheit to that at 210 degrees Fahrenheit. For oils of a given viscosity at 210 degrees Fahrenheit, the *viscosity ratio* is related to the viscosity index. Thus, for an oil of 140 Saybolt seconds viscosity at 210 degrees Fahrenheit, and viscosity index $\chi$, the *viscosity ratio* is $15 + 0.22\,(100\text{-}\chi)$.

From the viscosity requirements it follows that the viscosity-temperature curve of an ideal saturant for solid-type cables should exhibit a uniformly high value from −10 degrees centigrade to 85 degrees centigrade and then drop rapidly to a low value above 100 degrees centigrade. Unfortunately, no saturant having this characteristic has been found. The best compromise seems to be to select a saturant whose viscosity is fairly low at 110 degrees centigrade and which rises rapidly with decrease in temperature, but not so rapidly as to destroy the lubricating value at −10 degrees centigrade. Highly viscous saturants possessing *viscosity ratios* between 30 and 40 have been found very satisfactory.

**Table III—Percentage of Resin Insoluble in Oil**

| Oil | Resin R-1 | R-2 | R-3 | R-4 | R-5 | R-6 | R-7 | R-8 |
|---|---|---|---|---|---|---|---|---|
| O-2 | 6 | | | 0 | 0 | | | 0 |
| O-3 | 2 | | | 0 | 0 | | | |
| O-4 | 10 | 4 | 0 | 0 | 0 | 5 | 0 | 0 |
| O-9 | 7 | | | 0.3 | 0 | 8 | 0.3 | 0 |

The addition of resin to oil changes the viscosity characteristics as shown in figure 2. The effect is greater if the polymerized resin *R*-8 is used. It is seen that the addition of resin not only raises the viscosity, but also the *viscosity ratio*. This is due to the fact that the *viscosity ratio* of the resin itself is extremely high, about 10.[8] This effect of resin additions is advantageous if the oil alone does not possess a high *viscosity ratio*, as it leads to greatly reduced migration of the compound in service, without requiring a much longer impregnation period.

## Pour Point

The pour points of the oils are all below 0 degree centigrade, in some cases as low as −12 degrees centigrade. The oils do not set even at these temperatures because they are dewaxed. The addition of 15 per cent resin raises the pour point about 5 degrees centigrade. However, mixtures of resins with the most viscous oils possess sufficient lubricating value at −10 degrees centigrade for cable bending requirements.

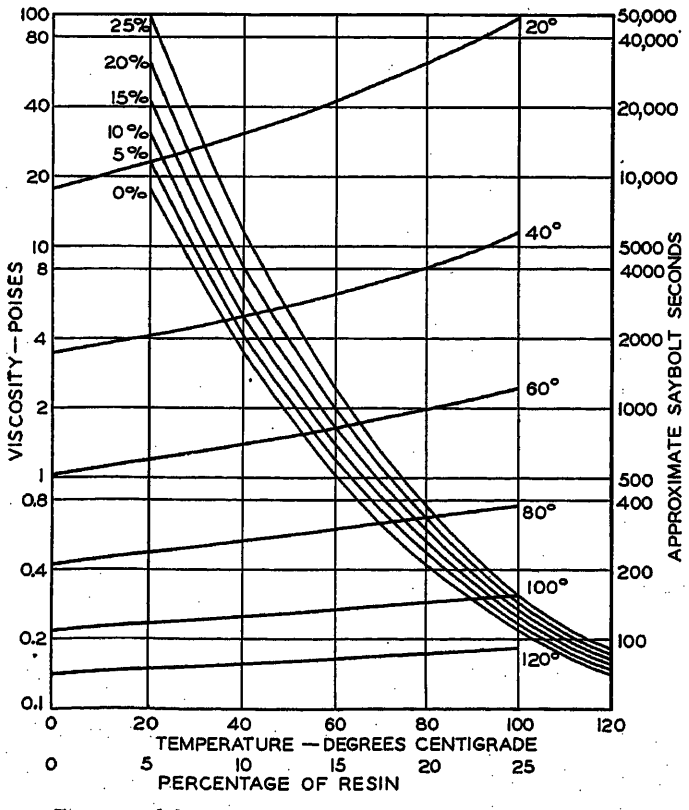



**Fig. 2. Variation of viscosity with temperature and viscosity with percentage of resin for mixtures of resin and oil O–4**

**Table IV—Specific Gravity and Coefficient of Expansion of Oils**

| Viscosity Index | Specific Gravity $\rho$ (at 25 Deg C) | Coefficient of Expansion $-(1/\rho)(d\rho/dT)$ (per Degree C) |
|---|---|---|
| High | 0.88 to 0.90 | 0.00070 |
| Medium | 0.90 to 0.92 | 0.00067 |
| Low | 0.92 to 0.94 | 0.00064 |

## Specific Gravity and Coefficient of Expansion

Oils of low viscosity index have higher specific gravities and lower expansion coefficients than oils of high viscosity

index as shown in table IV. The addition of 15 per cent resin to the oils increases the specific gravities and reduces the expansion coefficients 1 or 2 per cent.

### Surface Tension

The values for the different saturants at 110 degrees centigrade are from 28.5 to 32.5 dynes per centimeter. The variations in surface tension with temperature, type of oil, and addition of resin are similar to the corresponding variations in specific gravity.

## Electrical Properties

### Dielectric Constant

For well-refined mineral oils, the variations in dielectric constant $\epsilon$ with temperature and with type of oil are accounted for by the corresponding variations in specific gravity.[6] This may be seen by comparing the dielectric constant curves for oils *O*-2, *O*-4, and *O*-8 in figure 3 with the specific gravity data in table IV. The addition of resin to oil increased the dielectric constant as is also shown in figure 3. Part of this increase is caused by the increase in specific gravity imparted by the resin, and the remainder by orientation of the polar resin molecules. The data indicate that the dipole moments of the ester *R*-7 and the polymerized resin *R*-8 are larger than the moment of pure abietic acid *R*-5.

The dielectric constants of the materials increased slightly (less than 5 per cent) during the aging tests. The changes in dielectric constants were roughly proportional to the changes in power factor which are discussed later.

### Power Factor

The power factor-temperature curves of the oils are plotted in figure 4. Although there are large percentage differences in the values for the different oils, all the values

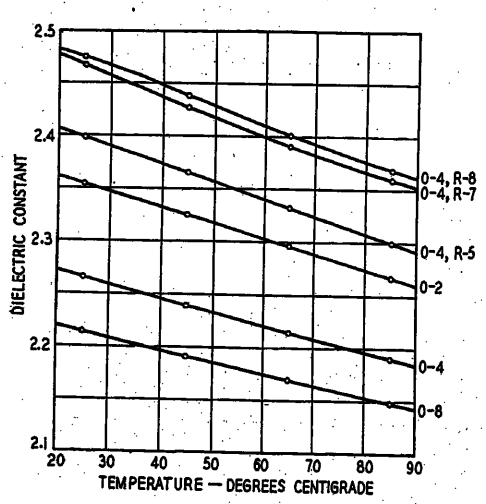



**Fig. 3. Dielectric constant-temperature curves of oils and oil-resin mixtures (15 per cent resin)**

are less than 0.004 at 85 degrees centigrade which is satisfactory for cable manufacturing purposes. These curves show that the relative increases in power factor per degree centigrade are about 6 per cent.

For a given oil, there is an approximately inverse relationship between the power factor and the viscosity, as has been shown by Kirch and Riebel[5] and Whitehead.[7] Compare figure 4 with figure 2. For this reason oils of high *viscosity ratio* often possess relatively steep power factor-temperature curves. It will be shown later, however, that relative steepness of the curve of the saturant has little effect on the curve of the saturated paper unless the absolute value of the saturant power factor at 85 degrees centigrade is high.

The effect of adding resins to oil on the power factor is shown in figure 5. It will be seen that if the resin contains oxidized constituents (*R*-2, *R*-6) or volatile constituents (*R*-3, *R*-7), the power factor of the resulting oil mixture is greater than that of the oil alone. This increase in power factor is especially large for oils which dissolve much of the oxidized resin as shown by the curve for *O*-3, *R*-2. If the resin has been largely freed of impurities (*R*-4, *R*-5), the power factor of the oil mixture is about the same as that of the oil alone. (Low power factors for purified resins in oils have also been reported by Kirch and Riebel.[5]) In some cases the addition of resin actually reduces the power factor, as may be seen by comparing the curves for oil *O*-9 with and without *R*-4. This may be due

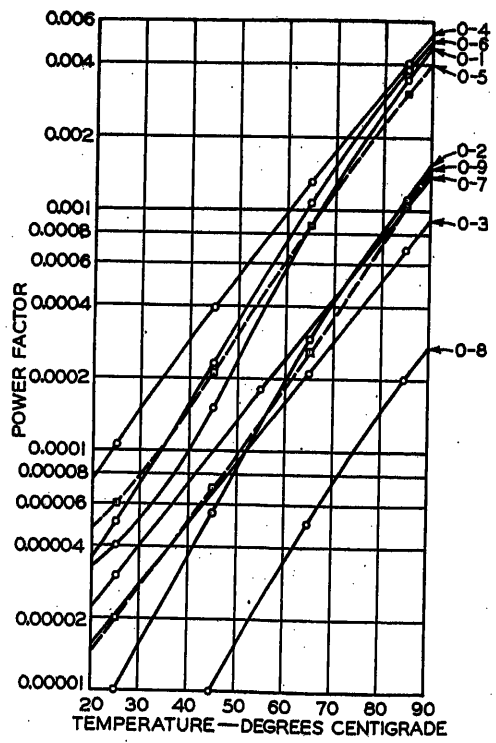



**Fig. 4. Power factor-temperature curves of oils**

in part to the fact that some volatile constituents are driven off in the mixing operation, and in part to the reduction of the mobilities of conducting ions existing in the oil caused by the increased viscosity imparted by the resin. The power factors of oil-resin mixtures bear no relation to the acid numbers.

### Conductivity

Values of a-c conductivity are related to the 60-cycle power factor thus, $\lambda_{ac} = 3.33 \times 10^{-11} \epsilon \delta$. Whitehead[7]

has noted that the ratio of a-c conductivity to long-time d-c (final) conductivity may be high for new oils, but is low for deteriorated oils. This has been confirmed in the present work, in which d-c measurements were made at 85 degrees centigrade on the saturants. Typical data are given in table V. Included in the table is the conductivity at one minute after voltage application, a measurement widely used in commercial insulation tests. This value lies between the a-c and final values, but at 85 degrees centigrade it is generally nearer the final value. The ratios of a-c to one-minute conductivity are from 1.2 to 3 for the new oils, but are usually only a few per cent greater than one for aged oils. For oils aged in contact with many metals, the ratios are also little more than one, but for oils aged with lead, the ratios are higher, often about 2. If the oil contains moisture, the ratio is high; if the oil is then aged

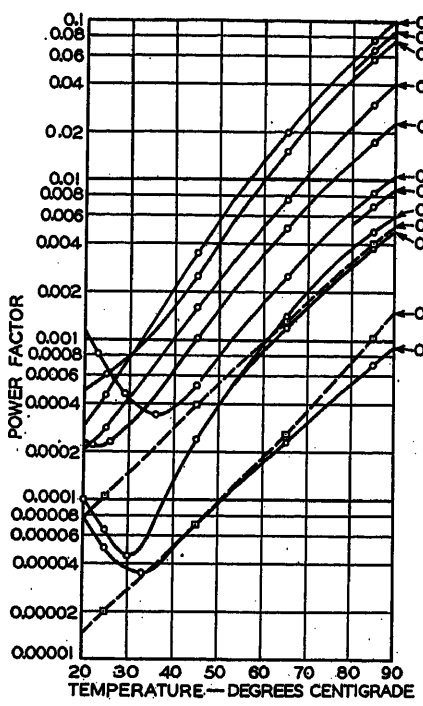



**Fig. 5. Power factor-temperature curves of oil-resin mixtures (15 per cent resin)**

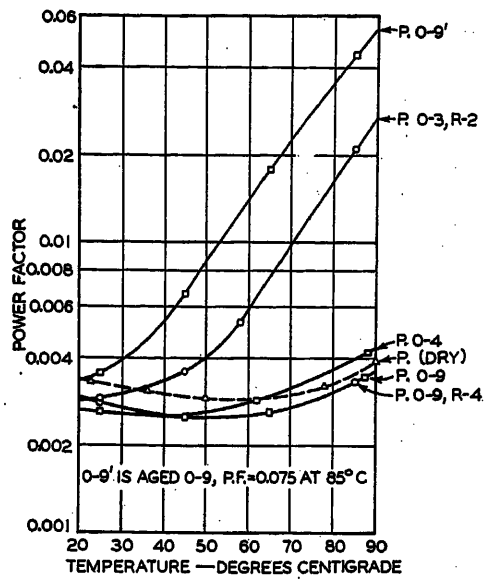
slightly, the a-c conductivity decreases while the final conductivity increases. The addition of resin to oil increases the final conductivity, even when it decreases the a-c conductivity.

### Power Factor of Impregnated Paper

The effect of variations in the saturant properties on the power factor of impregnated paper was investigated. Power factor-temperature curves of a high density paper impregnated with various saturants were determined, some of which are shown in figure 6. The typically flat power factor-temperature curve of the dried, unimpregnated paper is also shown. It is seen that if the saturant has a low power factor (either a straight oil or a mixture of an oil and a purified resin), the curve for the saturated paper is similar to that for the dried paper. If the saturant has a high power factor (either a straight deteriorated oil or a mixture of an oil and an impure resin), the curve for the saturated paper partakes more of the nature of the curve for the saturant, exhibiting high power factors at the higher temperatures.

The conditions necessary for the existence of a functional relationship between the power factor of a given type of paper impregnated with various saturants and the saturant power factors were deduced from Whitehead's work on dielectric loss.[7] These conditions are that the saturant

**Fig. 6. Power factor-temperature curves of saturated paper**




dielectric constants do not differ greatly and that *the saturants have equal viscosities*. For these conditions, values of saturant power factor $\delta_s$ and power factor of saturated paper $\delta_{sp}$ were read from the power factor-temperature curves. A family of curves of $\delta_{sp}$ versus $\delta_s$ was drawn, each curve corresponding to a certain saturant viscosity $\eta$, as shown in figure 7. It is apparent that $\delta_{sp}$ is not greatly affected by variations in $\delta_s$ below 0.003 at 85 degrees centigrade.

The curves in figure 7 are approximately of the form $\delta_{sp} = A + (B + C\eta)\delta_s$, where $A$, $B$, and $C$ are parameters. $A$ depends on the electrical properties of the paper, and $B$ and $C$ depend on the oil-to-paper ratio.

## Oxidation Stability

From the data presented in figures 4, 5, and 6, it is apparent that the power factor of impregnated paper is sat-

**Table V—Conductivities of Saturants at 85 Degrees Centigrade**

| Saturant | $\lambda_{ac}$ | $\lambda_1$ | $\lambda_f$ | $\lambda_{ac}/\lambda_1$ | $\lambda_{ac}/\lambda_f$ |
|---|---|---|---|---|---|
| O-9 New | 7.5 | 4.2 | 2.3 | 1.78 | 3.26 |
| Aged 50 hours | 6.8 | 4.1 | 3.0 | 1.66 | 2.27 |
| New + 10 per cent R-4 | 5.8 | 3.5 | 2.6 | 1.66 | 2.23 |
| O-4 New | 29.6 | 21.0 | 16.3 | 1.41 | 1.82 |
| Aged 100 hours | 117 | 115 | 112 | 1.02 | 1.05 |
| Aged 100 hours (lead) | 208 | 127 | 119 | 1.64 | 1.75 |

$\lambda_{ac}$ = a-c conductivity; $\lambda_1$ = one minute conductivity, $\lambda_f$ = final conductivity
Unit = $10^{-14}$ mho per centimeter

isfactory throughout the cable operating temperature range if the saturant power factor is satisfactory at 85 degrees centigrade. Consequently, in studying the oxidation stability of cable saturants, it is important to follow the changes in power factor at 85 degrees centigrade.

The oxidation test data are presented in the form of power factor versus time-of-aging curves. In these curves a slow rate of rise of power factor with time of aging indicates a high stability to oxidation.

The aging curves obtained for the 9 oils are shown in figure 8. Oils *O*-1 and *O*-3 (of the light acid refined type), which contain appreciable amounts of certain types of residual constituents, are seen to be poorest in oxidation stability. Oils *O*-5, *O*-6, *O*-7, *O*-8, and *O*-9 are more stable, the stability being proportional to the degree of refining. Most of these more stable oils were refined by recently developed processes which yield highly paraffinic oils (see table I). It should be pointed out, however, that naphthenic oil *O*-2 and paraffinic oil *O*-4, refined by similar acid processes, have nearly the same stability. This suggests that naphthenic oils are not inherently less resistant to oxidation, and that their stability might be improved if better methods of refining them were used.

The oils which are poorest in oxidation stability also have the greatest solvent powers for impurities, and are therefore most susceptible to contamination.

The effect of adding various resins to oil *O*-4 on the oxidation stability is shown in figure 9. The power factor of the oil mixed with the impure resin *R*-2, although higher than that of the oil initially, changes but little with aging, and is much less than that of the oil alone after aging. The power factor of the oil mixed with the purified resin *R*-4 increases but slowly from its low initial value with aging. Such stabilization of the oil is also produced by additions of the resin esters *R*-6 and *R*-7 and the polymerized resin *R*-8, although to a lesser extent.

In the series of resins *R*-2, *R*-4, and *R*-5, the stabilizing value decreases somewhat with increased purification. The partially purified resin *R*-4, however, is nearly as effective as the unpurified resin *R*-2, for part of the apparent effectiveness of *R*-2 is due to the fact that some of the originally dissolved oxidized constituents sludge out during aging.

The oxidation stabilities of all types of mineral oils is improved by the addition of resins, as may be seen by comparing the aging curves for the mixtures of *R*-4 with the oils, figure 10, with the curves for the oils alone, figure 8. Each oil-resin mixture has a useful life which is about 5 times that of the corresponding oil alone.

There are often large and varying departures from linearity in the power factor versus time-of-aging curves shown in figures 8, 9, and 10. If, therefore, the power factors before and after 100 hours of aging are analyzed alone, as is often done in evaluating the oxidation stability of liquid dielectrics, false conclusions may be drawn.

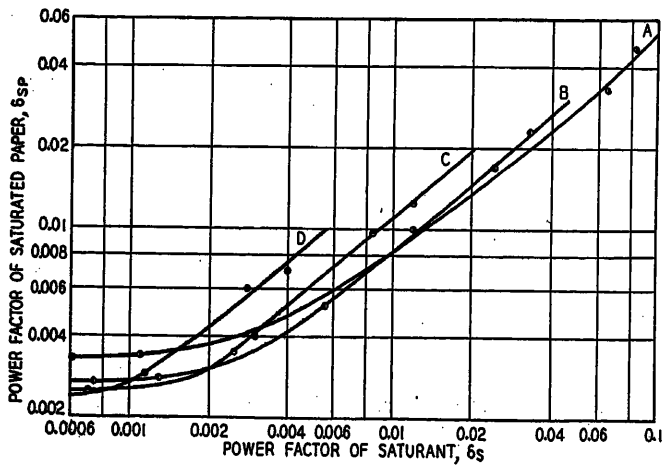



**Fig. 7. Variation of power factor of saturated paper, $\delta_{sp}$, with saturant power factor, $\delta_{sp}$ for various saturant viscosities, $\eta$**

| Curve | $\eta$— Poises | Approximate Temperature—Deg C | Approximate Equation of $\delta_{sp}$ |
|---|---|---|---|
| *A* | 0.5 | 85 | $0.0033 + 0.48\ \delta_s$ |
| *B* | 1 | 71 | $0.0027 + 0.60\ \delta_s$ |
| *C* | 2 | 58 | $0.0025 + 0.84\ \delta_s$ |
| *D* | 4 | 47 | $0.0024 + 1.22\ \delta_s$ |

**Table VI—Catalytic Powers of Metals on Oxidation of Oil O–4**

| Catalyst | Power Factor at 65 Degrees Centigrade: New | Aged | Increase | (Increase–0.005)/0.005 |
|---|---|---|---|---|
| None | 0.0013 | 0.0063 | 0.0050 | |
| Pb | 0.0013 | 0.0183 | 0.0170 | 2.4 |
| Cu | 0.0013 | 0.040 | 0.039 | 6.8 |
| CuO | 0.0013 | 0.026 | 0.025 | 4.0 |
| Cu-CuO-Pb | 0.0013 | 0.084 | 0.083 | 15.6 |
| Cd | 0.0013 | 0.0138 | 0.0125 | 1.5 |
| Sn-plated Cu | 0.0013 | 0.0079 | 0.0066 | 0.32 |
| Sn-plated Cu (scratched) | 0.0013 | 0.0080 | 0.0067 | 0.34 |

1,100 cubic centimeter samples of oil aged at 65 degrees centigrade for 176 days. Surface area of metal strips = 105 square centimeters

## Catalysts

When the oils were aged in contact with copper, lead, and steel strips, the catalytic effect of the metals accelerated the rate of power factor change for most of the oils, as may be seen by comparing the aging curves in figure 11 with those in figure 8. The rates of deterioration of the 2 oils of lowest viscosity index, *O*-1 and *O*-2, were not accelerated, but slightly retarded. This result was carefully checked.

The presence of metals in oil-resin mixtures did not change the rate of deterioration. This may be due to the fact that the dissolved oxygen was consumed near the surface of these mixtures. It at least indicates that the resins do not readily form harmful compounds with metals.

A study was also made of the relative catalytic powers of metals on the deterioration of oil. In these tests the aging temperature was reduced to 65 degrees centigrade so that the ordinary chemical combination of dissolved oxygen with the body of the oil would be reduced to a low value, and so that most of the oxidation would take place at the

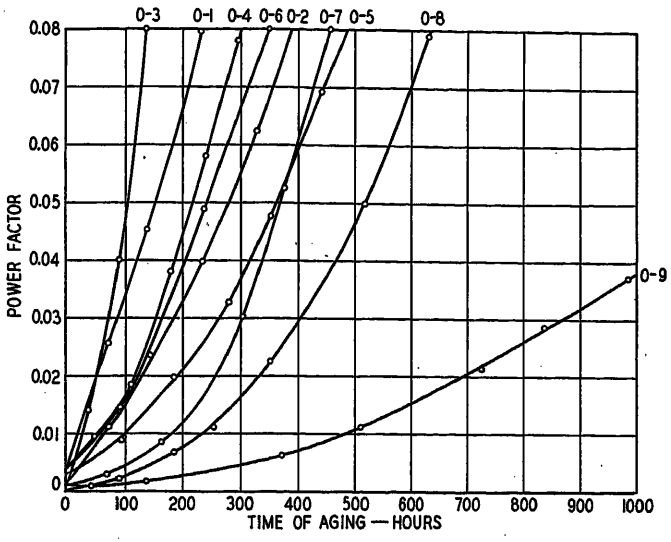



Fig. 8. Straight oils

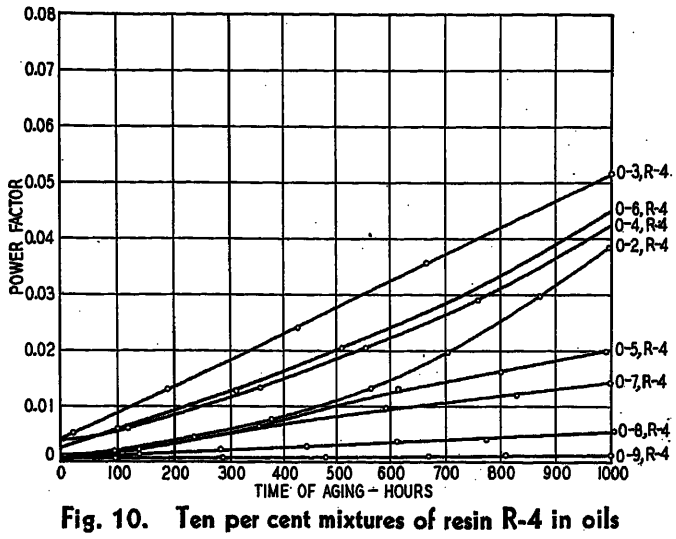



Fig. 10. Ten per cent mixtures of resin R-4 in oils

Fig. 9. Fifteen per cent mixtures of resins in oil O–4

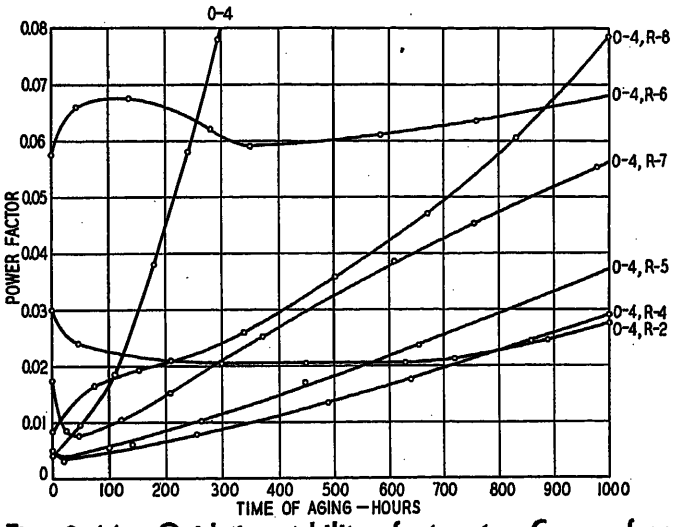
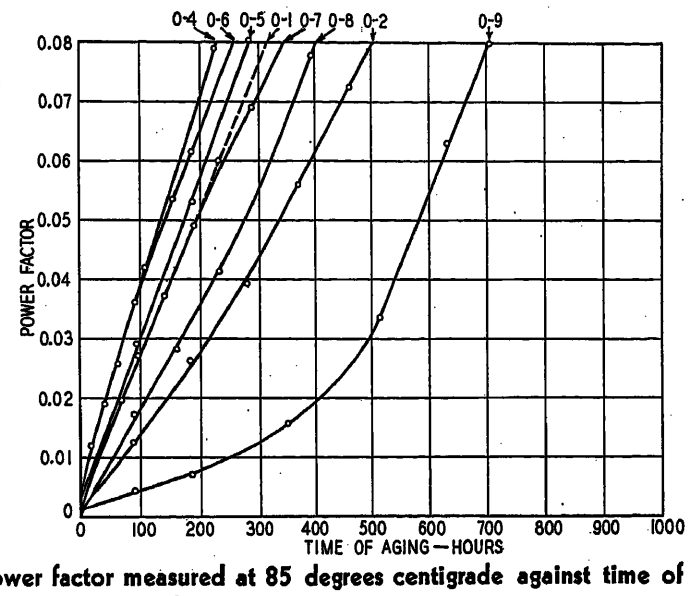



Fig. 11. Straight oils in contact with Cu, Pb, Fe




**Figs. 8–11. Oxidation stability of saturants. Curves of power factor measured at 85 degrees centigrade against time of aging at 120 degrees centigrade**

metal surfaces. The differences in catalytic effects of the metals were thus accentuated. It was found that the power factor versus time-of-aging curves were nearly linear and so only the initial and final values are given in table VI. It is of interest to note that the catalytic effect of copper is 21 times that of tin. The presence of dissimilar metals in contact causes little or no additional effect through battery action, because the absolute conductivities of the oils are very low.

## Effects of Gaseous Ionization

In the tests for the determination of stability to gaseous ionization, the applied electric stress produced highly energized gaseous ions in the voids. These ions, on striking the saturated paper at the ends of the voids, caused chemical changes in the materials. The changes were chiefly polymerization and condensation of the saturant molecules, leading to the formation of the familiar "*X*" or wax and to the evolution of gas. Chemical changes involving gas molecules also occurred under certain conditions.

### Wax Formation and Gas Evolution

Some of the wax patterns obtained in the tests are shown in figure 12. It is apparent that there is a large variation in the tendencies of the oils to form wax. A correlation was found between the wax formation, expressed in arbitrary units, and the viscosity index of the oils. This is indicated in figure 13. The correlation is nearly as close as the probable error in estimating wax formation, some 10 per cent, even though the oils studied are of different types and methods of refinement. Oils rich in naphthenic or residual constituents are much more resistant to gaseous ionization than the highly paraffinic oils. Figure 13 indicates also that the addition of resin to oils increases the stability to ion bombardment, at least for the more paraffinic oils.

The data plotted in figure 13 are the amounts of wax at

the ends of the artificial voids. For most of the compounds this was the only wax formed. But for oils of very low viscosity index, both with and without resin, wax was also present on the surfaces of the paper sheets at other places. If the total wax were considered, the wax formation versus viscosity index curves would be U-shaped, the values at very low viscosity indices being too ill-defined to be indicated.

No gas evolution was detectable in the ionization tests performed with hydrogen gas present. A small amount

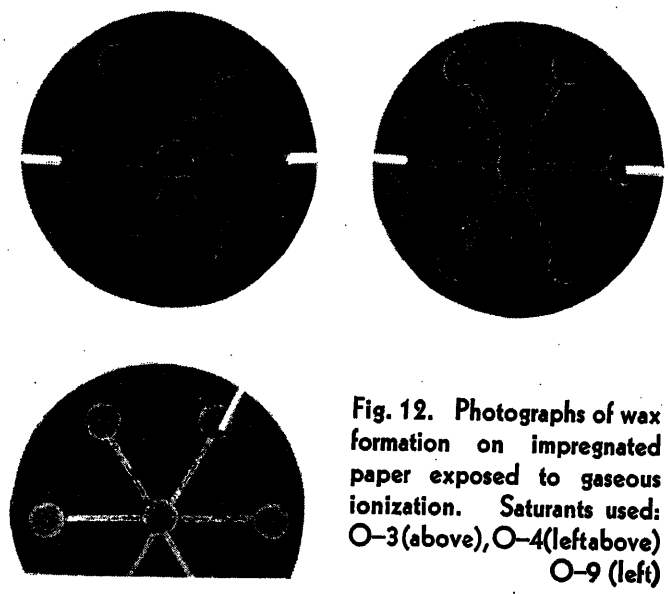


Fig. 12. Photographs of wax formation on impregnated paper exposed to gaseous ionization. Saturants used: O–3 (above), O–4 (leftabove) O–9 (left)

was observed when $CO_2$ was used, but this was independent of the saturant. There is evidence that this gas evolution was due to the breaking down of $CO_2$ into CO and O in the regions of very high stress at the electrode edges. Part of the evolved oxygen entered into the wax formation at the electrode edges, but not in the artificial voids. No significant changes in power factor of the saturated paper occurred in the ionization tests carried out under $CO_2$ or hydrogen.

The results of preliminary tests in which saturants in a glass cell under high vacuum were subjected to electric stress indicate that the gas evolution varies with the viscosity index of the oil and the addition of resin in a manner similar to that depicted by the curves in figure 13, except that the range of variation is much less.

### Combined Ionization and Oxidation

When gaseous ionization tests were carried out under reduced air pressure instead of under an inert gas, it was found that the gas pressure in the cell decreased with time. This took place at room temperature only when voltage was applied and ionization occurred. This indicates that the glow discharge facilitates the combination of oxygen with cable saturants by what might be termed an "electrocatalytic" action. This is substantiated by the fact that the wax formed in these tests was much greater in amount and darker in color than that formed in the tests with inert gases. Also, the power factor of the impregnated sheets increased markedly during the tests under reduced air pressure, although this effect was much smaller for resin-containing saturants than for straight oils. The data are given in table VII.

### Gaseous Ionization Pressure

Gaseous ionization in insulation voids, in addition to promoting chemical changes, was observed to exert a physical pressure on the insulation surrounding the voids. One manifestation of this pressure is that much of the wax formed in the oil films on the paper surfaces at the ends of the voids was forced to the edges of the voids where the ionization was less severe. This can be observed in the wax patterns in figure 12. Another manifestation, which was most pronounced after very long periods of ionization, is that some wax was forced through the paper sheets in the direction of the field. It is likely that ionization pressure was responsible for the effects observed by Proos,[8] namely, that the displacement of saturants away from regions of high stress in cables was greater with simultaneous application of voltage and heat cycles than with application of heat cycles alone. It is also likely that the ionization pressure, by forcing the saturant from the paper, facilitates the formation of the microscopic carbonized paths through paper which have been found by Robinson[3] to be sufficient to initiate a "treeing" mechanism resulting in eventual breakdown of the cable insulation. In order that the tendency of the ionization pressure to force the saturant through the paper may be resisted without the application of hydrostatic pressure, as in the oil-filled cable, it is necessary that the paper be dense and that the saturant be high in viscosity and surface tension, and strongly adsorbed by cellulose.

## Discussion

The observation made in the ionization stability tests that the gas evolution from oils of low viscosity index is less than that from oils of high viscosity index may be explained by the fact that the former oils contain more residual constituents than the latter (see table I). The residual constituents of the oils include aromatic compounds. Compounds of this type, although simpler in character, were found to evolve less gas than simple paraffinic compounds in the early tests carried out at the Detroit Edison laboratory.[9] It has also been recently shown by Nederbragt[10] that additions of small amounts of aromatic compounds to mineral oils are sufficient to lower the gas evolution considerably. The explanation usually given for this is that much of the gas, chiefly hydrogen, which is evolved instantaneously is reabsorbed by the double bonds in the molecules of the aromatic compounds. Since the molecules of the resins discussed in this paper also contain 2 double bonds, the reduction in gas evolution by resin additions to oils is also explained.

The majority of the molecules comprising the paraffinic and the naphthenic constituents of oils do not contain double bonds. It is possible that, on exposure to ionization, it is easier for hydrogen atoms to be detached from the open chain groups which form a large part of the structure

of the molecules of the paraffinic constituents than from the ring groups which predominate in the molecules of the naphthenic constituents. This would be a basis for explaining why the oils of very high viscosity index polymerize to form wax more readily than the oils of lower viscosity index, and why petrolatum, the molecules of which consist almost entirely of open chain groups, waxes even more readily than highly paraffinic oils.

The effect of resin additions in reducing wax formation is more difficult to explain. It is known from lubrication theory that a very small percentage of polar material added to a mineral oil can, by becoming adsorbed on metal surfaces, give a preferred orientation to the majority of oil molecules (non-polar) in the vicinity of the surfaces. Resin molecules, being polar, undoubedly become adsorbed by paper. This probably causes a similar preferred orientation of the oil molecules in the vicinity of paper-oil interfaces. The direction of this orientation may be such that those portions of the oil molecules which are exposed to the gaseous ion impacts are less vulnerable to their effects.

A comparison of the oxidation stability curves presented in figures 8 and 11 with the composition of the oils given in table I indicates that most of the paraffinic and naphthenic constituents and some of the residual constituents are stable to oxidation. The aromatic constituents are probably stable. The unstable residual constituents, which are usually dark in color, also render oil more susceptible to contamination.

The solvent refining processes commonly used in America in the production of lubricating oils of high viscosity index remove naphthenic and residual constituents which are stable to oxidation in addition to those which are unstable. These processes improve oxidation stability at the expense of greatly reducing the stability to gaseous ionization. In refining cable impregnating oils, processes should be used which remove only those constituents which are unstable to oxidation.

Oil oxidation products are hydrophilic, as shown by the spreading of aged oil on water. Many of them are acidic. They cause the high power factor of aged oils by dissociating to form conducting ions. Since all these properties are possessed by the oxidation products, it is sometimes concluded that all hydrophilic substances, especially acids, also have the property of causing high power factor, and that such substances should not be added to insulating oils, at least not in large amounts. It has been shown in this paper, however, that certain purified resins, which are hydrophilic and acidic in character, are important exceptions to this hypothesis, for their presence in oils has little or no effect on the power factor. Moreover, the addition of these resins has been shown to be beneficial from the standpoint of stability.

The basic parent substance of the resins is abietic acid, which has the empirical formula, $C_{20}H_{30}O_2$. This substance is far less reactive than most organic acids, partly because of its high molecular weight and partly because of the way in which the acid group is attached to the molecule. This is why purified resin does not esterify readily or form harmful compounds (soaps) with metals, and why it has a low ionic dissociation constant (low power factor) in oil solutions.

There are several indications in the oxidation stability tests of oil-resin mixtures (for example, the data given in table VII) that the stabilizing influence of the resin is not due to a reduction in oxygen absorption, but to the fact that the resin oxidation products dissociate to form fewer conducting ions than do oil oxidation products. The data in figure 9, which show that crystalline abietic acid is nearly as effective as commercial resins in stabilizing oil power factor, indicates that most of the oxygen absorbed by the resins is taken up by the double bonds of the resin molecules.

**Table VII—Ion Bombardment Tests Under Reduced Air Pressure**

| Saturant | Oxygen Consumed, Cubic Centimeters | Wax Formed (Arbitrary Units) | Power Factor at 65 Deg C | | |
|---|---|---|---|---|---|
| | | | Start | End | Increase |
| O-3 | 258 | 1,000 | 0.0032 | 0.0375 | 0.0343 |
| O-9 | 215 | 1,000 | 0.0026 | 0.0416 | 0.0390 |
| O-9, R-4 | 219 | 1,000 | 0.0026 | 0.0049 | 0.0023 |

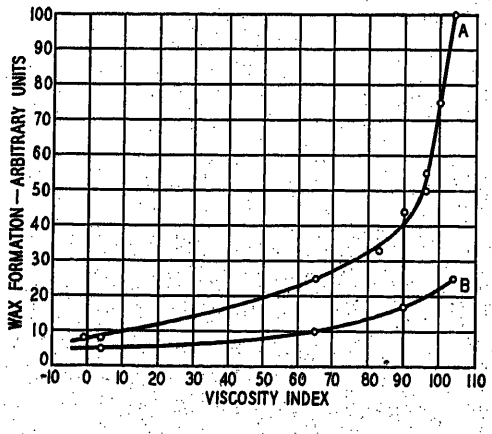



**Fig. 13. Wax formation of saturants exposed to gaseous ionization as a function of viscosity index of the oils**

*A*—Straight mineral oils
*B*—Oil-resin mixtures

## Correlation With Cable Life

It may be well to consider a few results of cable life studies in connection with the results presented in this paper. Life tests made by Whitehead[11] and more recently by Race,[12] although under oil-filled cable conditions, showed that, other things being equal, specimens saturated with naphthenic oils had longer lives than those made with paraffinic oils. The saturants used in the solid-type cables having good service records have been found to be very stable to gaseous ionization. Resin-containing cables have established good service records, although the older types of resin-containing cables did not appear to advantage in some of the load cycle life tests made in the past. The writer believes this was mainly due to the exaggeration of the higher dielectric loss of these older cables under the accelerated test conditions which led to thermal instability, a fault of the test rather than of the cables. With an improved, less accelerated life testing technique, Halperin and Betzer[13] have lately found that

the use of resin in cables of recent manufacture has resulted in increased stability and life.

## Conclusions

The results of the investigation may be summarized as follows:

1. Much valuable information can be obtained by subjecting cable saturants to various simplified tests and by correlating the results with viscosity index and chemical composition.

2. The addition of resin to mineral oils reduces migration of the saturant in cable operation without correspondingly increasing the time required for impregnation.

3. Oil-resin mixtures are not high in power factor unless the resin contains oxidized or volatile constituents.

4. The power factor of paper impregnated with mixtures of oils and properly purified resins is approximately the same as that of straight oil saturated paper.

5. For a given type of paper and for saturants of the same viscosity, the power factor of impregnated paper is a function of the saturant power factor.

6. Both naphthenic oils (low viscosity index) and paraffinic oils (high viscosity index) may possess good oxidation stability. The most stable oils now available are paraffinic.

7. The catalytic effect of metals on oil oxidation is greater for paraffinic oils than for nonparaffinic oils. The catalytic effect of copper is much greater than that of lead which in turn is much greater than that of tin.

8. The addition of resin to all types of mineral oils improves the oxidation stability as measured by power factor change.

9. Highly paraffinic oils are less stable to gaseous ionization than oils low in paraffinic constituents.

10. The addition of resin to oils containing some paraffinic constituents increases their stability to gaseous ionization.

11. Gaseous ionization in insulation voids exerts a pressure which tends to force the saturant from the paper.

12. Gaseous ionization in the presence of oxygen exerts an "electrocatalytic" effect on the oxidation of cable saturants. This results in a copious, dark wax formation and an increase in power factor which is less for resin-containing saturants than for straight oils.

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# Distribution Lightning Arrester Performance Data

THE intelligent application of lightning arresters requires a knowledge of their performance characteristics under conditions which are likely to be encountered in service. Data have been presented relating to the impulse characteristics of insulation both as used on lines and in transformers. In order to know what protection may be secured with certainty in service, data are also required concerning the rates of voltage rise to be expected on distribution type arresters and the current encountered as a result of natural lightning. These data are being obtained, in some measure at least, through the use of impulse current measuring devices in series with arresters in service. Very little satisfactory information is available, however, with respect to the actual rates of potential rise, in fact most of such information is based on deduction rather than actual measurement.

It was necessary, some years ago, to arrive at a reasonable basis for comparing the operating performance characteristics of arresters, and standards were finally set up which admittedly are on a basis which is somewhat empirical. The test wave for arresters having a maximum permissible line to ground voltage of 6 kv or less is specified as 50 kv per microsecond, while the test wave for arresters having a maximum permissible line to ground voltage above 6 kv and including 15 kv is specified as 100 kv per microsecond.

Lightning arresters have not only a breakdown characteristic, but they also have in general a potential drop across the arresters due to the flow of current through the resistance in series with one or more gaps provided in the arresters. With all types of distribution arresters this potential drop, or *IR* drop as it is usually called, increases as


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Personnel of AIEE lightning arrester subcommittee: J. R. North, *chairman;* H. W. Collins, R. H. Earle, I. W. Gross, H. Halperin, C. F. Harding, K. B. McEachron, J. R. McFarlin, A. M. Opsahl, H. K. Sels, A. H. Schirmer, L. G. Smith, A. H. Sweetnam, and J. J. Torok.

## Table I—Line Type Arrester Characteristics (3 Kv–15 Kv)

| Arrester Rating—*Kv | | Gap Breakdown—Crest Kv | Voltage (IR Drop) Across Arrester—Crest KV When Discharging Currents of 1,500 Amp | 3,000 Amp | 5,000 Amp |
|---|---|---|---|---|---|
| 3 | Max | 22.0 | 13.5 | 15.5 | 17.5 |
| | Ave | 17.0 | 10.5 | 12.0 | 13.5 |
| | Min | 12 0 | 7.5 | 8.5 | 9.5 |
| 6 | Max | 45.0 | 27.0 | 30.0 | 32.5 |
| | Ave | 34.5 | 20.5 | 23.0 | 25.0 |
| | Min | 24.0 | 14.5 | 16.0 | 17.5 |
| 9 | Max | 64.0 | 40.0 | 44.0 | 48.0 |
| | Ave | 49.0 | 30.5 | 34.0 | 37 0 |
| | Min | 34.0 | 21.5 | 24.0 | 26.0 |
| 12 | Max | 75.0 | 52.5 | 58.5 | 62.5 |
| | Ave | 58.0 | 40.5 | 45.0 | 48.0 |
| | Min | 41.0 | 28.5 | 31.5 | 33.5 |
| 15 | Max | 86.0 | 65.5 | 73.0 | 78.0 |
| | Ave | 66.0 | 50.5 | 56.0 | 60.0 |
| | Min | 46.0 | 35.5 | 39.0 | 42.0 |

Gap breakdown taken on rate of voltage rise of 50 kv per microsecond for 3 kv and 6 kv arresters, and 100 kv per microsecond for 9 kv, 12 kv, and 15 kv ratings.
All arresters tested with a 10 x 20-microsecond wave.
The 60-cycle spark potential of all arresters shown in this tabulation will not be less than 150 per cent of the arrester rating.
* These ratings are maximum permissible line to ground root-mean-square voltages.

the current increases, but not linearly. Therefore, data relating to the potential across the arrester during the time of current flow are necessary for the proper evaluation of the long time protective ability of the arrester.

The present Standard requires a test current having a crest value of 1,500 amperes, with a rate of current rise of 150 amperes per microsecond and a decay to half value in a time not less than 10 microseconds. Certain tolerances are, of course, permitted. Since, however, the current values to be expected in practice are known over a considerable range of values, performance data at other current magnitudes than those specified in the Standard are required.

To make these necessary data generally available to the industry, the lightning arrester subcommittee has asked the manufacturers of arresters to submit information on their products, with respect to breakdown characteristics under standard rates of rise as outlined and *IR* drops for crest values of current of 1,500, 3,000, and 5,000 amperes. The manufacturers have supplied this information together with the expected tolerances in production. With these data available, table I and the accompanying graphs have been prepared showing the protective characteristics of line type arresters rated 3 kv to 15 kv.

The impulse breakdown data from table I are plotted in figure 1, showing not only average values, but also the maximum and minimum. Figure 2 shows the maximum, minimum, and average *IR* drop characteristics for the standard current wave of 1,500 amperes crest. The corresponding potentials across the arrester for 3 values of current are shown on figure 3. In each case where average values are given, they are the numerical average of the average value given by the manufacturers. The maximum and minimum values for each make of arrester were obtained by applying the tolerances given by each manufacturer to his average value. For each rating, the highest and lowest values of the maximums and minimums were selected as representing the total spread in performance characteristics.

It is hoped that these data as here presented will be of material assistance in determining the proper place of the lightning arrester as a protective device. The comparison between the surge voltages allowed by an arrester under various conditions and the performance characteristics of other apparatus associated with the arrester should lead to an intelligent evaluation of the protection provided by the arrester.

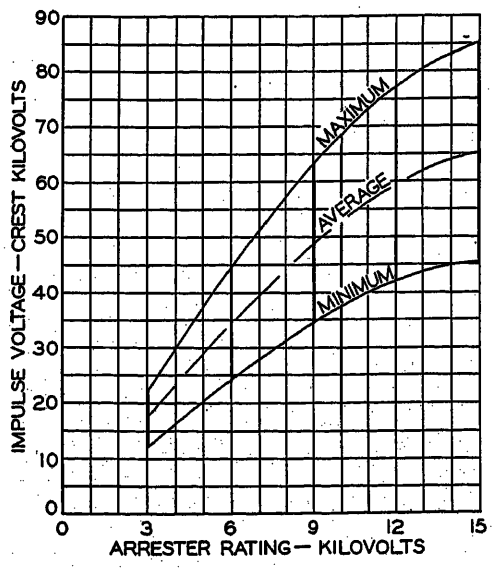



**Fig. 1. Gap breakdown voltages, line type arresters**

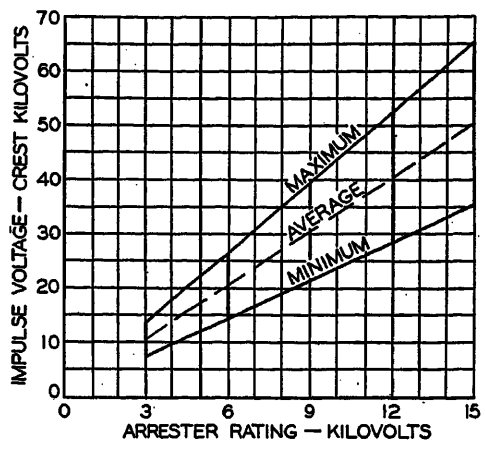



**Fig. 2. IR drop at 1,500 amperes, line type arresters**

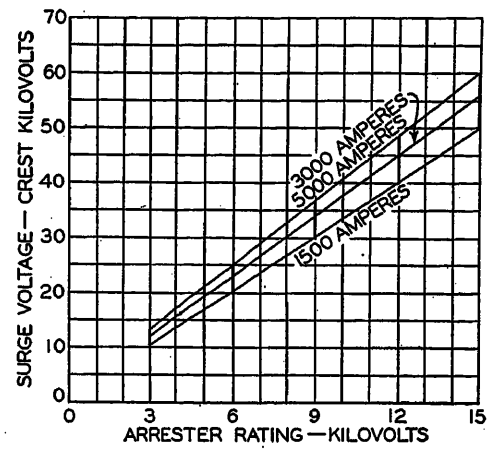



**Fig. 3. Average IR drop, line type arresters**

# Coincidental Electric Drives

By L. E. MILLER
MEMBER AIEE

A "coincidental electric drive" may be defined as a drive consisting of several units of one machine, or a group of machines; each unit or machine driven by a separate motor. For successful operation, each unit or machine must have a speed bearing a definite relation to the speed of each of the other units. This speed relation may be constant or varying.

In operating a coincidental drive, 2 classes of speed must be considered, designated as primary speed and secondary speed. The primary speed is the speed of a group of motors as a whole. The change in this basic speed is of greatest importance, since the speed must be changed in order to change the output of material from the machine.

The secondary speed is that speed of any of the individual units, differing from the primary basic speed, and which accomplishes a successful degree of coincidence between the various units or machines in the drive. In operating a group drive, it is desirable to separate the means of accomplishing primary speed changes from the means of accomplishing secondary speed changes. With a-c motors, primary speed changes can be readily accomplished by changing the frequency, and, therefore, the basic speed of the whole system. On d-c drives, the primary speed change can readily be accomplished by changing the applied voltage, thus changing the basic speed of the whole system.

Secondary speed changes are much more easily accomplished in d-c drives than in a-c drives, since changes may be accomplished by change in field strength of individual motors. Due to the ease with which this secondary change may be accomplished on d-c motors without affecting primary speed changes, d-c motors are used more frequently in coincidental drives than are a-c motors.

To consider drives consisting of 2 or more motors which must operate in a different speed relation to each other, a review is desirable of that which basically determines the speed at which any motor, a-c or d-c, will operate. A clear understanding may be possible if the subject is approached from the standpoint of torque required and torque produced by the motor. If, at any instance, the torque produced by the motor exceeds the torque required, the excess torque will result in acceleration of the motor. If the torque required is in excess of the torque produced, the motor will decelerate. The acceleration or deceleration will continue until the torque balance is established.

If there is a change in certain of the electrical values, such as the voltage on d-c motors, or the frequency on a-c motors, the speed will certainly be affected, because these changes in electrical values will have an effect upon the torque produced. This change in speed, either upward or downward, will continue until the torque balance is again established. If the torque demand changes, an unbalance will result and there will be a speed change either upward or downward, which will result in such a readjustment of the electrical factors as to accomplish the torque balance; at which point there will be no further change. This method of approach requires no distinction between a-c or d-c motors, and is universal in its application.

The torque of either a d-c or an a-c motor is represented by the following equation: Torque = a constant × number of conductors in the rotor × flux per pole × the current per rotor conductor × the cosine of the angle between the stator and rotor flux. (In the case of a d-c motor this cosine is 1.)

In either an a-c induction motor or a d-c motor, a reduction in the speed of the rotor results in an increased rotor current with a consequent increased torque, other conditions remaining the same. (In the case of an a-c motor, this resulting increase in torque continues only until the breakdown torque of the motor is reached.)

Coincidental electric drives are very largely used in the handling and processing of material. If, during the handling or processing, there is no elongation or contraction of the material, it is quite obvious that each unit or machine must operate at such a speed as to handle the same length of material per minute. If there is elongation, each following section or machine must handle a longer length of material per minute. If the speed of the following section is too slow, loops will develop. If the speed of the following section is too fast, excessive tension will be produced in the material, possibly resulting in slippage or breakage. The process may require the reeling of material on a spindle with a constant rate of delivery of the material in the reel. The speed of the reel must decrease in proportion to the increased diameter of material and reel.

Considering again the definition previously given for coincidental electric drives, it can be seen that this definition may be expanded to cover a number of drives used in industry. For convenience, such coincidental drives may be grouped under 4 headings:

### True or Exact Coincidence

In such a drive, the various motors may operate at exactly the same speed. The electric clocks throughout the country may be considered as an illustration of this type of coincidental drive. Another illustration is the use of 2 motors, each driving one-half of a leaf bridge. Still another and quite interesting illustration is the remote control of a steering gear on a ship by means of a synchrolock.

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### Adjusted Coincidence

This group covers those drives where some modification of true coincidental relation is required, but after this relationship has been established, it becomes fixed and does not change. This may be illustrated by a sectionalized paper machine drive where there is some draw or shortening of the paper due to the drying process.

### Approximate Coincidence

This heading is used to cover those drives where various units operate at approximately a fixed speed relation, but where for short periods there may be a considerable departure from coincidental speed with the final recovering of the over-all coincidental relation. A textile range with storage boxes furnishes an illustration of this type of drive, as does also a continuous pickling line with storage pits.

### Instantaneous Coincidence

Under this heading may be classed a drive where the desired speed relationship between the different units is constantly changing at a predetermined rate of change. One of the more interesting cases of instantaneous coincidency in practical application occurs in the winding of strip material on a reel and maintaining approximately constant tension at the time. In such cases, coincidency between the mill and the reel must be maintained from the time the strip is first drawn taut by the reel until the strip leaves the mill, but as can readily be seen, the relations required for coincidency change inversely as the diameter of the roll of material changes.

In drives of this type, it is not only necessary to obtain coincidency in speed, but it is also desirable to obtain uniform tension during the reeling of the material. This uniformity of tension has been especially stressed in the reeling of metallic strips in order to obtain more accurate strip and to obtain this result with less annealing between rollings. Slipping clutches have been used in the past on many such drives, but since they fail to function as well as desired, and since they do not even approach uniform tension, there has been a constant demand for other and more accurate means of accomplishing the results desired.

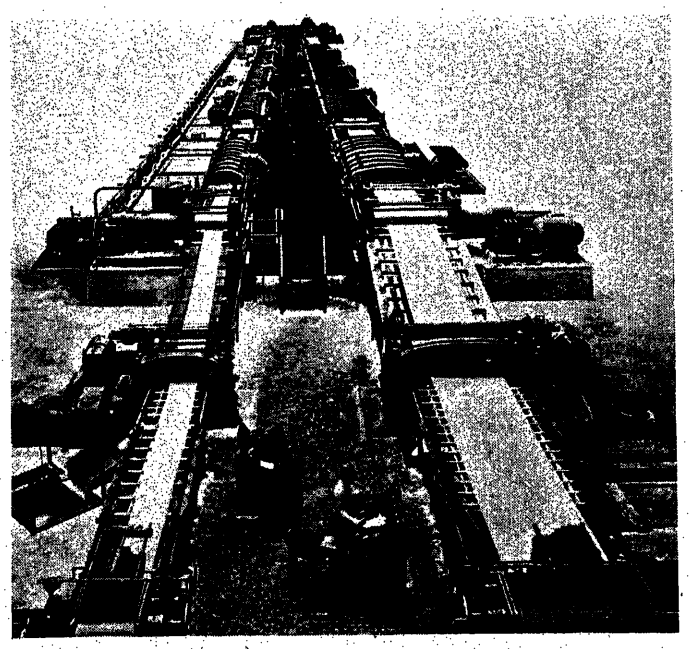


**Fig. 1. A continuous pickling line illustrating an application of approximate coincidence**

The ideal condition for an application of this sort is obtained when the torque produced by the driving unit varies directly with the diameter of the roll on which the material is being wound, and since the diameter of the roll varies inversely with the speed at which the roll must rotate, we arrive at the conclusion that the torque of the driving unit must vary inversely with the speed at which the driving unit operates.

A d-c motor, having its armature current maintained constant by varying its field, fulfills this requirement for all practical purposes, since as is shown in the torque equation, its torque varies directly with its field strength, and its speed varies inversely with its field strength. The problem in producing such a drive, therefore, becomes one of producing a regulator which will automatically maintain a constant current in the armature of a d-c motor by adjustment of the field strength.

An ideal type of regulator should:

*a.* Respond rapidly to changes in current, and adjust its rate of response to the current change required.

*b.* Continue its change in the field strength until current change is entirely corrected.

*c.* Respond to small changes of current.

*d.* Respond properly to either an increase or decrease in current.

*e.* Make minimum change in field strength to get proper correction in current.

*f.* Be sufficiently dampened in action to prevent causing surging.

Various types of regulators have been used in maintaining constant current on such applications. Of these, the following four are the most common. Each has given satisfactory results.

1. The vibrating type relay having one or more contacts connected across fixed resistors was probably the first type used.

2. A motor-driven rheostat, with the direction of armature rotation of the regulator controlled by relays responsive to the current in the reel driving motor armature, was developed as early as 20 years ago.

3. A regulator consisting of vertical stacks of graphite or carbon plates with silver inserts near one end arranged to tilt by the action of a torque motor, which is responsive to the current of the armature of the driving motor, has been used on many applications.

4. The regulator with which the author is most familiar is sufficiently different from the regulators previously mentioned, to merit a more detailed description. It is felt that in this regulator are incorporated those features of a good regulator previously mentioned. This regulator consists of a control motor and a rheostat which is in series with the shunt field of a driving motor. The rheostat is made up of a number of resistance tubes having a large number of taps. These taps are connected to a commutator. A slip ring is mounted at one end of this commutator and this ring is electrically connected to the last tap of the rheostat. Thus it can be seen that the commutator and ring form parallel electrical paths.

The control motor, in its mechanical construction, is quite similar to a small d-c motor except that it has 2 separate and distinct windings on the armature; each

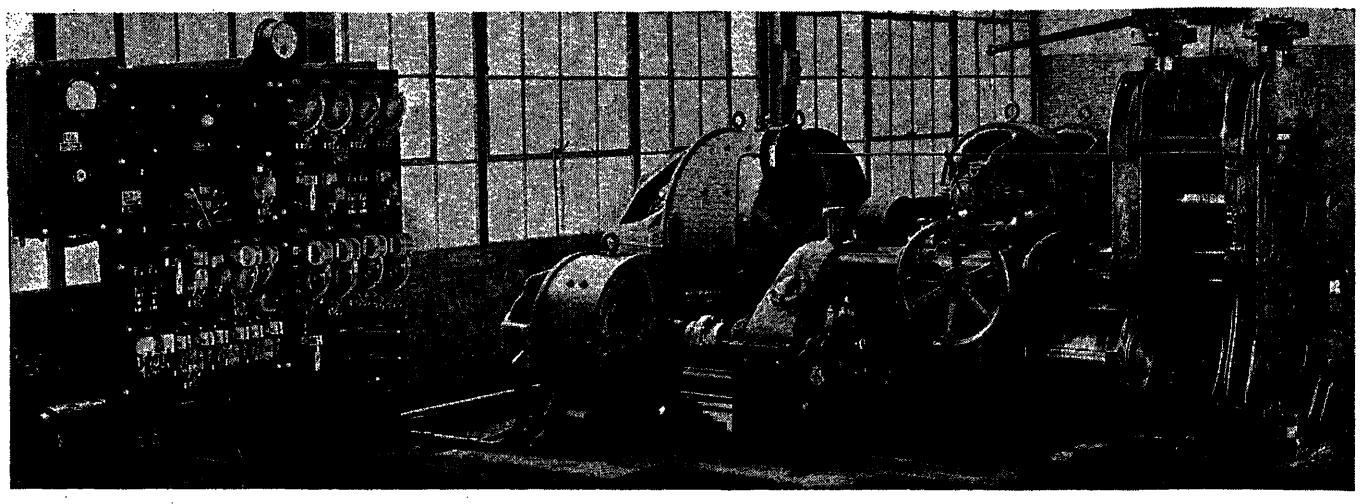


**Fig. 2. A mill and wind-up reel illustrating an application of instantaneous coincidence. Strip is delivered directly from the mill to the reel**

winding being connected to its own commutator. One winding, referred to as a spring or reference winding, consists of a large number of conductors of a small cross-sectional area. This might be considered as a very slow speed motor winding. It is connected in series with a resistance across a constant potential line. It gives the effect of a very long spring capable of being extended an infinite distance without changing the force produced.

The second winding is referred to as the torque winding, and consists of a fewer number of turns of a larger cross-sectional area. This winding might be considered as an ordinary high speed motor winding. It carries a definite proportion of the current passing through the armature of the motor being regulated.

The armature with its 2 windings operates in the flux field of a conventional d-c motor, and hence, current passing through either or both of the windings tends to produce rotation of the armature. The shaft of this combination armature has an arm mounted on it which carries 2 brushes electrically connected to each other, but insulated from the arm. One of the brushes rides upon the commutator of the rheostat mentioned before, and the other rides upon the slip ring which is electrically connected to one end of it. The result of one complete revolution is to change the condition of the rheostat, step by step, from a condition of full resistance to a condition of zero resistance.

The windings of the control motor are so connected that the current passing through the torque winding causes rotation in a direction tending to reduce the resistance in the rheostat, while current passing through the spring or reference winding causes rotation in a direction tending to increase the resistance in the rheostat. Thus, it can be readily seen that a condition of balance can be obtained which will cause a stationary condition of the armature, but when this condition of balance is disturbed by a change in the current in the torque winding, a rotation causing a corrective change in the rheostat will be produced. This rotational correcting action will continue until correction is established.

In regulating devices performing a function similar to that described there is frequently a tendency to hunt or to cause hunting on the part of the motor they are controlling. This is especially true of devices which tend to give true correction, and where the strength of the response to change is, as it should be, proportional to the change in current. This, of course, can be eliminated by dash pots, frictions, clock escapements, and other mechanical means. All such means, however, introduce friction which reduces the sensitivity of the regulator, since the frictional part of the retarding force is the same regardless of whether a small or large correction is indicated.

To remove this possible cause of trouble, a copper cylinder surrounding the armature of the control motor is introduced. This serves as an effective dampener and does not reduce the sensitivity for small changes in current. When the change in current is small, the rotation is slower, and the dampening action is negligible. When the change is current is large and the tendency to respond is greatly increased with the possibility of over-running and causing hunting, the dampening action from the cylinder is increased as the square of the change in speed of the control motor.

Referring to figure 4, we have a simplified schematic diagram showing the connections for a typical application making use of a regulator such as described. A generator $G$ is connected mechanically to a mill for processing material. This generator $G$ supplies a source of potential

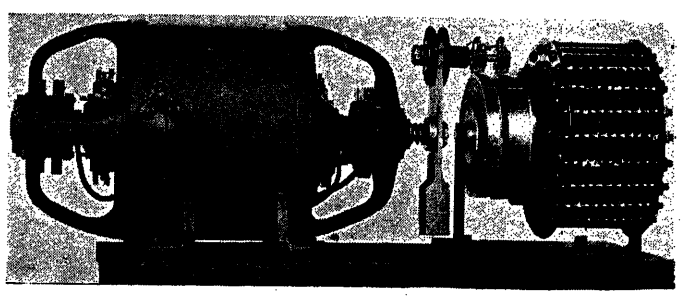
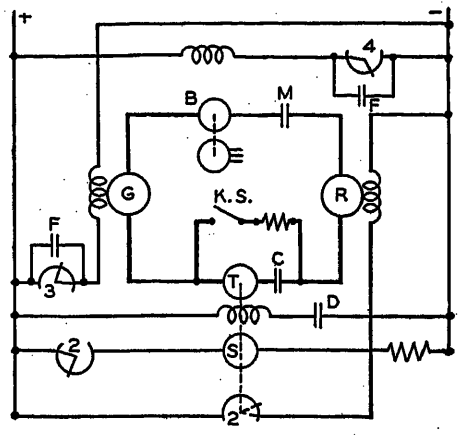


**Fig. 3. A constant-current regulator of the type described in the context. The cover has been removed from the rheostat to give a clearer view**




*R*—Reel motor
*G*—Main generator
*B*—Booster generator
*T*—Torque winding
*S*—Spring winding
*M*—Main line contactor
*C*—Torque winding contactor
1—Tension rheostat
2—Regulator rheostat
3—Main generator rheostat
4—Booster generator rheostat
*D*—Regulator field rheostat
*F*—Field rheostat shorting contactors

**Fig. 4. Simplified schematic diagram of connections as used with the regulator described**

to operate a reel motor *R*. Connected in series with the generator *G* and reel motor *R* is an independently driven booster generator *B*. This generator *B* supplies current to the reel motor when the generator *G* is stationary, and thus maintains a tension on the material between the mill and the reel, when the mill is shut down while material is still being processed.

Since the generator *G* operates at the same speed as the mill, the normal speed of the reel motor *R* will be such as to give the same lineal speed of take-up material as is being delivered by the mill. Adjustments from the normal speed of the reel motor *R* to accommodate the build-up of material on the reel are automatically produced by the regulator rheostat.

The torque winding *R* of the regulator, parallel with an adjustable resistance, is connected in series with and between the generator *G* and the reel motor *R*. The spring winding *S* of the regulator is connected in series with a fixed resistor and an adjustable rheostat across a source of constant potential. The regulator rheostat 2 is connected in series with the shunt field of the reel motor *R* and across a constant potential. Major changes in tension, produced by changing the current at which the regulator functions, are caused by changing the adjustable resistance paralleled with the torque winding, and minor or vernier changes are accomplished by changing the rheostat in series with the spring winding.

The operation of the regulator is such that once the balanced condition is predetermined and set, an increase in current will cause the torque of the torque winding to overcome the torque of the spring winding, and the rheostat arm will be moved in a direction to increase the field strength of the motor being regulated. This motion will continue until correct current is established. A decrease in current will have an opposite effect, and motion will be in the direction of decreasing the field strength.

In studying regulators, such as the one described and others, we should not be misled into thinking that we have absolute accuracy of tension at all times. A motor is not a meter, and even a meter is not absolutely accurate. By this we do not refer to the calibration inaccuracy which is common with most meters, but rather, due to its dampening and inertia, to its lack of instantaneous accuracy. In a motor we have similar inaccuracies considerably magnified. For instance, in a motor we have a dampening action due to the inductance of the armature circuit. Also, we have present an inertia not only of a motor armature, but also of the mandrel on which the material is being wound, as well as the material on the mandrel.

No method has as yet been developed that will maintain constant tension by the use of a regulator or other device during the accelerating or decelerating period. It should be pointed out that extra current is necessary during the accelerating period. However, since the accelerating rate will vary from time to time, and the frictional losses will be more or less variable, the extra torque for acceleration can bear no fixed relation to the torque required to produce tension; and the current cannot be determined with any degree of accuracy. On the other hand, it is generally desirable to cause, either by the regulator or other control devices, extra current to flow during the accelerating period. The reverse of this is true during the decelerating period.

In view of the fact that it is difficult to determine by watching meters just what is taking place in one of these wind-up drives, it would seem that a better study could be made by the use of undamped oscillograph readings. Such readings have been made on a typical application of a drive of this sort.

Oscillogram figure 5 shows the speed, armature voltage, armature current, and field current. The film was taken during the final period of winding a coil from strip steel. The armature voltage is apparently quite steady. The speed shows, as it should, a steady decrease. The field current shows indications of vibrations of small amplitude and a steady increase in value. This again is more or less normal. The armature current shows variations of small amplitude, and the maximum change in value is about 5 per cent. This does not come, as can be noted, in the form of a gradual increase from the beginning to the end of the process, but occurs only as infrequent peaks or valleys. The mean change appears to be not exceeding 3 per cent.

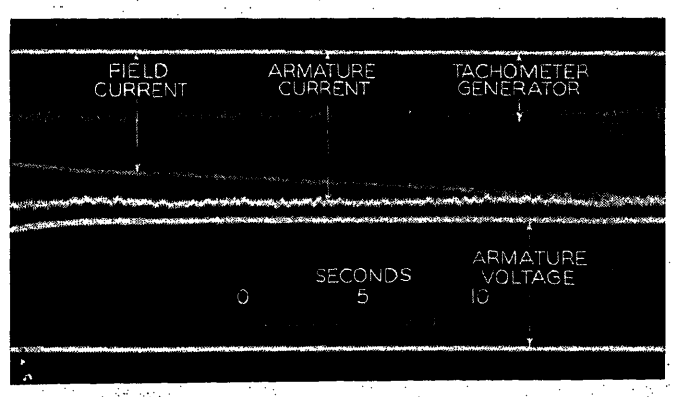



**Fig. 5. Oscillogram obtained during the winding of strip steel into a coil. Shows gradual rate of change of motor field current and speed, and approximately constant armature current and voltage**

Oscillogram figure 6 is a continuation of oscillogram figure 5 carrying the build-up to very close to its final value. The characteristics are the same as in figure 5. It is impossible to see the rheostat steps in the field current curve, since there are 180 steps in the rheostat, and the change per step is only about 0.04 inch on the original 6-inch wide film. From the film we find that the regulator responded rapidly enough to keep the current from varying to any great extent from the predetermined value, and the response was not so rapid as to give any tendency toward a hunting condition. Visual observation bore out the fact that the regulator did not over travel, and, therefore, did not have to correct itself by returning from a too advanced position. This test was made on a reel driven by a 100-horsepower 3- to 1-speed range motor. The build-up on this particular coil was such as to cause the motor to operate through a speed range of 2 to 1, and required about $^3/_4$ of the normal full load rating.

In attempting to get as much of a complete run as possible on one oscillograph reading, the film was, of necessity, run at a very slow speed. In doing this, however, as can be noticed, the peaks and valleys of the armature current reading were so bunched together as to make an almost solid line. A further study was desired in order to bring more plainly into view the actual fluctuations of the armature current. Figure 7 shows the results of this study. In this case the film speed was increased to about 6 inches per second, as can be seen by the timing wave made from a 60-cycle power supply. Here the curve of armature current was sufficiently elongated to give a very definite view of the peaks and valleys separated from each other. On this curve, the armature voltage shows 2 very definite frequencies, one a comparatively low frequency with a change of not very great amplitude, and another a quite high frequency with a change of an even smaller amplitude. The ripple of vibration in the voltage curve does not seem to bear any particular relation to the ripple found in the armature current curve, but no doubt, has some influence on it. Another fact which may have had some influence in causing a variation in the armature current was noted in watching the actual winding up of the strip upon the mandrel. The catch for securing the strip to the mandrel projected beyond the periphery of the mandrel, causing an eccentric shaped coil. This was only a minor eccentric-

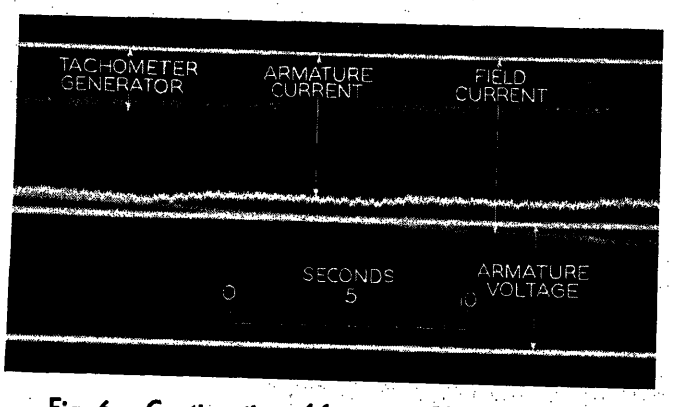



**Fig. 6. Continuation of figure 5. The coil has now approached its maximum size**

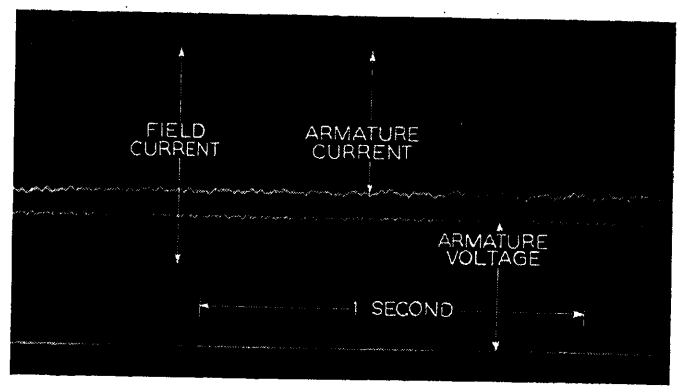



**Fig. 7. A higher speed oscillogram of the same operation as figures 5 and 6. Peaks and valleys occurring in armature current are shown in more detail**

ity, and while theoretically it had some effect upon the armature current, we are not justified in concluding that it was the entire cause of the ripples occurring therein.

In considering an application of this type, there is still another inaccuracy present which should be recognized; namely, the frictional losses in the motor, gears, and reel. When operating near the normal load, this inaccuracy is for all practical purposes negligible, but when operating at very low loads, as may be the case when only one mill and reel are available to cover a wide range in tension, this inaccuracy can easily become very material.

As an example of this, let us assume the current required to produce the torque to overcome friction is 10 per cent of the normal current rating of the motor, and let us assume that current variation permitted by the regulator is 5 per cent, as shown in oscillograph figures 5, 6, and 7. Then if the current required for overcoming friction and producing tension is 100 per cent of the normal rating, the variation in tension will be $5/(1.00 - 0.10) = 5.56$ per cent, which is a very good result. If, on the other hand, the current required to overcome friction and produce tension is assumed to be 20 per cent of the normal rating of the motor, then the variation in tension will be $5/(0.20 - 0.10) = 50$ per cent. This may be satisfactory on many applications, but is certainly too great on many others, and seems to indicate the possibility of unsatisfactory operation in attempting to make a mill and reel cover too great a range in tension. It is the author's belief that a 5 to 1 range in tension is as high as is practicable in an application of this type.

## Conclusion

Coincidental electric drives are being used more and more in industrial applications. Many such drives have been applied with insufficient knowledge of the actual requirements of those drives, and with insufficient study of the details of that which must be accomplished to produce a successful drive. Some of these drives are now working with passable, although not entirely satisfactory, results. Improvements, both as to economy and operation, can be expected in the future by the study of those drives already applied, and by continued effective co-operation between the operating and manufacturing engineers.

# Impulse Operation of Magnetic Contactors

By CARROLL STANSBURY
MEMBER AIEE

Magnetic contactors as commutating devices for the application of power for very brief periods (as in resistance welding practice) have encountered limitations which have been considered inherent in their nature. The author has found that this is not necessarily the case, and describes a method of operating magnetic contactors which to a great extent avoids the usual limitations and gives short periods of great accuracy.

THE MAGNETIC contactor has been one of the most important factors in the application of electricity to industry. Although its most extensive use in the past has been in motor control, another application of great and growing importance in recent years has been in the resistance-welding industry. The duty which the contactor is called on to perform in this field is the commutation of a single phase circuit of low power factor, with loads ranging from 1 or 2 kva up to over 1,000 kva. The periods of power application vary from 2 or 3 cycles up to one second or more (references 1, 2, 3, 4).

There are certain very important classes of resistance welding, however, on which it has been found essential to use periods of power application which are too short for the use of magnetic contactors by conventional methods. Such welding includes the welding of aluminum alloys, stainless steel, and various light welding of nonferrous metals in small light parts where the extreme localization of heat resulting from short-time welding is advantageous, (reference 5). The timing periods involved are on the order of 1 or 2 cycles or even $^1/_2$ cycle in some cases.

Cam-operated contactors driven by synchronous motors have been used for this purpose and also all-electronic controllers using thyratron and ignitron tubes have been widely applied (references 6, 7, 8, 9, 10). (Reference is here made to control for single spot welding as distinguished from the type of seam welding control which consists of a series of over-lapping spots applied at very high speed through roller electrodes.)

The magnetic contactor has not been able to enter this field successfully heretofore because certain limitations appeared to mark off a range of application below about three cycles to which it is not applicable. However, in the natural competition of ideas and practices it was inevitable that attempts would be made to overcome these limitations. The incentives for such attempts were considerable, provided magnetic contactors could be applied to this field with a simplicity and cheapness comparable to that with which they are applied to the less critical installations.

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## General Problem

It will perhaps best bring out the nature of the problem to suppose at first that power is to be supplied to a single-phase load in separate periods of 10 cycles duration. If a contactor of suitable size is selected and oscillograms relating magnet-coil current to the closed or open condition of the main contacts are examined, it is found that if the coil circuit is closed at a given instant, the main contacts will touch about 2 cycles later, and that the contactor magnet will seal about 2 cycles after that.

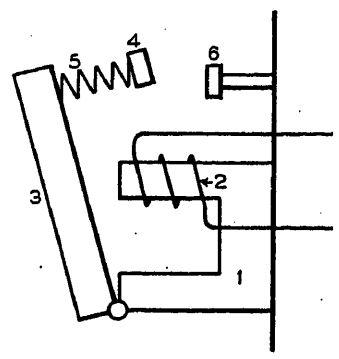



**Fig. 1. Essential elements of typical magnetic contactor**

Elements represented are: stationary magnet structure 1, magnet coil 2, armature 3, moving contact 4, contact spring 5, stationary contact 6

Magnetic blowout and return ("tail") spring omitted for simplicity

Similarly, in opening, the contactor requires about 2 cycles after the coil circuit is interrupted before the main contacts separate. To meet the above requirements, therefore, some sort of timing device is used which closes the magnet circuit for 10-cycle periods. Its contacts close 2 cycles before the main contacts touch, and open 2 cycles before the main contacts separate. For purposes of the present analysis it will be assumed that the timer used is non-synchronous in action. That is, the closing and opening of its contacts are at random relative to the phase of the alternating supply voltage.

The timing results obtained would be somewhat disappointing if accurately measured, for reasons which would include some or all of the following:

1. The timing device itself would probably have an error of $\pm^1/_2$ cycle or more
2. There would probably be a variable amount of arc on the pilot-device contacts, affecting the accuracy of commutation of the coil circuit
3. Due to the nonsynchronous closing and opening of the coil circuit of the contactor, variable transients would occur affecting the duplication of action of the contactor magnet
4. The use of a contactor with an a-c magnet involves having a direct iron-to-iron seal on the magnet face. The actual sealing

would be slightly different each time, which would affect the accuracy of opening of the contactor

5. There would be a variable amount of arc on the main contacts of the contactor.

None of these factors is serious at 10 cycles, but all become increasingly so as the required period is reduced. Experience has shown that 3 or 4 cycles is the lower limit for most applications, because the percentage variation in the energy input to the weld becomes excessive at shorter periods.

It is possible to set up a specification for an ideal program of energizing the contactor magnet simply by prescribing that the above defects should be absent. Such a specification would be something like the following:

1. The timing device proper must be accurate to a very small fraction of 1 cycle.

2. The pilot device must operate without arc.

3. The timing device must be synchronous in operation.

4. The contactor magnet must operate without direct iron-to-iron seal.

5. Arc on the main contacts must either be eliminated or be held to a uniform effect.

## Accurate Timing Element

The essential elements common to practically all magnetic contactors are indicated schematically in figure

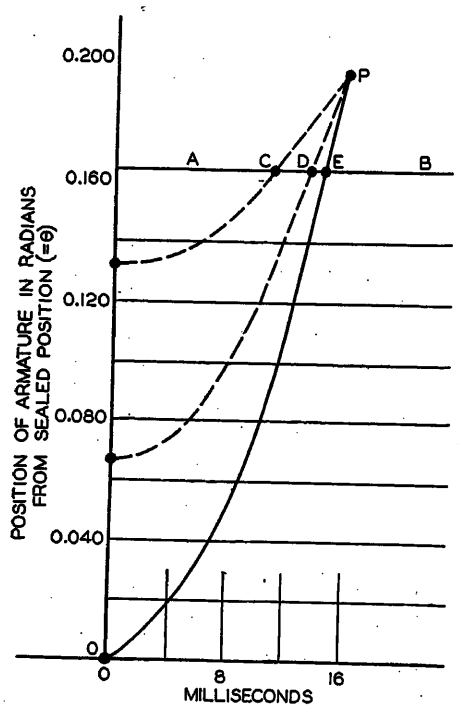


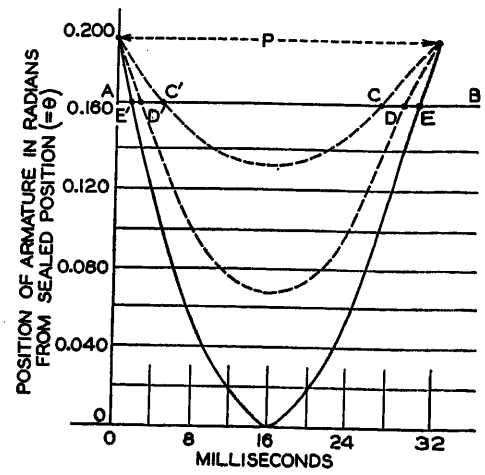

**Fig. 2. Curves representing opening motion of magnet armature**

1. It is immaterial for the present discussion whether the armature is hinged or slides, or whether it moves horizontally or vertically. The number of contacts and contact springs is also immaterial.

In a typical magnetic contactor of average size the moving armature 3 is a laminated steel structure weighing several pounds. It constitutes as high as 85 per cent of the total mass which is set in motion by the magnet. In order to obtain fast operation for resistance welding and similar applications, design tendencies have naturally been toward reducing the moving mass, increasing the magnet pull by using intermittent duty coils, and increasing the opposing spring forces in contact springs and tail spring, if used.

When a magnetic contactor is energized, only part of the armature travel is completed when the contacts meet. Further forward movement of the armature is necessary (during which contact spring 5 compresses) to

**Fig. 3. Motion of armature during impulse operation of contactor**




provide for contact wear and for magnet travel during opening before the contacts separate, so that suitable separating speed may be attained. Expressed briefly, armature movement equals arc gap plus wear allowance.

Assume that the magnet is holding its armature in the sealed position with the contact spring 5 correspondingly compressed and that the magnet is then de-energized. The resulting outward motion of the armature is that of a mass accelerated by a spring (frictional and gravity forces being small compared with that produced by the spring). Then if

$I$ = moment of inertia of armature
$T_s$ = initial outward torque due to contact spring
$\theta$ = angular travel of armature outward from sealed position
$t$ = seconds after initial instant
$K$ = reduction in contact spring torque per radian of opening motion

$$I\frac{d^2\theta}{dt^2} - (T_s - K\theta) = 0 \qquad (1)$$

The solution of this is (assuming $\theta = 0$ when $t = 0$):

$$\theta = \frac{T_s}{K}\left[1 - \sin\sqrt{\frac{K}{I}}\left(t + \frac{\pi}{2}\sqrt{\frac{I}{K}}\right)\right] \qquad (2)$$

If $I$ is in pound-inches,[2] $T_s$ in inch-pounds, $K$ in inch-pounds per radian, and $\theta$ in radians:

$$\theta = \frac{T_s}{K}\left[1 - \sin\sqrt{\frac{12 \times 32.16K}{I}}\left(t + \frac{\pi}{2}\sqrt{\frac{I}{12 \times 32.16\,K}}\right)\right] \qquad (3)$$

Using equation 3, the angular motion of the armature may be plotted as a function of time as in figure 2, wherein the full-line curve shows the armature motion following

its release from the sealed position (the curves of figure 2 apply to an actual contactor which may be considered as typical).

Now if the armature were held at some position intermediate between the sealed position and that at which the contacts just touch, as at $B$ or $B$,[1] and released, equation 3 shows that the armature would move in accordance with the corresponding dotted curve of figure 2. It can be shown that these curves constitute a family all of which intersect at point $P$, which is the angular position

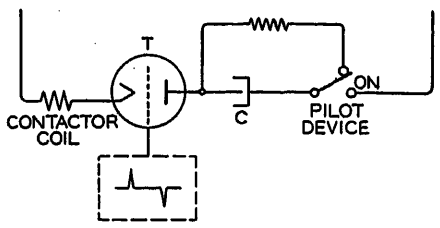



**Fig. 4. Circuit providing actuating current impulse for contactor coil—charging type**

at which deformation of the contact spring 5 is entirely relieved. However, in an actual contactor the contact spring 5 is restrained by a mechanical stop of some sort before this point is reached. As a result, the contact 4 is moved away from engagement with contact 6 at the angular position of the armature represented by the line $A$—$B$. The slope of the various curves at points $C$—$D$—$E$ is proportional to the speed of separation of the contacts.

Evidently the process of acceleration of the armature by the spring is reversible. This fact is represented by figure 3. If the armature were in some way caused to move in the closing direction at an angular speed corresponding to the slope of the curve at $E^1$ at the instant the contacts engage, its movement thereafter would be in accordance with the full-line curve, and the total period during which the contacts would maintain a closed circuit would be represented by the interval $E^1E$. (This statement neglects friction losses, which experiment proves to be justifiable.) Similarly, a slower armature speed at the instant the contacts touch would result in movement in accordance with one of the family of dotted curves, with slightly reduced interval. The only reason the interval is reduced is the restraint of the contact spring, as explained above.

We are thus dealing with the inherent period of the mechanical system consisting of the contactor armature and the contact spring. The armature might be likened to the balance wheel of a watch, while the contact spring plays the part of its hair spring. Operated in this way the contactor is its own timing device.

If the mechanical arrangement were such that the armature could oscillate in both directions under influence of the spring, it can be shown from equation 3 that the period of full oscillation would be

$$2\pi\sqrt{\frac{I}{386K}}$$

Therefore the interval $p$ in figure 3 is

$$p = \pi\sqrt{\frac{I}{386K}} \qquad (4)$$

It would appear from the above that a contactor timed in this way is inherently inflexible as far as time adjustment is concerned. In fact it is the fixed nature of the timing which gives the system its inherent stability and reliability. Nevertheless, it is found to be a simple matter in practice to obtain timing adjustments over a sufficient range, as will be brought out in a later paragraph.

## Actuating Impulse

It was assumed in the foregoing that the armature was in some way to be put in rapid motion prior to the instant the contacts touch. It was further assumed that the application of the accelerating force would not be continued after that instant. This could be done mechanically by the action of a motor-driven cam, by the sudden release of a compressed spring, by pneumatic means, etc., etc. However, it has been found most convenient and satisfactory to accomplish this by momentarily energizing the contactor coil by a single unidirectional pulse of current. A suitable current pulse for this purpose must be accurately reproducible and it must bear a definite phase relation to the a-c supply voltage. Other desirable characteristics will appear later in the description of the control. Apparently the simplest method of generating suitable current pulses is by the use of charging or discharging currents of capacitors.

Figures 4 and 5 show the 2 alternative circuits which have been successfully used in practice. It will be seen that both circuits involve a single-pole double-throw

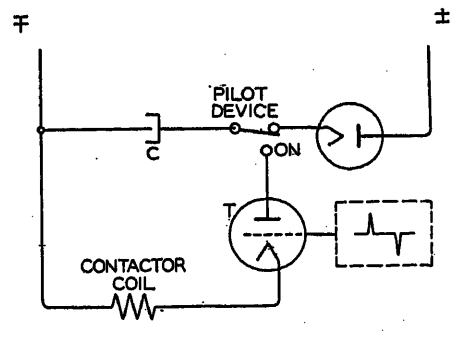



**Fig. 5. Circuit providing actuating current impulse for contactor coil—discharging type**

pilot device, a capacitor $C$, and a thyratron $T$. For either circuit, when the pilot device is put in the *on* position, these elements are connected in series with the contactor coil.

As the contactor coil has both resistance and self-inductance, the circuit of figure 4 (neglecting the action of thyratron $T$) is the classical case of $L$, $C$, and $R$ connected in series with a d-c source (reference 11). (For the convenience of the reader, formulae appropriate to this type of transient are given in an appendix to this

paper, together with a brief description of the method by which the electrical and mechanical performance of a given contactor and circuit may be predicted.)

As is well known, if in the $L$, $C$, $R$ circuit of figure 4, $CR^2 < 4L$ the current flow when the pilot device is closed will consist of a series of damped oscillations (or would, but for the presence of the thyratron $T$). This is illustrated in figure 6 which was made with the thyratron omitted. By way of comparison, figure 7 illustrates the

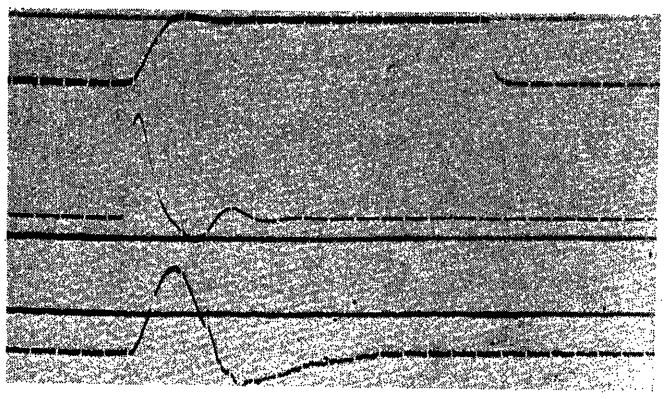


**Fig. 6. Oscillogram of impulse operation of contactor**

Actuating current as in figure 4, except thyratron omitted
Upper trace—Potential across capacitor $C$
Middle trace—Magnet-coil current
Lower trace—Magnet armature motion
Interruptions in trace are at one-cycle intervals

case in which the constants are such that no current oscillations occur.

Examination of the type of current pulse in figure 6 or 7 shows neither to be well suited for the present purpose, which obviously requires for clean-cut operation a single pulse of current, without either subsequent smaller pulses as in figure 6, or gradual cutoff as in figure 7. The presence of the thyratron $T$ (together with the use of suitable circuit constants) provides for such a pulse by preventing subsequent current flow after the first single half-oscillation. To show this figure 8 was made under the same conditions as figure 6 except for the presence of the thyratron in the circuit. Figure 8 and figure 9 are typical of actual operation with the charging and discharging circuits, respectively.

The thyratron also serves to time the start of the pulse to the desired synchronous relation to the a-c supply to the welder circuit. This triggering action is accomplished by applying a sharp-peaked wave to the grid to allow the thyratron to start conducting (after the pilot switch is closed) only at a definite point in the a-c cycle (reference 12). The phase position of the peaked wave is made adjustable throughout 360 electrical degrees to permit adjustment of the phase of the instant of separation of the contacts.

As explained in the caption of figure 6, the lower trace of each oscillogram shows the motion of the magnet armature. In each case, this trace is shown in relation to 2 horizontal lines, one of which represents the position of the armature with the contacts just touching, while the other represents its position when in the sealed position. These lines were made in turn by holding the armature in the touch and sealed positions, respectively, during a passage of the oscillograph film. The time interval between the 2 points of intersection of the trace of armature travel with the *touch* line therefore corresponds to the actual closed-circuit period. The portion of the trace between these points is equivalent to the curves of motion of figure 3. The quantitative agreement will be evident by comparing figure 8 with figure 3, the timing gaps in the former being at one cycle, or 16.7 millisecond, intervals.

It will be noted in the oscillograms that, after opening, the armature pulls out further than the position of rest

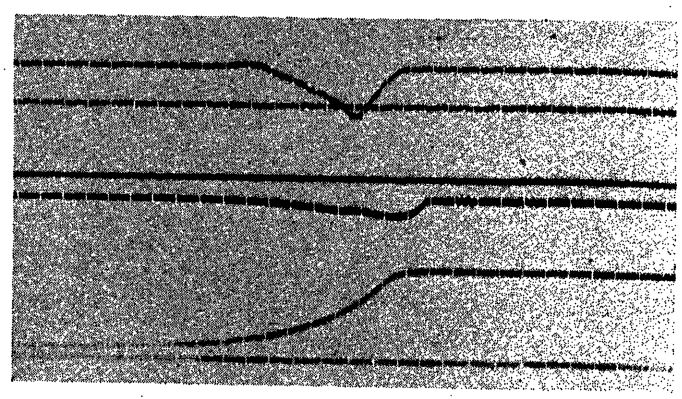


**Fig. 7. Impulse operation with aperiodic actuating impulse**

Circuit as in figure 4, $CR^2 > 4L$

and is then restored thereto in a period of about 4 cycles. This action is possible on this particular contactor because it includes a flexible stop in the open position which has a snubbing action of this type to prevent bouncing.

The operation of the circuit in figure 5 is essentially the same as that of figure 4 except that operation is obtained on the discharge instead of the charging current. Figure 4 is suited for use on a d-c supply circuit whereas figure 5 is suited for a-c supply or may be used on d-c with the rectifying tube omitted.

## Time Adjustment

From the explanation accompanying figures 2 and 3 above, it will be seen that adjustment of timing by mechanical means would be possible, either by use of weights attached to the moving armature, to increase its mass, by adjustment or interchange of contact springs, or both. In practice, however, entirely electrical adjustment by changing the capacity in the circuit is very much more convenient and desirable. Such adjustment results in variation of the speed of the armature at the instant the

contacts touch, and figure 3 shows that some time adjustment is available in this way, as the closed interval can be changed from $E^1$-$E$ to $D^1$-$D$ and so on. Furthermore, by providing more capacity than necessary for sealing the armature, longer periods than that represented by the interval $E^1$-$D$ in figure 3 are available. Experience has shown that, by providing a nonmagnetic spacer to prevent an iron-to-iron seal on the magnet face, quite satisfactory accuracy for longer timing periods up to about 5 cycles is obtainable.

The greatest percentage of the work for controllers of this type is in the short range where the contactor operates on the true impulse basis. Where such short time with suitable accuracy is available in the controller, it is generally preferable to hold the time of application constant and adjust the energy input for different types of work by adjusting the welding current.

The performance curves of figure 3 and the oscillograms herein apply to a contactor having a somewhat higher natural period than would generally be applied to this work. Actual contactors now being used have lighter armatures and higher spring tensions and have a natural closed-contact period of about 1 cycle. Laminated magnets are necessary in order to obtain suitable speed.

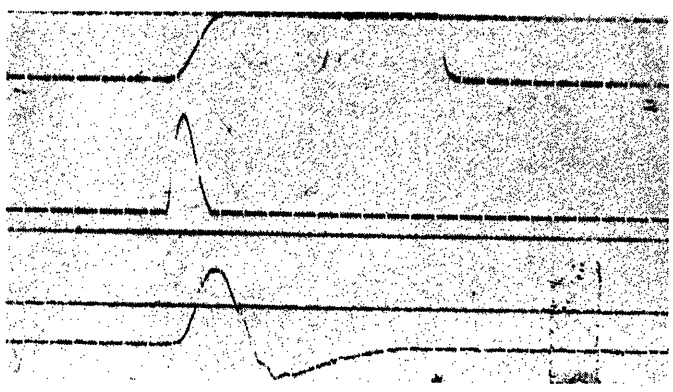


**Fig. 8. Impulse operation with oscillation prevented by thyration**

Circuit as in figure 4; $CR^2 < 4L$
This is normal type of impulse operation with the charging circuit

## Arc on Main Contacts

Phase adjustment of the coil current pulse makes possible adjustment of the instant of opening of the main contacts to avoid objectionable arcing. It is possible to adjust away from a condition of heavy arc, and experience shows that the arc that is obtained is quite uniform and permits excellent uniformity of the welding results. On stainless steel and light nonferrous welding the arcing is not a factor, but it becomes important on the high currents used in aluminum welding.

Automatic means for adjusting the instant of opening of the contacts have been developed and successfully operated. Commercial installations used to date have, however, had manual adjustment only.

## Commercial Applications

Figure 11 shows a commercial impulse controller using the circuit of figure 5. The contactor which is used with this control is of more or less conventional type as far as appearance is concerned, but has an unusually small magnet for the size and capacity of the contacts and has unusually high contact spring pressure in order to reduce its natural closed period to 1 cycle.

Commercial experience covers a period of about 18 months at the time of writing and includes separate installations in regular production service on stainless steel, aluminum, light nonferrous welding, and machine driven operation in one-cycle welding on steel at more than 5 welds per second. The method is particularly suited to applications of the last-mentioned type because operating without sealing the magnet eliminates the principal cause of magnet wear. Operation is quiet for the same reason.

## Conclusions

The method of control described herein conforms to the specifications given in a early paragraph of this paper as essential for successful short period operation of magnetic contactors. Moreover, it results in a contactor control in which the noise of magnet impact, and the problem of magnet wear, are eliminated. The controls built on this principle have fulfilled expectations in service over a considerable period and on a variety of work.

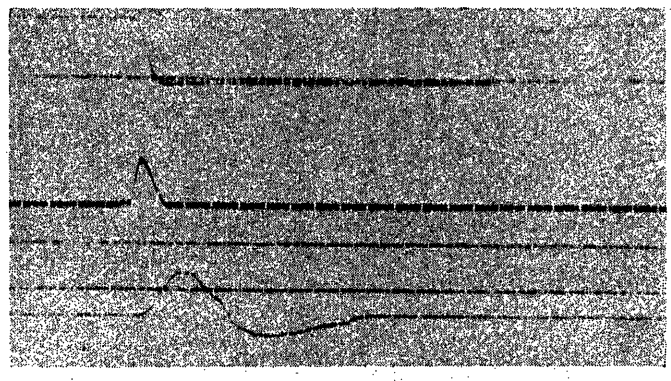


**Fig. 9. Normal impulse operation with discharging circuit**

Circuit as in figure 5; $CR^2 < 4L$

Although the present exposition of the method has emphasized its application to the resistance welding field, this is primarily for purposes of illustration and because that field appears to be the most important immediate application. It is quite possible that the method is applicable as a machine element for other purposes.

## Appendix—Calculation of Armature Motion

In order to predict the performance of a given contactor in impulse operation, it is necessary to have the following information:

1. The self-inductance $L$ and a-c resistance $R$ of the magnet coil as a function of turns and of magnetic gap. (It appears to be a satisfactory approximation to use 1.5 times the d-c resistance for $R$)

2. The pull characteristics of the magnet as a function of ampere-turns and magnetic gap

3. The moment of inertia of the armature, contacts, and other moving parts, both when moving freely and after contacts engage. Calculated values based on estimated gyration radii of components are sufficiently accurate for practical purposes

4. Torque of unbalanced weight and friction torque of armature and other moving parts

5. Torque exerted by contact springs as a function of magnetic gap.

**Symbols**

$i$ = instantaneous coil current, amperes
$e$ = instantaneous potential across capacitor, volts
$E$ = d-c supply volts in figure 4 or initial (fully charged) capacitor volts in figure 5
$t$ = seconds from instant pilot device is put in on position
$L$ = self-inductance of coil, henries
$R$ = a-c resistance of coil, ohms

$$\beta = \sqrt{\frac{1}{CL} - \frac{R^2}{4L}}$$

Although for a given coil $L$ is a variable depending on the magnetic gap, and although the armature is in motion during the passage of the pulse of coil current, analysis of a number of oscillograms of coil current and armature motion has shown that a good approximate prediction of the current pulse is obtainable by using for $L$ the value corresponding to the armature at rest in the open position. Using this value of $L$ it is essential, in order to obtain a circuit in which the current transient has an oscillating tendency, to make $CR^2 < 4L$. If this requirement is met by the circuit constants selected (reference 11),

$$i = \epsilon^{-\frac{Rt}{2L}} \cdot \frac{E}{L\beta} \sin \beta t \qquad (5)$$

for either figure 4 or figure 5. Equations for potential across capacitor are, for figure 4:

$$e = E\left[\epsilon^{-\frac{Rt}{2L}}\left(\cos \beta t + \frac{R}{2L\beta} \sin \beta t\right) - 1\right] \qquad (6)$$

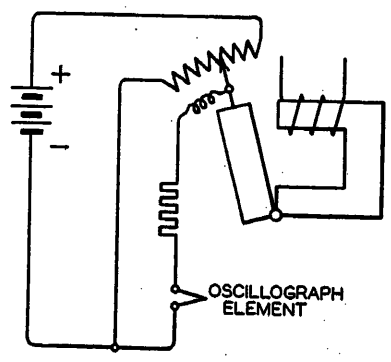



**Fig. 10. Method of recording armature movement on oscillograms**

The brush of the voltage-divider rheostat (mass and friction of which are negligible) is moved by the armature

and, for figure 5:

$$e = E\epsilon^{-\frac{Rt}{2L}}\left(\cos \beta t + \frac{R}{2L\beta} \sin \beta t\right) \qquad (7)$$

By the use of equation 5 it is possible to plot an approximate curve representing the coil current pulse as a function of time for any assumed set of constants.

Having this prediction of coil current as a function of time and the other information listed above, it is a matter of straightforward mechanics to predict the motion of the armature. The method used by the writer for doing this is a step-by-step calculation in which the net torque and resulting acceleration is taken as constant for each of a succession of equal short periods of time (0.002 sec. has been found suitable for the time increments).

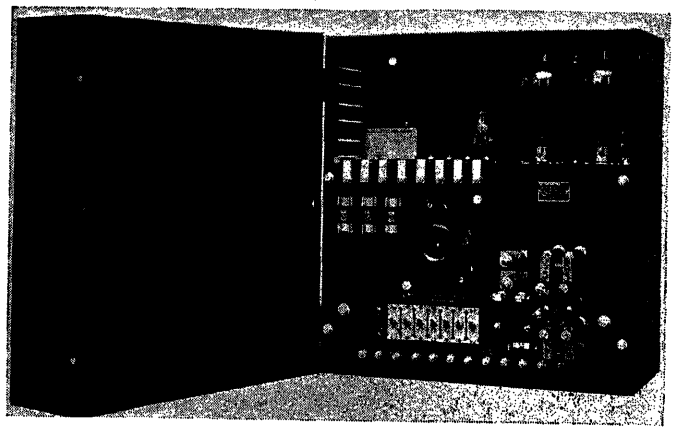


**Fig. 11. Commercial controller for impulse operation of contactor**

Contactor not shown; handwheel in center of panel is for phase adjustment; the row of snap switches is for adjustment of the main capacitor; relay and thermal strip timer allow time for heating of thyratron cathode

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# A-C Motor Protection

By C. W. KUHN
MEMBER AIEE

## Synopsis

An investigation of motor protection can be made by a comparison of the proper motor and thermal overload relay data. Convenient data for this are motor "protection" curves for comparison with "tripping time" curves of thermal overload relays. These motor curves should include single phase operation of polyphase motors as this is one of the abnormal conditions for which motors should be protected. The capacity of the motor at different expected ambient temperatures should be compared with the capacity of the overload relay at its corresponding ambient temperatures.

MOTOR PROTECTION is an important consideration in any a-c motor installation. This is recognized in industry by the almost universal use of motor protection. It is of particular importance in the design and use of automatic motor-driven equipment such as compressors, pumps, electric refrigerators, oil burners, and the like, which may represent definite fire hazards as the result of motor failure.

Almost all a-c motor protection today is by means of thermal overload devices. These thermal overload devices are not necessary units for the operation of the motors they protect but increase the use which can safely be made of them. Frequently they are not given the consideration they merit. This is partly due to lack of data, in convenient form, for the adequate consideration of a thermal overload application.

It is the purpose of this paper to outline the data necessary for a study of a-c motor protection by thermal overload devices and to present a method of calculating some of the more important factors based on the usual motor performance curves.

## Motor Characteristics

The important motor characteristics to determine adequate motor overload protection are:

1. "Protection" curve
2. "Locked rotor data"
3. "Load" curve

"Protection" curves show the time required for the motor windings to reach a certain maximum safe temperature. Time values for these curves are preferably measured, starting with windings at 25 degrees centigrade. The temperature rise of the motor windings is conveniently measured by means of thermocouples placed in the motor slots. Figure 1*A* and figure 1*B* show "protection" curves for 2 designs of a-c motors. Curves are included for single-phase operation of polyphase motors. Such single-phase operation may result from a blown fuse and is one of the hazards against which polyphase a-c motors should be protected.

While the curves of figure 1*A* show that any protection satisfactory for polyphase operation would protect the motor when operating single phase, the reverse is sometimes true. Single-phase operation of some polyphase motors results in higher temperatures of the active winding than would be obtained for the same current with normal polyphase operation. This is an important factor in motor design and one which is not always given consideration.

"Locked rotor data" merits special consideration and should consist of the following particulars:

1. Current at normal voltage
2. Current at normal voltage of polyphase motors with only one phase in circuit
3. Time required to reach the maximum safe temperature for 1 and 2 starting with ambient temperature of 25 degrees centigrade

The motor "load" curve shows the continuous load in amperes at which the motor will reach a maximum safe

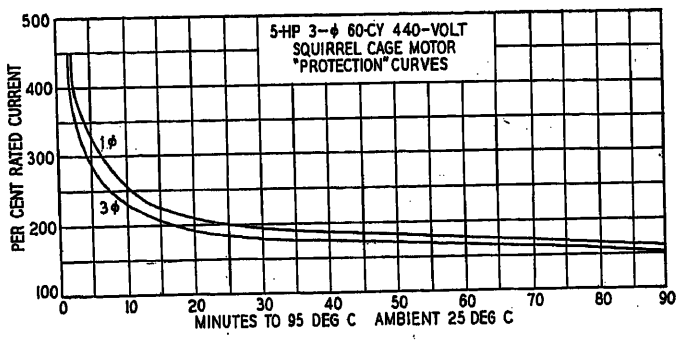



Fig. 1A

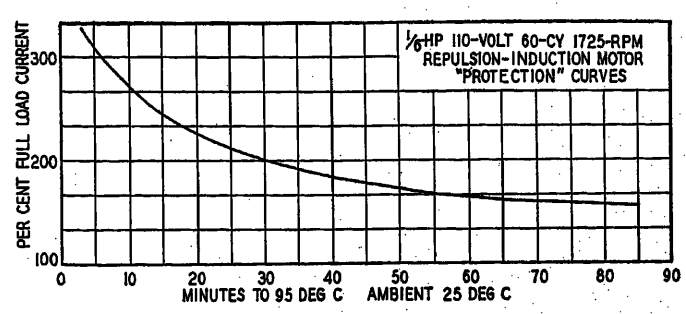



Fig. 1B

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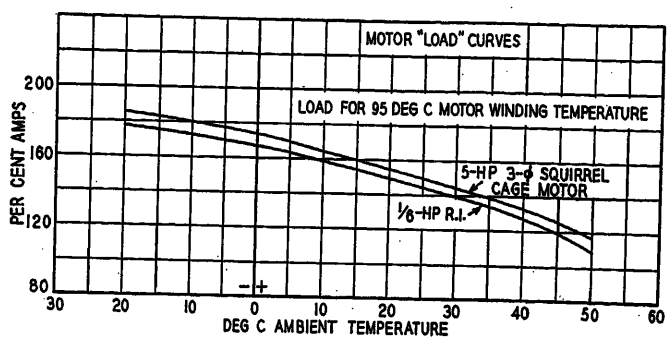



Fig. 2

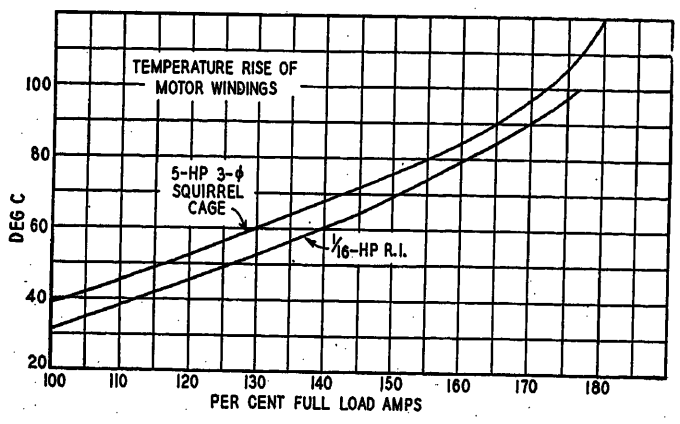



Fig. 3

temperature for various ambient temperatures. Such curves are shown in figure 2 for 2 designs of motors. Data for motor "load" curves can be obtained by determining the temperature rise of the motor winding for continuous operation at different loads as shown in figure 3. The permissible temperature rise at any ambient temperature is the difference between the selected maximum safe temperature and the ambient temperature considered.

## Calculating Motor Temperature Curve

In the absence of actual test data, an investigation for determining motor protection can be made from the usual motor performance curves as shown in figures 4*A* and 4*B*. From these curves a "temperature rise" curve for continuous duty standard motors can be calculated on the basis of a 40 degree centigrade rise of the motor windings at full load. The current and watt loss causing this temperature rise can be obtained from the efficiency and current curves of the motor. The approximate temperature rise at higher current loading is proportional to the watt loss in the motor. A "temperature rise" curve calculated on this basis is shown in comparison with an actual test curve for the same motor in figure 5. From these data we can determine a motor "load" curve as previously explained.

## Thermal Overload Relay Characteristics

Two important thermal overload relay characteristics for motor protection are:

1. "Tripping time" curve
2. "Tripping current" curve

The "tripping time" curve for a thermal overload relay shows the time required to trip the relay at various current values, in an ambient temperature of 25 degrees centigrade. One convenient method of varying the performance of the simple industrial thermal overload relay in this respect is by changes in heater coil design. Curves of figure 6 illustrate some possibilities in this respect. Curve *A* is suitable for the protection of most standard types of motors. Curve *B* shows the performance of a special fast tripping heater coil for the protection of the internal start type of motor. Curve *C* shows the performance of a special slow tripping heater coil for use with the more rugged types of motors with high-inertia starting loads.

To provide thermal overload relays whose operating characteristics more closely follow motor characteristics, designs can be used with additional heat-storage mass to assimilate the effect of the motor frame. Such designs, however, are not generally used for industrial or small-motor applications, their added cost being justified only on large generators and motors.

The "tripping current" of a thermal overload relay depends upon the ambient temperature in which it is operating. This is illustrated by the curves of figure 7. These further show a difference in the effect of ambient temperature as a result of different tripping temperatures of the thermal overload relays. For an ideal thermal overload relay design the tripping temperature should be

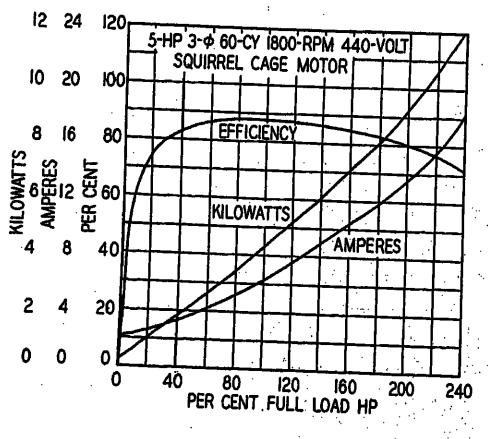



Fig. 4A

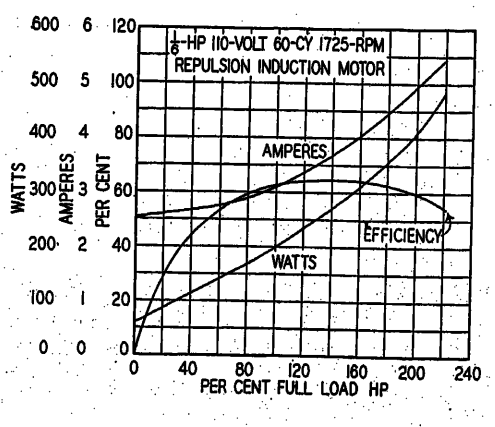



Fig. 4B

such that ambient temperature will change the tripping current to maintain a maximum, safe motor temperature.

The current rating of a thermal overload relay as established by the Underwriters Laboratories requires that it *must* trip at rated current in a 40 degree centigrade ambient temperature. Any manufacturing variation must be such as to cause it to trip at a value below its rated current.

## Thermal Overload Relays

There are 2 general types of thermal overload relays used for industrial applications, i.e., bimetal and solder film. Each of these is manufactured in a variety of ingenious mechanisms. Similar performance can be obtained with either type, as to tripping temperature, time characteristics, etc. Either type can be made with or without current adjustment.

The solder-film type of overload relay is capable of current adjustment by movement of the thermal member with respect to the overload heater. The amount of current adjustment obtainable by this method is limited to approximately 20 per cent. A relay of this type is shown in figure 8. Another method of obtaining current adjustment with this type of thermal overload relay is by use of current transformers with variable taps and adjustment of the magnetic circuit.

Current adjustment is most readily accomplished with a bimetal overload relay by changing the movement (which changes the tripping temperature) required for the bimetal to trip the overload relay. An adjustable thermal overload relay of this type is shown in figure 9.

The chief advantage of the adjustable overload relay is the possibility of its use for motors of different current ratings. Current adjustment is unnecessary on a particular motor application. If the overload rating is proper for that motor, higher current adjustments are dangerous from the standpoint of motor burnout, and lower adjustments are unnecessary for motor protection. Two manual a-c starters with nonadjustable thermal overload units of the solder-film type are shown in figure 10.

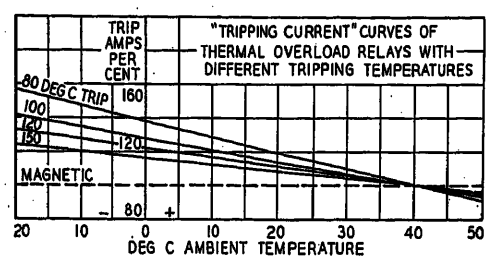



Fig. 7

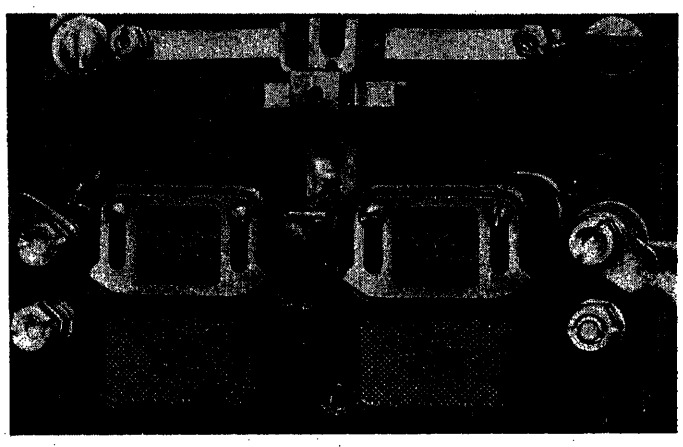


Fig. 8. Adjustable solder-film thermal overload relay (Cutler-Hammer)

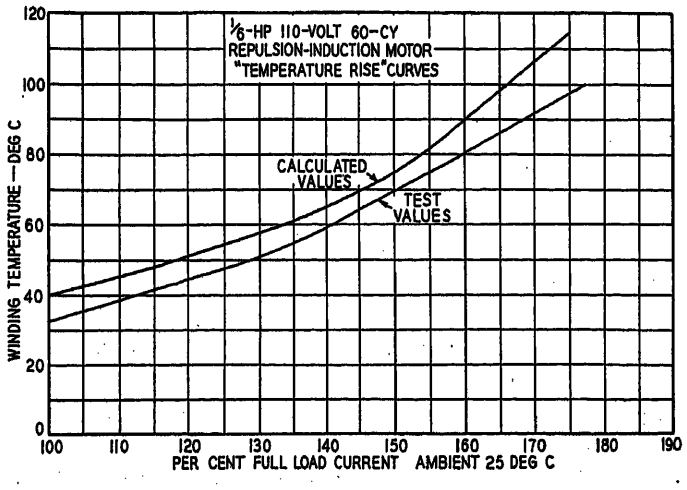



Fig. 5

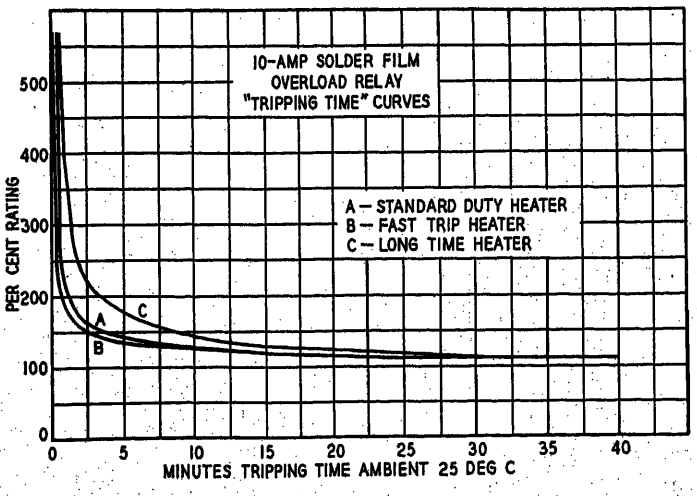



Fig. 6

## Motor-Mounted Overload Devices

Overload devices built into the motor are at present receiving increased consideration, particularly in the small-motor field. These devices are of the same general type as the separately mounted overload units and should be distinguished from those operating primarily from motor temperature. They differ, of course, in detail of construction to meet space and mounting conditions. In general, they incorporate separate heaters for adequate motor protection under locked-rotor conditions. In some designs they are heated by the current which flows

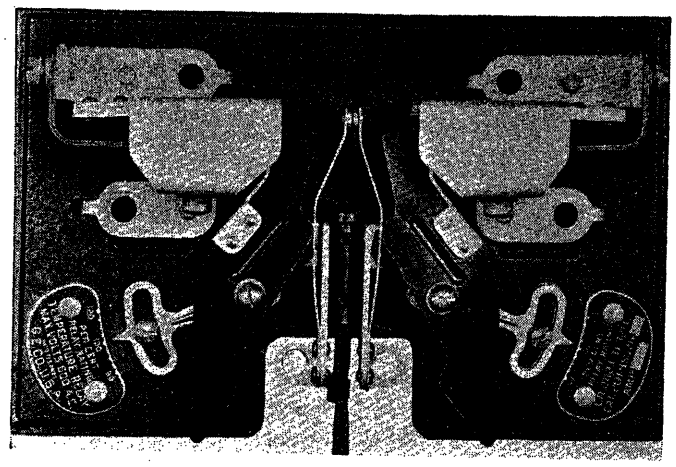


**Fig. 9. Adjustable bimetal thermal overload relay (General Electric)**

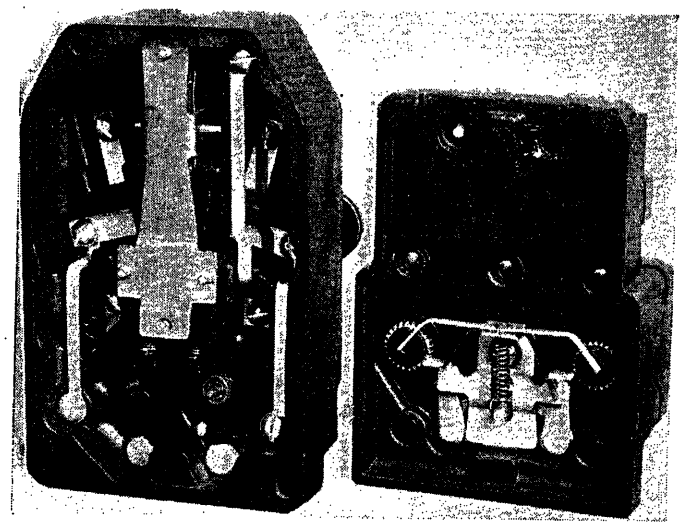


**Fig. 10. Manual starters with nonadjustable solder-film thermal overload units (left, Cutler-Hammer; right, General Electric)**

through the overload mechanism or the bimetal operating strip.

The performance of a thermal overload device built into a motor differs from that of a separately mounted overload unit. Its tripping current is obviously influenced by motor temperature. Consequently, the time characteristics of such an overload device more closely approximate those of the motor, and greater capacity is obtained for carrying short time, heavy overloads. Figure 11 shows motor "protection" and thermal overload relay "tripping time" curves for a solder-film overload relay mounted in the end bell of a capacitor-start motor.

Such motor-mounted overload devices do not, however, follow motor characteristics as closely with variations in ambient temperature. If the motor were to reach the same maximum safe temperature under all conditions, the temperature surrounding the overload would tend to remain constant and the tripping current would be constant. Obviously such conditions cannot be obtained inasmuch as the motor requires materially increased current at lower ambient temperatures for a given maximum safe motor temperature. Therefore, the motor will tend to run cooler at normal ambient temperatures if adequately protected at maximum ambient temperature by a built-in overload device.

## Cycling Overload

The "cycling overload" is an automatic resetting thermal overload device. The contacts are placed in the line circuit to the motor. When it trips, the motor is de-energized. When it resets, the motor again attempts to start. This type of motor protection is only used commercially for fractional-horsepower motors. Its principal application is on motors for refrigeration. Such motor protection is not a new development in this field although its use has recently become more widespread.

**Fig. 11**

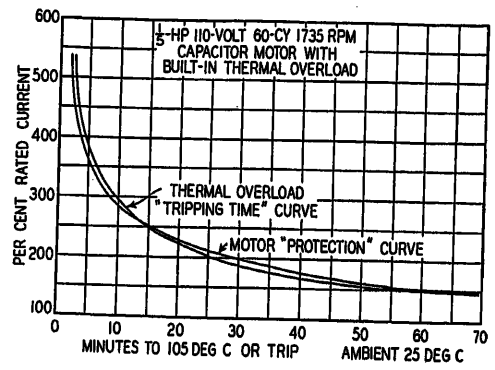
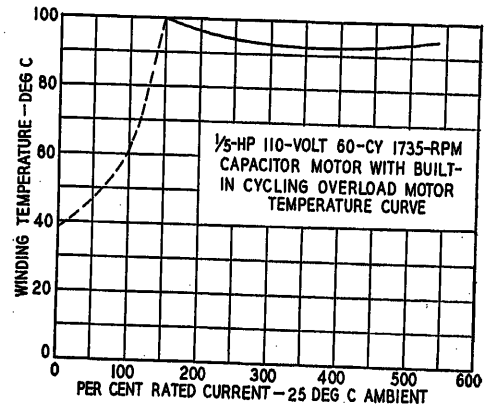



**Fig. 12**




The use of "cycling overloads" for domestic refrigerators has 2 advantages over the manually reset type of overload protection. It permits the use of a smaller motor for starting a refrigerator which has been out of service in warm weather by stopping the motor periodically. This first starting, after being out of service, requires considerably more power than that required to cycle the refrigerator after it has reached normal operating temperatures. The other advantage is that it will restart the refrigerator after a shutdown due to such temporary conditions as, low voltage during a storm, which may cause the refrigerator motor to stall and the overload device to trip.

The "cycling overload" like any other can be used either as a separately mounted device or it can be built into the motor. Figure 12 shows motor temperatures for continuous cycling on overload at various heavy overloads including locked rotor conditions.

## Determining Motor Protection

Motor overload protection can be determined by a comparison of the proper motor and thermal overload relay data. For industrial control applications the following considerations are important.

1. The tripping time of the thermal overload relay should be less than the time required for the motor to reach a dangerous temperature at any load. This can be determined by comparing the "tripping time" curve of the thermal overload relay with the "protection" curves of the motor. The latter should include single phase as well as polyphase operation for polyphase motors.

The thermal overload relay will have a higher rating than the full load rating of the motor for most applications. This overload capacity must be decided upon when comparing "tripping time" and "protection" curves and both considered in common terms of amperes or motor full-load current.

2. Locked-rotor protection can be determined from motor "locked-rotor data" and the "tripping time" curve of the thermal overload relay. The tripping time of the thermal overload relay selected should be less than the time for the motor windings to reach a dangerous temperature. Consideration should be given single-phase performance as well as polyphase performance of polyphase motors.

3. To obtain the best motor protection and to permit operating the motor continuously at maximum safe load, it is generally desirable to have the thermal overload relay installed where it will be subject to the same ambient temperature as the motor. When this relation exists it is an easy matter to determine motor overload protection by comparing the motor "load" curve with the "tripping current" curve of the thermal overload relay. Again this comparison can best be made on a common basis of amperes or per cent motor full-load current.

Installations which require the thermal overload relay to operate at materially different ambient temperatures than the motor should have motor "load" curve and thermal overload relay "tripping current" curves investigated for the corresponding expected ambient temperatures. Complete motor overload protection under such conditions will result in limiting motor capacity below the safe value which would be permitted if both motor and thermal overload relay were installed in the same ambient temperature.

The performance of thermal overload devices built into motors can best be determined by tests of the combined assembly. Such installations are effected by air circulation in the motor and heat conducted from the motor parts to the thermal overload device.

"Cycling overload" applications are likewise best made from actual test data of the combination motor and "cycling overload." An investigation can be made for separately mounted "cycling overload" applications, similar to that outlined for industrial control. It is essential, however, to investigate cycling conditions particularly those for locked rotor. The time the "cycling overload" contacts are closed under such conditions is very short and the motor is energized only a small percentage of the time. A necessary requirement for motor protections is that the "cycling overload" have a smaller "per cent time on" at locked rotor current than the ratio of full-load motor loss watts to locked rotor watts.

Industry is conscious of its a-c motor overload protection problem. This is indicated by the development work being done by both control and motor manufacturers. Perhaps further advancement will be made in the art in the not too distant future.

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# Survey of Marine Radio Progress

A paper entitled "A Survey of Marine Radio Progress, With Special Reference to R. M. S. 'Queen Mary'" by Commander F. G. Loring, W. L. McPherson, and W. H. McAllister, was read before The Institution of Electrical Engineers in London, England, on March 3, 1937. This 35-page paper, with 29 illustration and tables, gives a general survey of the field of marine radio with a view to placing on record the state of the art as of 1936. A short summary of progress during the past 5 years with particular reference to the nature and volume of traffic, the types of communication involved, and the growing use of direction-finding equipment by navigators is given. Special attention is paid to the types of radio equipment now customarily fitted in cargo vessels and in passenger vessels other than those of the "express steamer" class.

In order to give a description of the problems and how they are met on "express steamer" class of vessels, the R. M. S. "Queen Mary" is used as an example. The actual radio station of this ship and its associated power supply and antenna systems are described. The control room arrangements handle 4 independent duplex circuits which require special precautions to insure efficient multiplex working, quick change of wave length, high-speed transmission and reception, and simultaneous communication on both telephony and telegraphy with both sides of the Atlantic.

With the introduction of subscriber's ship-to-shore radiotelephone service, terminating equipment was required for ship installation. The primary function of the equipment is to prevent local interaction between radio transmitter and receiver, and in addition it may provide a "privacy" system to render speech unintelligible to unauthorized listeners.

On the "Queen Mary" service was planned to be of the same nature as that furnished on the transoceanic radiotelephone links, so that the terminating equipment is more complete than hitherto fitted in ships and includes a privacy system. Communication equipment is housed in 3 separate rooms: the power room, near the engine room of the ship, which contains 2 45-kva alternators (one a spare unit) operated from the d–c supply of the ship; the transmitting room, on the sun deck, which contains the 4 main transmitters and the power control and distribution board; and the operating room, on the sun deck and about 400 feet from the transmitting room, which contains all receivers, telephone terminal equipments, remote-control apparatus, transmitting keys, high-speed transmitting and receiving apparatus, and a complete emergency station. Thirteen antennas are required for transmitting and receiving on various frequencies and for the direction finder.

# Sixty-Cycle Calibration of the 50-Centimeter Sphere Gap

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ONE OF the important functions of the Institute is to provide specifications relating to the standardization of testing equipments and methods. Since the publication of AIEE Standards No. 4, May 1928, considerable progress has been made in the extension and revision of the calibrations for the grounded sphere gap for both 60-cycle and impulse voltages. This paper presents data which should be of assistance in establishing the calibrations of ungrounded sphere gaps. In addition to these data, the paper also describes the equipment and method used in determining the crest voltage applied to the spheres and the means of determining the spacing at spark-over. Data are also presented upon the effect of ultraviolet irradiation of the spheres.

## Summary

1. Ultraviolet radiation of the spheres materially improved the consistency of the sphere gap.

2. As compared with the nonirradiated gap the spark-over spacing of the irradiated gap was slightly but definitely increased over the whole range.

3. The curve of the nonirradiated gap checks the calibration as given in AIEE Standards No. 4 up to approximately 300 kv but falls below standard curve above this point.

4. The vacuum-tube type crest voltmeter used in conjunction with a capacitance potential divider was found to be very satisfactory and convenient both for calibrating the sphere gap and for everyday measurements of 60-cycle crest voltages.

## General Description of Equipment and Setup

The photograph of figure 1 illustrates the spheres, resistors, leads, etc. and the manner in which they were supported. The spheres were of copper, 50 centimeters in diameter, conforming to the AIEE specifications. The shanks were of 3-inch diameter smooth brass tubing, and were 6 feet long. As will be seen from figure 1, each sphere was supported at the shank by 2 pairs of ropes, each pair arranged in the form of a $V$ and fastened to the shank in such a manner as to leave the shank free of loose rope ends, collars, etc. At the upper ends of the $V$ each rope was passed over a small pulley fastened to the wooden frame. The axis of the gap was 12 feet above the concrete floor of the laboratory. With the exception of the shanks, supporting ropes, Uviarc lamp, floor, etc., no other bodies were within 16 feet of the spheres. Individual adjustment of the 8 supporting ropes allowed careful aligning of the gap.

A total series resistance of 2 ohms per volt (effective value) was enclosed in the shields at the ends of the shanks, half of the resistance in the lead to each sphere. The leads from the resistances to the transformer terminals were composed of 3- and 4-inch diameter galvanized iron pipe.

It will be seen that some considerable precautions were taken to eliminate corona formation. In this respect the arrangement was satisfactory as corona became noticeable only at voltages greater than the accepted accurate range of the gap.

The gap spacing was adjusted by pulling back either or both spheres. It may be noted here that the upper ends of the ropes supporting the spheres were so located that there was always tension upon the ropes used to pull back the spheres, thus eliminating all slack or tendency of the spheres to swing. One sphere was provided with a relatively coarse adjustment and the other with a closely controlled continuously variable adjustment. This allowed each sphere to be pulled back approximately the same amount so that the sphere axes would be in line at spark-over.

The sphere spacing at spark-over was measured by means of a telescope, set with its axis perpendicular to the axis of the sphere gap and arranged to slide on carefully aligned ways in a direction parallel to the axis of the sphere gap. A white background shown in figure 1 facilitated accurate setting of the vertical cross hair on the sphere surfaces. The spacings were determined from the readings of a centimeter scale, fixed in position relative to the telescope base. Repeated checks of a given spacing indicated that the error of setting the telescope cross hairs and reading the scale was less than 0.3 millimeter.

Variable voltage for the spheres (up to 600 kv effective center grounded) was provided by 2 135-kva 300-kv (effective) transformers having their primary windings supplied from a tap-changing regulating transformer. Tertiary windings in the transformers were used only to provide a check upon the regulator settings. Each transformer was equipped with a condenser-type high-voltage bushing which was used as the high-voltage condenser of a capacitance potential divider. The capacitance of each bushing was carefully determined over the entire voltage range.

The crest voltage applied to the spheres was measured by means of a vacuum-tube crest voltmeter used in conjunction with the capacitance voltage divider. This crest voltmeter, primarily developed for use in this calibration work, has proved itself to be a reliable and consistent instrument for day-to-day measurement of 60-cycle crest voltages. With conservative operation of the vacuum tubes and other parts, it appears that the instrument re-

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The writers express their appreciation to Doctor C. F. Harding, head of the school of electrical engineering, Purdue University, for his interest and encouragement in this work.

tains its calibration for an indefinite period. Some other advantageous features of the vacuum-tube crest voltmeter are:

1. Crest voltage readings are obtained independently of wave shape.

2. The crest voltage reading is proportional to the average crest of a number of successive cycles and is unaffected by occasional surges or high-frequency oscillations in the voltage supply.

3. It does not load the capacitance voltage divider, or otherwise affect its ratio.

4. Provides a continuous indication of crest voltage and responds quickly to changes in the crest voltage.

5. Crest voltage readings are to a high degree independent of the supply voltage to the instrument. This is because the operation depends not upon the absolute currents in the vacuum tubes, but rather upon the differential current which is caused to be a function of the applied crest voltage.

The obvious disadvantage of the instrument is that a high-voltage capacitor of known and constant capacitance is required for the potential divider.

The source of ultraviolet radiation was a 220-volt Uviarc operating at approximately 4 amperes and with a drop of 170 volts across the tube. This source was placed 12 feet from the axis of the gap and at the same height above floor level.

## Method of Calibration

The general procedure in determining the relation between voltage and spark-over distance is to assume one of the variables as independent, and to adjust the second until spark-over occurs. The choice usually depends upon the manner and convenience with which the respective factors may be uniformly varied or held constant as the case may be. Thus the spacing may be fixed and the voltage increased to spark-over or the voltage may be set at some desired value and the spacing reduced. The latter method was chosen in this case, since, with the voltage controlled by a tap-changing regulating transformer, this latter method eliminated the possibility of surges or oscillations in the voltage due to sparking at regulator contacts.

In determining the spark-over distance corresponding to a given voltage each sphere was pulled back an equal amount to provide a spacing approximately correct for the voltage used. The sphere with fine adjustment was then pulled back still farther and the voltage applied and set to the desired value. The spacing was then gradually and uniformly reduced until spark-over occurred. The spheres were held at this spacing and the spacing determined by means of the telescope. In this way a large number (10–20) of readings, both with and without ultraviolet irradiation, were taken for each voltage with an average interval of about 3 minutes between readings.

In the first calibration 12 points were taken up to spacings approximately equal to the sphere diameter. A second calibration was then made using 11 intermediate points and later several of the original points were rechecked. The fact that a smooth curve can be drawn through all the points should be reasonable proof of the accuracy of the work and of the consistency of the setup.

Barometer, temperature, and humidity readings were obtained frequently and the final results corrected to a relative air density of unity.

It was quite frequently noticed, when beginning a series of readings after an interval during which the gap had not been sparked over, that the first 2 or 3 spacings obtained were higher than subsequent spacings, in other words, the gap seemed to break down easier. Accordingly from 3 to 6 "clean up" spark-overs were allowed before actually taking data.

With due care, the spacing of the spheres could be reduced very gradually and uniformly with no tendency toward mechanical oscillation or other undesirable motion of the spheres. During this operation the crest voltmeter reading was observed up to the instant of spark-over. Thus, any slight and gradual changes of voltage would be indicated. In general, however, neither the tertiary voltmeter nor the crest voltmeter indicates the presence of short-time surges or high-frequency oscillations which may exist in the power supply system due to external causes, such as switching operations or suddenly changing loads. Occasional erratic readings were obtained and these were

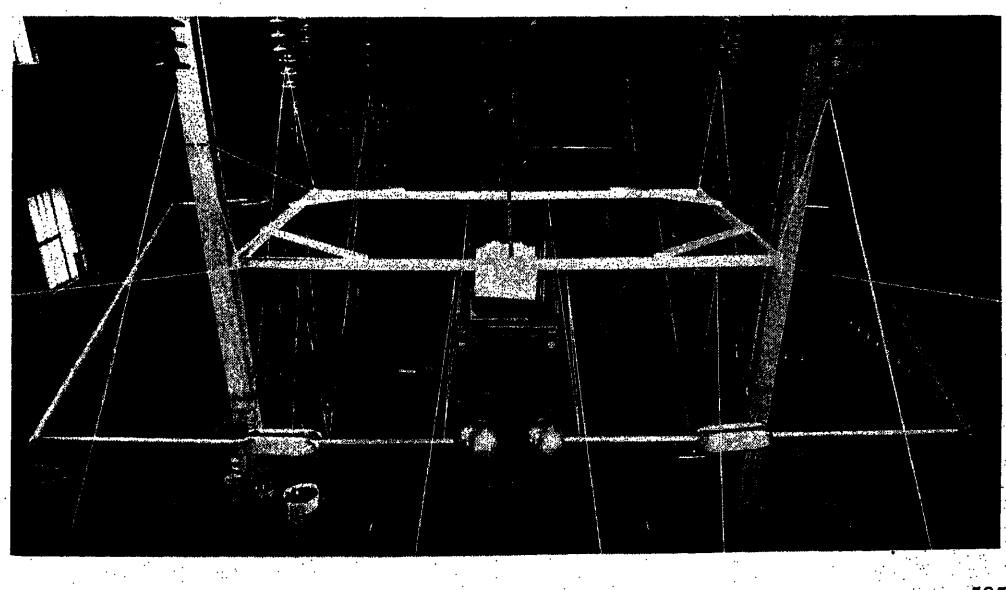


**Fig. 1. Photograph showing arrangement of 50-centimeter ungrounded sphere gap**

attributed to the above factors and were not used in averaging the results.

## Calibration Data

Table I presents the calibration data for the actual test points and is presented principally to illustrate the effect of ultraviolet radiation in decreasing the scattering of individual readings and increasing the spacing.

Table II provides the final calibration data, the values being taken from a smooth curve drawn through the points of table I. Data from the calibration as given in AIEE Standards No. 4 is also provided for comparison.

## Accuracy of Results

As stated before the telescope settings for a given spacing could be repeatedly checked within 0.3 millimeter or within 0.15 millimeter of the average of a large number of readings. There was, however, a second possible error in the measurement of spacing due to a possible change in the angular position of the telescope as it was moved laterally along the parallel ways. Such a change could be caused either by a localized high spot, or by a general and gradual curvature or bowing of the ways. In the former case the high spot might be permanent in which case its effect would be averaged out in drawing the final smooth curve, or the high spot might be caused by loose foreign matter so that its effect would be minimized in averaging a large number of readings for a given point. In the case of a gradual bowing of the ways the error would tend to be of constant percentage. These factors were duly taken into account and considerable care was taken to assure that the motion of the telescope was as nearly truly parallel as possible. It is believed that the maximum possible error is not greater than one millimeter and that the probable error, in consideration of the averaging processes mentioned above, is of the order of 0.5 millimeter.

The accuracy of measurement of the crest voltage depended upon the accuracy of the calibration and of the reading of the crest voltmeter, and on the accuracy of the determination of the ratio of the capacitance voltage divider. The crest voltmeter as mentioned before is not affected by surges and reads the average crest value of a number of cycles. Hence any individual voltage reading might be in error by an undetermined amount depending on the presence and magnitude of any high-frequency surges in the distribution system. Such disturbances were relatively infrequent and it is felt that their ultimate effect was negligible.

The accuracy of calibration and of reading the crest voltmeter were each within $1/4$ of 1 per cent. The ratio of the voltage divider was determined by individual measurements of the capacitance of the condenser-type bushing over the entire voltage range and of the capacitance of the series low-voltage condenser. Except for the extreme upper end of the curve where corona became noticeable, it is believed that this ratio was determined within 1 per cent. Thus the maximum possible error in determining the crest voltages was of the order of $1\frac{1}{2}$ per cent with an estimated probable error of the order of one per cent.

In consideration of the probable errors in determining the spacing and the crest voltage, and of the averaging processes previously mentioned, it may be stated that the final calibration data of table II are accurate to a probable one per cent.

**Table I—Test Data for 50-Centimeter Ungrounded Sphere Gaps Corrected to Standard Atmospheric Conditions (Delta = 1)**

| Voltage, Kilovolts Crest | Average Spacing, Millimeters | | Maximum Deviation From Average Spacing in Per Cent | | | |
|---|---|---|---|---|---|---|
| | Non-irradiated | Irradiated | Nonirradiated + | Nonirradiated − | Irradiated + | Irradiated − |
| 72.2 | 25.1 | 25.1 | 2.7 | 0.4 | 0.4 | 0.0 |
| 106.2 | 37.4 | 38.2 | 1.6 | 1.0 | 0.1 | 0.4 |
| 125.6 | 44.9 | 45.8 | 0.4 | 0.7 | 0.9 | 0.4 |
| 181.5 | 66.1 | 67.0 | 0.8 | 0.3 | 0.7 | 0.7 |
| 212.6 | 78.3 | 79.5 | 0.5 | 1.1 | 0.6 | 0.6 |
| 256 | 95.2 | 96.6 | 1.4 | 1.5 | 0.3 | 0.2 |
| 282 | 107.8 | 109.8 | 0.9 | 0.8 | 0.6 | 0.1 |
| 325 | 126.0 | 127.5 | 0.8 | 0.1 | 0.2 | 0.1 |
| 352 | 138.7 | 140.8 | 0.6 | 0.4 | 0.1 | 0.1 |
| 364 | 144.8 | 146.0 | 1.5 | 1.0 | 0.7 | 0.6 |
| 397 | 161.5 | 164.0 | 0.7 | 0.4 | 0.1 | 0.1 |
| 403 | 164.1 | 167.1 | 2.2 | 1.8 | 0.8 | 0.6 |
| 430 | 181.6 | 183.0 | 0.5 | 0.3 | 0.5 | 0.4 |
| 464 | 200.6 | 204.0 | 0.3 | 0.3 | 0.2 | 0.2 |
| 498 | 218.4 | 223.0 | 0.7 | 0.9 | 0.5 | 0.1 |
| 536 | 244.0 | 244.7 | 0.4 | 0.6 | 0.4 | 0.1 |
| 570 | 265.9 | 266.6 | 1.4 | 0.8 | 0.2 | 0.2 |
| 618 | 292.5 | 293.5 | 0.4 | 0.3 | 0.6 | 0.4 |
| 637 | 308.8 | 311.9 | 1.1 | 1.0 | 0.1 | 0.2 |
| 675 | 337.5 | 336.6 | 1.0 | 1.2 | 1.0 | 0.4 |
| 719 | 366.1 | 370.2 | 0.7 | 0.6 | 0.8 | 0.3 |
| 736 | 381.9 | 383.7 | 0.4 | 0.6 | 0.2 | 0.3 |
| 790 | 428.4 | 431.3 | 0.8 | 0.6 | 0.4 | 0.5 |
| 802 | 445.0 | 443.1 | 0.9 | 0.9 | 0.2 | 0.3 |

**Table II—Calibration Data for 50-Centimeter Ungrounded Spheres (Delta = 1)**

| Sphere-Gap Spacing, Centimeters | Spark-Over Voltage, Kilovolts Crest | | |
|---|---|---|---|
| | Nonirradiated | Irradiated | Standards No. 4 |
| 5.0 | 139 | 137 | 139 |
| 7.5 | 204 | 201 | 204 |
| 10.0 | 266 | 263 | 265 |
| 12.5 | 322 | 318 | 326 |
| 15.0 | 374 | 369 | 381 |
| 17.5 | 422 | 416 | 431 |
| 20.0 | 465 | 460 | 475 |
| 22.5 | 507 | 502 | 516 |
| 25.0 | 545 | 542 | 557 |
| 30.0 | 624 | 621 | 632 |
| 35.0 | 695 | 692 | 702 |
| 40.0 | 764 | 761 | — |
| 45.0 | 808 | 806 | — |
| 50.0 | 850 | 847 | — |

## Conclusions

Ultraviolet irradiation of spheres produces a distinct lowering of the spark-over voltage for a given spacing and

(*Concluded on page 600*)

# Probable Outages of Shielded Transmission Lines

By S. K. WALDORF
MEMBER AIEE

## I. Synopsis

Based on the observed phenomenon that flashover of transmission-line towers provided with 2 overhead ground wires occurs only when the product of tower-footing resistance and tower surge current exceeds the insulation strength, the probable outages that will occur on a line can be obtained by a simple method. Only those factors enter into the calculations which have become generally accepted quantitatively.

Computations have been made for 3 transmission lines and the results compared with operating records. The agreement has been very good.

## II. Introduction

SINCE the introduction of the surge-crest ammeter and complementary magnetic links, data have been accumulating which indicate that flashover due to a lightning stroke to a tower occurs only when the product of tower surge current and tower-footing resistance exceeds the insulation strength of the line.[1] If an insulated line conductor is struck, flashover almost invariably occurs. Hence, for a transmission line to be highly resistant to lightning, overhead ground wires are needed to shield the line conductors from direct strokes, and tower footing resistances must be co-ordinated with line insulation.

In order for estimates of line performance to be made in any particular case, several factors must be known quantitatively. These factors are:

1. Degree of shielding of line conductors provided by the overhead ground wires
2. Line insulation strength
3. Tower-footing resistance of every tower of the line
4. Tower surge currents caused by lightning

## III. Evaluation of Factors

At the present time, the art has advanced sufficiently that overhead ground wires can be so placed as to be highly effective in shielding line conductors from lightning.[1,2,3] For evaluating the efficacy of any given arrangement of ground wires and line conductors, scale models can be tested in the laboratory, utilizing an impulse generator.

The second factor to be evaluated is insulation strength, which is much affected by the rapidity of rise and fall of the applied voltage. There is evidence available, though not conclusive, that most lightning strokes cause tower voltages which do not attain their maxima for several microseconds.[5,6,7,8] These data indicate that the impulse strength of line insulation can be taken without serious error as that obtained with the standard $1\frac{1}{2}$ x 40 microsecond wave rather than with the 1 x 5 microsecond one.[9] Due to capacitive-coupling effects between overhead ground wires and line conductors, the strength of insulation installed on a transmission line is greater than that of the insulator strings alone.[10]

The values of ground resistance used for the calculations are those obtained by conventional methods of measurement. The resistance of a tower footing should include only that of the foundation and that of any auxiliary grounding connected to the tower which is in the immediate neighborhood of the tower. The overhead ground wires should be insulated from the tower during measurement.

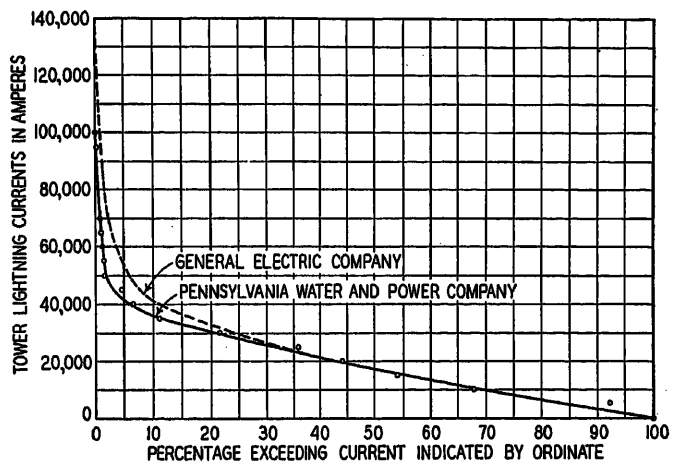



**Fig. 1. Distribution of lightning currents in towers believed struck by lightning**

Observations made with the surge-crest ammeter have shown that tower currents of various intensities produced by lightning occur in a fairly regular manner. The distribution of intensities of current in towers struck by lightning is shown in figure 1. The General Electric Company[1] and Pennsylvania Water and Power Company curves are in relatively close agreement. The tower currents included in the former curve were caused by 358 separate strokes. The data included in the Pennsylvania Water and Power Company curve were obtained during 1934, 1935, and 1936 from 419 strokes. From these curves, the fourth factor needed for calculation can be evaluated.

A paper recommended for publication by the AIEE committee on power transmission and distribution. Manuscript submitted January 13, 1937; released for publication March 6, 1937.

S. K. WALDORF is test engineer for the Pennsylvania Water & Power Company, Baltimore, Md.

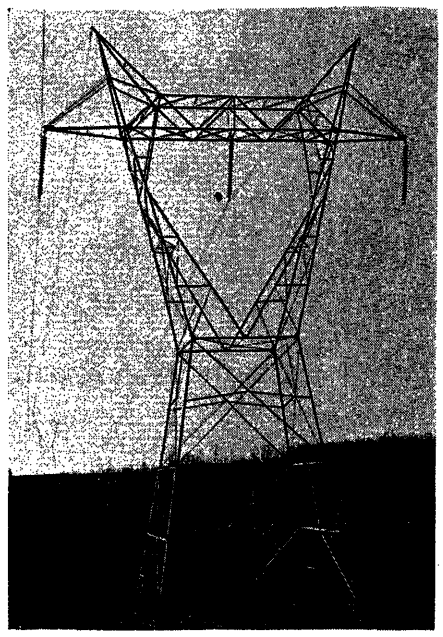


**Fig. 2. Single circuit, horizontal configuration, suspension tower of the Safe Harbor-Westport-Takoma 230-kv line**

Two overhead ground wires are installed

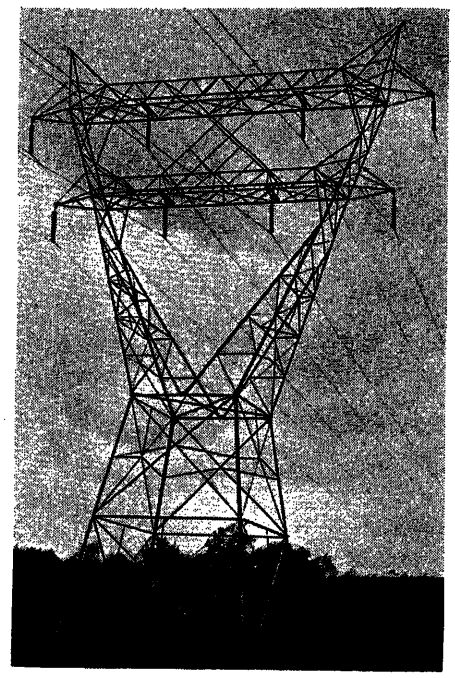


**Fig. 3. Four-circuit, single-phase suspension tower of the Safe Harbor-Perryville 132-kv line**

Two overhead ground wires are installed

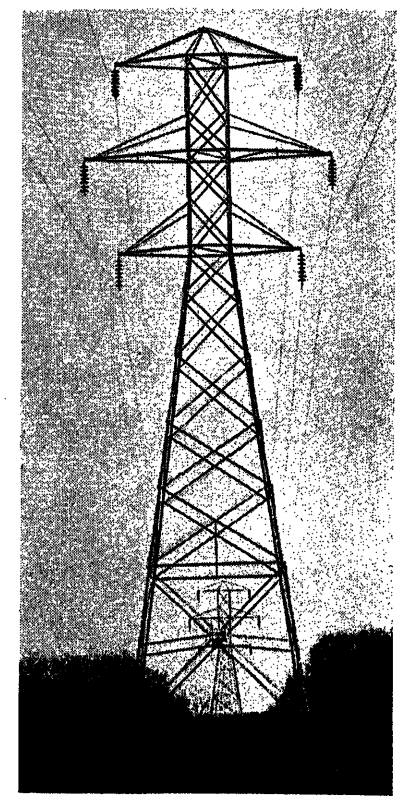


**Fig. 4. Tower of Holtwood-York 69-kv line before installation of lightning protection**

## IV. Basis of Probability Calculations

When calculating the number of outages which will probably occur on a transmission line by the method presented here, there are some assumptions made which operating experience has indicated are reasonable. These are:

1. Two overhead ground wires can and will be so provided that any strokes terminating on the line will contact only a tower or overhead ground wire. If the shielding provided is imperfect, strokes to line conductors will nullify any estimates to some extent.

2. Ohmic ground resistance as determined by conventional methods in most cases approximates the footing impedance effective during lightning discharges to a line structure.

3. Flashover occurs on a shielded line only when the product of tower footing resistance and tower crest current exceeds the insulation strength of the line at the struck tower.

4. The insulation strength of the line referred to in 3 is that determined by the conventional $1^1/_2 \times 40$ microsecond wave with electrostatic coupling effects taken into account.

5. Clearance between ground wires and line conductors at midspan is such that the flashover value there is co-ordinated with that at towers.

6. Over a period of time, and with a large number of instances, lightning phenomena and related data are amenable to statistical methods.

7. All sections of a transmission line are equally subject to lightning. If such should not be the case, the line may be divided into sections which meet this requirement.

**Table I—Probability of Outage Data and Calculations Safe Harbor-Westport-Takoma 230-Kv Line**

| Ranges of Tower-Footing Resistance | Towers in Range | | Maximum Safe Tower Current for Towers in Range | Percentage of Tower Currents in Excess of Safe Values | Probability of Flashover |
|---|---|---|---|---|---|
| | Number | Per Cent | | | |
| 0– 5 | 49 | 10.3 | 495,000 | 0 | 0 |
| 6–10 | 141 | 29.6 | 247,500 | 0 | 0 |
| 11–15 | 126 | 26.4 | 165,000 | 0 | 0 |
| 16–20 | 136 | 28.5 | 124,000 | 0.2 | 0.00057 |
| 21–25 | 13 | 2.7 | 99,000 | 0.7 | 0.00019 |
| 26–30 | 5 | 1.1 | 83,000 | 1.5 | 0.00017 |
| 31–35 | 3 | 0.6 | 71,000 | 2.4 | 0.00014 |
| 36–40 | 2 | 0.4 | 62,000 | 3.0 | 0.00012 |
| 41–45 | 1 | 0.2 | 55,000 | 4.5 | 0.00009 |
| 46–50 | 0 | 0.0 | 50,000 | 5.5 | 0 |
| 51–55 | 1 | 0.2 | 45,000 | 7.5 | 0.00015 |
| Totals | 477 | 100.0 | | | 0.00143 |

Flashover voltage of insulator strings (20 5 1/4-inch units) with $1^1/_2 \times 40$ microsecond wave = 1610 kv
Coupling factor for 2 overhead ground wires = 0.35
*Line Data:* (See figure 2)

To illustrate the underlying probability theory, a transmission line of $a$ towers will be considered. Over a period of time, there is one chance in $a$ that any one particular tower will be struck by a particular stroke of lightning. If there should be more than one stroke, the chances are increased in direct proportion.

As flashover is not caused by every stroke terminating on a tower, the critical intensity of the lightning current for a given tower can be found from the following relation:

$$\text{Maximum safe tower current} = \frac{\text{Flashover voltage of insulator strings}}{(\text{1-Coupling factor}) \times \text{Tower footing resistance}}$$

From figure 1, suppose that $b$ *per cent* of the number of strokes $c$ to the line per year are found to cause tower

currents which exceed the critical value calculated for the particular tower considered. Then, the probable number of flashovers which will be experienced by this particular tower is:

$$\frac{1}{a} \times \frac{b}{100} \times c \text{ flashovers per year}$$

If the probable flashovers per year are found for every tower of the line, and then summarized, the probable flashovers per year for the entire line will be obtained.

**Table II—Grounding Data, Safe Harbor-Perryville 132-Kv Line and Holtwood-York 69-Kv Line**

| Ranges of Tower Footing Resistance | Towers in Range | | | |
|---|---|---|---|---|
| | Safe Harbor-Perryville | | Holtwood-York | |
| | Number | Per Cent | Number | Per Cent |
| 0– 5 | 24 | 13.4 | 36 | 20.4 |
| 6–10 | 70 | 39.1 | 87 | 49.1 |
| 11–15 | 48 | 26.8 | 41 | 23.2 |
| 16–20 | 34 | 19.0 | 13 | 7.3 |
| 21–25 | 2 | 1.1 | 0 | 0 |
| 26–30 | 1 | 0.6 | 0 | 0 |
| Totals | 179 | 100.0 | 177 | 100.0 |

As shown later, the calculation need not be made for each tower of a line, but only for groups arranged according to tower footing resistances.

## V. Typical Application of Method

The probable outages that will be experienced on the Safe Harbor-Westport-Takoma 230-kv line[11,12] have been calculated by the method just outlined. The procedure followed will be given in detail.

*Sample Calculation:* (See table I)

$$\text{Maximum safe tower potential} = \frac{1610}{(1 - 0.35)} = \frac{1610}{0.65} = 2{,}475 \text{ kv}$$

$$\text{Maximum safe current for towers of 21–25 ohm range} = \frac{2475}{25} = 99{,}000 \text{ amperes}$$

From the upper curve of figure 1, approximately 0.7 per cent of measured tower currents exceed 99,000 amperes. Also, from table I it is found that 2.7 per cent of the towers comprising the line have footing resistances in the 21–25-ohm range.

Therefore, probability of outage due to towers in 21–25-ohm range = 0.027 × 0.007 = 0.00019. The probability for the entire line is the sum of those for the towers in the individual ranges.

Hence, probability of outage for entire line = 0.00143. Lightning current observations have indicated 115 strokes to this line in 1935 and 108 in 1936, or an average of 112 strokes to the line per year.

Probable outages per year = 112 × 0.00143 = 0.16. This is equivalent to one probable outage in 6 or 7 years.

The method can be used for estimating the performance of projected transmission lines or of existing lines for which improvements are comtemplated. This was done for the Holtwood-York line described in section VI before improvements in lightning protection were installed, and the result obtained was not greatly different from that reported in section VI. The principal difficulty in applying the calculation in such cases is estimating the tower footing resistances which will be obtained. The best approach to the solution of this difficulty is the analysis of data obtained on lines situated in territory comparable to that of the line considered.

**Table III—General Line Data, Safe Harbor-Perryville 132-Kv Line and Holtwood-York 69-Kv Line**

| | Safe Harbor-Perryville | Holtwood-York |
|---|---|---|
| Length (miles) | 31.5 | 22.8 |
| Insulator size | 5¼ inches | 4¾ inches |
| Insulators in suspension | 12 | 8 |
| 1½ x 40 microsecond flashover | 1,025 kv | 675 kv |
| Average strokes to line per year | 48 | 31 |

## VI. Calculated Performance and Operating Experience

The test of any method of estimating the probable performance of transmission lines during lightning seasons must necessarily be the operating records. At this time it is possible to give such a comparison of estimated and actual performance for three transmission lines over various periods of time. Although the operating period is relatively short in each case for any conclusions to be drawn, the results thus far are believed to be significant.

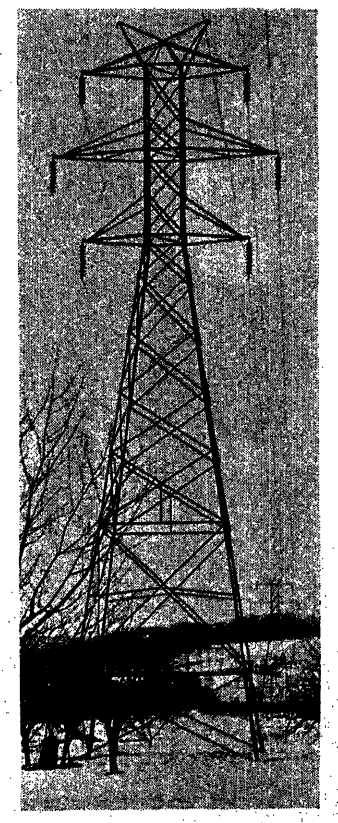


**Fig. 5. Double-circuit, vertical configuration, suspension tower of the Holtwood-York 69-kv line**

Present appearance, with 2 overhead ground wires installed

As shown in section V, calculations indicate that over a period of time there should be about one outage of the Safe Harbor-Westport-Takoma 230-kv line every 6 or 7 years. This line has actually been in service for only 5 years, during which time one outage occurred.

In figure 3, is shown a tower of the Safe Harbor-Perryville 132-kv line which supplies energy to the electrified section of the Pennsylvania Railroad between Washington and Perryville. This line has been in operation through the lightning seasons of 1935 and 1936 without any outage occurring, even though the surge crest ammeter links indicated 27 strokes to the line in 1935, and 69 in 1936. In tables II and III are given data for this line. Calculations indicate that there will probably be one outage every 4 years over a period of years.

Table IV—Actual and Probable Outages of 3 Transmission Lines

| Line | Years of Operation | Lightning Outages per Year | |
|---|---|---|---|
| | | Actual | Probable |
| Safe Harbor-Westport-Takoma | 5 | 0.20 | 0.16 |
| Safe Harbor-Perryville | 2 | 0 | 0.27 |
| Holtwood-York (improved) | 1¼ | 0 | 0.38 |

The Holtwood-York 69-kv line until 1935 operated without any overhead ground wire or auxiliary grounding. The appearance of the line at that time is shown in figure 4. By August 1935, 2 continuous counterpoises[13] and 2 overhead ground wires were installed which eliminated all flashovers in the subsequent period through 1936 (about 1¼ lightning seasons). The present appearance of the line is shown in figure 5. Line data are given in tables II and III. Calculation shows that one outage in about 3 years can be expected on this line.

## VII. Summary

Data have been accumulating which permit the computation by a simple method of the probable lightning outages of a transmission line protected by overhead ground wires. Only those factors enter into the calculations which have become generally accepted quantitatively.

The results of computation and the operating record of 3 transmission lines are compared in table IV.

The agreement of results of computation and experience, and the simplicity of the method warrant its use for estimating the probable lightning performance of shielded transmission lines over a period of years.

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## Calibration of the 50-Centimeter Sphere Gap

(*Continued from page 596*)

has a decidedly beneficial effect in reducing the scattering of individual readings.

If ultraviolet light is to be used with sphere gaps, the gap calibration should be determined under the irradiated condition. Although no tests were made in this work using varying intensities of irradiation, it seems probable that the calibration and use of the irradiated sphere gap should be, for the greatest accuracy, specified for a particular range of radiation intensities.

The results of this investigation indicate that, for non-irradiated spheres, the previous calibration gives crest voltages which, in the range above 250 kv, are from 2 to 12 kv too high. For the irradiated spheres the previous calibration appears to be in error by a still greater amount, and gives voltages which are too high over the entire range.

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# Discussions

## Of AIEE Papers—as Recommended for Publication by Technical Committees

ON this and the following 33 pages appear discussions submitted for publication, and approved by the technical committees, on papers presented at the sessions on electrophysics, electrical machinery, induction machinery, power transmission, and tensor analysis at the 1937 AIEE winter convention, New York, N. Y., January 25–29. Authors' closures, where they have been submitted, will be found at the end of the discussion on their respective papers.

Members anywhere are encouraged to submit written discussion of any paper published in ELECTRICAL ENGINEERING, which discussion will be reviewed by the proper technical committee and considered for possible publication in a subsequent issue. Discussions of papers scheduled for presentation at any AIEE meeting or convention will be closed 2 weeks after presentation. Discussions should be (1) concise; (2) restricted to the subject of the paper or papers under consideration; and (3) typewritten and submitted in triplicate to C. S. Rich, secretary, technical program committee, AIEE headquarters, 33 West 39th Street, New York, N. Y.

## Expansion Theorems for Ladder Networks

**Discussion and authors' closure of a paper by Michel G. Malti and S. E. Warschawski published in the January 1937 issue, pages 153–8 and 152, and presented for oral discussion at the electrophysics session of the winter convention, New York, N. Y., January 28, 1937.**

J. J. Smith (General Electric Company, Schenectady, N. Y.): This paper gives a systematic method of finding the currents and voltages in ladder networks under steady-state conditions. The usual method for such problems has been to find a general solution containing unknown constants and then evaluate these by satisfying certain boundary conditions. While this is readily done for the simpler types of networks, the determination of these constants corresponding to a given physical problem is often a difficult one for more complicated networks. For such cases the solutions given in equations 24*a* and 24*b* supply a direct method of obtaining the result.

It would appear desirable to make it clear at the outset of the paper that these solutions apply only to steady-state conditions since this is not apparent now until one has followed through the work. I wonder if the authors have made any further studies with regard to the extension of their solution to transient conditions.

The problem solved by the authors is of the type Heaviside refers to as "given the cause, find the effect" since they assume a certain network and derive its admittance at a given frequency. In his paper last year Malti showed how the method he followed was also directly applicable to the inverse of the Heaviside expansion theorem since such problems do not require the solution of the complex integral corresponding to equation 6. The inverse problem of the type "given the effect, find the cause" is also of interest since in this case we are given the admittance we desire at various frequencies and wish to find a physical network which will have such characteristics. I should like to inquire if the authors have looked into the possibilities of applying their method to this type of problem.

M. G. Malti: Smith raised 2 important questions which I shall answer separately.

*a*. We are now engaged in preparing a paper covering the extension of this work to the transient state. We hope to publish this paper at some future date.

*b*. The inverse problem (given the cause, required the effect) is extremely involved. We hope to undertake this problem after we have worked out some of the comparatively more simple cases.

## Abrasion—A Factor in Electrical Brush Wear

**Discussion and author's closure of a paper by V. P. Hessler published in the January 1937 issue, pages 8–12 and 16, and presented for oral discussion at the electrical machinery session of the winter convention, New York, N. Y., January 28, 1937.**

M. S. Coover (Iowa State College, Ames): The research investigations on electrical brush wear that are being conducted under the direction of Hessler have served to bring to light some significant fundamental information on the subject. Anyone even superficially familiar with the phenomena of sliding electrical contacts is aware of the many variables that are not only simultaneously present in the normal operating cycles of machines from time to time, but that they are probably difficult to separate and evaluate positively in a research of any kind. Only by eliminating as many of the variables as possible and attempting to control those elements that the investigator chooses to retain can anything like dependable data be procured. The information submitted indicates that Hessler has a good understanding of the problems involved and that he has made a logical approach to them.

The photomicrographs of ring surfaces show a striking contrast between the paths produced by graphite anode and graphite cathode brushes. It seems clear that these photomicrographs give rather convincing evidence that the more rapid wear of the graphite cathode brush is produced by a ring surface condition most likely attributable to the ionization of the ring material.

The test data indicate that brush wear is caused largely by abrasion. It is interesting to discover from the information in figure 11 that the trailing metallic brush without current actually wore more rapidly than the leading metallic brush did with current. This is quite the opposite from the experience with graphite brushes. Since the author has so advantageously made use of photomicrographs to explain at least in part the action of wear in the case of carbon or graphite brushes, it suggests that possibly the same procedure might be employed for metallic brushes. Hessler does not present such photomicrographs in his paper, nor does he make reference to them. Perhaps he intends to bring out this point later.

The writer believes that the test data plotted in figure 8 and figure 9 give some quantitative idea of the breakdown of total wear into its principal components, namely, mechanical brush wear, and electrical brush wear, although no information has been included on the current densities used. It would be instructive to make comparison of these data with observations using zero current on all four brushes, other conditions remaining the same.

It is hoped that this important study can be carried further. Certainly, the new information justifies it. A better understanding of the phenomena that take place with moving electrical contacts would be of inestimable value to both designer and operator.

R. M. Baker (Westinghouse Electric & Manufacturing Company, East Pittsburgh, Pa.): Hessler has shown in a very interesting manner the large effect of abrasion on brush wear and an extension of this investigation to include operation with different gases, different brush grades and different ring material should not only help a great deal in explaining the whole process of brush wear but should also be of great value in assisting the design engineer in the choice of brushes for various applications.

It has been generally realized that the smoothness of the brush track affects brush wear, for brushes often wear much more rapidly just after the ring surfaces have

been freshly turned or stoned than later, after the rings have become polished in operation. It has not been realized generally, however, that abrasiveness could be produced in a brush track by current-carrying brushes, so that a currentless brush running in this same track would wear almost as rapidly as the brushes which carry current.

There is a seeming contradication to the findings of this paper which will be described. If a number of brushes operate in parallel on a slip ring and one of these brushes voluntarily drops its current, this brush simultaneously ceases to wear. This condition is probably brought about either by some inhomogeneity in the brush or more likely by some foreign material being picked up from the ring surface. This not only would cause the brush to drop its current but would also cause it to stop wearing. Thus one might reconcile the experience with brushes operating in parallel and having poor current division with the results of Hessler's paper.

The writer must raise a question regarding conclusion 2 of this paper. A great deal of testing experience has shown the polarity effect to be in agreement with what the author finds for carbon brushes, but opposed to what he finds for metal graphite brushes. Using his nomenclature, it is always the cathode brushes which have been found by the writer to wear most rapidly. This polarity also shows many times as much ring wear as the other polarity. The discrepency may be due to the high absolute humidity maintained by Hessler in his experiments. The moisture content (14 grains per cubic foot) is about double what one finds on the average warm summer day. The high ambient temperature may also have some effect but the ring temperature probably does not rise much above the ambient due to the small electrical and mechanical losses in the contacts. The high humidity may also account in part for the large difference in brush wear at the two polarities when the brushes are not tracking. Some of the author's own data (reference 2 in paper) indicates this fact.

**M. S. May** (Speer Carbon Company, Saint Marys, Pa.): Hessler is to be congratulated on his article for the large number of readings which he has apparently made and for the new ideas brought out relative to brush wear. It was formerly thought that some mysterious "electrolytic action" caused the increased brush wear when current was flowing as compared with that under no-load conditions. Hessler has shown that this difference is due to some roughening of the commutator by current with a resulting abrasion of the brush material. It is unfortunate, however, that the test could not have been of greater duration between individual readings as 24 hours is a very short period on which to base results of brush wear.

One point brought out by Hessler was of particular interest to me. In his present paper as well as his earlier one presented a year ago, he shows that the anode brush wears faster than the cathode in case of metal grades and that the cathode wears faster than the anode with the electrographite or carbon grades. This condition prevails whether the anode and cathode

Table I

| Grade | Type | At 100 Amperes Per Square Inch: Wear per 1,000 Hours | At 100 Amperes Per Square Inch: Watts at Surface |
|---|---|---|---|
| *A* | Electrographite | 10 | 112 |
| *B* | Electrographite | 10 | 100 |
| *C* | Carbon-graphite | 16 | 82 |
| *D* | Carbon-graphite | 16 | 75 |
| *E* | Metal-graphite | 38 | 11 |
| *F* | Metal-graphite | 44 | 16 |
| *G* | Metal-graphite | 38 | 12 |

brushes run on individual tracks or in the same tracks. To my knowledge, there is no satisfactory explanation of this condition. It appears possible that the metal may be carried with the current to a degree sufficient to reverse the condition that prevails with the non-metal grade. This would be going back to the electrolytic theory and I would appreciate Hessler's comments.

Hessler's statement that brush wear is due primarily to abrasion is borne out by the following data tabulated from his article and indicating the brush wear is least in the grades having the maximum amount of electrical energy dissipated at the brush surfaces.

But if we assume that the abrasion is due to roughening of the ring by the current, we still have to explain why the roughening and brush wear are in inverse ratio to the wattage dissipated and bear no relation to the amperage carried.

Tests conducted over long periods on slip rings using a-c current and brushes of standard rotary-converter size indicate that other factors are involved than those discussed by Hessler. For example, a hard, heavy metal brush may wear the ring considerably more but show a lower rate of brush wear than another metal grade run under identical conditions. In this case, the brush which runs on the rougher ring shows the lower rate of wear, apparently due to properties of the brush itself.

Hessler's comments on the use of metal and nonmetal brushes on the same ring, call to mind the troubles encountered occasionally in winter on rotaries and attributed to high friction resulting from low humidity. These manifest themselves in very rapid brush wear. We have had some success in such conditions by using one pure graphite brush on each ring to supply lubricant to the metal brushes which carry the load.

There is one point that I believe should be brought out in considering Hessler's reports. The abrasion action mentioned by him as causing brush wear is not to be confused with the abrasive action discussed in brush catalogs and by brush salesmen. This latter is a characteristic of the brush itself due to the presence of hard mineral or carbon particles in the brush material. It is desirable under certain conditions to use such an abrasive brush to assist in keeping clean the ring or commutator surface or to wear down the mica where it is not undercut. It will generally be observed that an abrasive brush has a shorter life than a non-abrasive one, other things being equal, and in this respect, abrasion built into a brush has the same net result as that considered by Hessler.

**R. E. Hellmund** (Westinghouse Electric & Manufacturing Company, East Pittsburgh, Pa.): Various investigators of contact phenomena are all in agreement that the oxide film forming on the slip rings in air is an important factor. A great deal of evidence has been submitted to substantiate this point of view and some additional evidence is contained in the papers presented today. However, it is difficult to explain the difference in behavior of various grades of carbons and ring materials by the oxide film formation alone. Some investigators offer in explanation of some of the differences found the presence of varying amounts of abrasive material in the carbons, and the specific resistance of the carbon material is, of course, also considered of influence. I have always felt that in addition to these factors, certain loose graphite particles may have some influence on contact resistance. (See "Sparking under the Brushes of Commutator Machines," R. E. Hellmund and L. R. Ludwig, ELECTRICAL ENGINEERING, March 1935, page 315, and my discussion of paper "Sliding Contacts—Electrical Characteristics," by R. M. Baker, ELECTRICAL ENGINEERING, July 1936, page 821.) It is rather surprising to me that this point of view has not been accepted by various investigators at least to the extent of making investigations along this line, particularly in view of the fact that they make reference to the loose graphite particles in their investigations of brush and ring wear. In an article on the subject, "Brush Wear in Hydrogen and in Air," *Electric Journal*, June 1936, page 287, Baker has advanced what appears to be a plausible explanation of certain phenomena observed in connection with the wear of brushes. In this article it is assumed that the high temperatures prevailing near certain spots of the carbon surface tend to loosen some graphite particles by the oxidation of the binding material that takes place in the presence of oxygen. Regardless of how these graphite particles become loose, there is no doubt of their presence because they can frequently be observed in practice. It would therefore seem expedient to investigate any possible influence they may have on the contact resistance.

Figure 1*A* shows the ring, brush, and oxide film and it is assumed that at *a* the oxide film has been punctured. If, as a result of this, current passes from the brush to the ring or from the ring to the brush, the highest brush temperatures will exist in this neighborhood and it is quite likely that graphite particles 1, 2, and 3 will become loose. If this occurs any appreciable distance from the edges of the brush, any theory must take into account the subsequent location and behavior of these particles. It they happen to be located in the puncture of the film as indicated in figure 1*A* they are bound to participate in current conduction and therefore will probably influence the contact resistance until they are disposed of, either by burning up or by being removed from under the brush. It is difficult to imagine that all of these particles will remain within the puncture; it is more likely that at least some of them will be carried along and thus may enter between the oxide film and the brush, as indicated by particles 4, 5, and 6 in figure 1*B*. If this condition prevails, which it is likely to do under the negative brush where as a rule

the greatest amount of brush wear takes place, the separation of the brush from the oxide film by the particles as shown in figure 1*B* would no doubt have some influence on the contact resistance and might lead to irregularities and sparking under the brush. It is not impossible that the irregularities in the contact voltage shown in figure 2*C* of the paper by Baker and Hewitt can be explained in this manner. Another possibility which should be considered is that the graphite particles are harder than the oxide film and therefore may be forced into the film as shown in figure 1*C*. Under

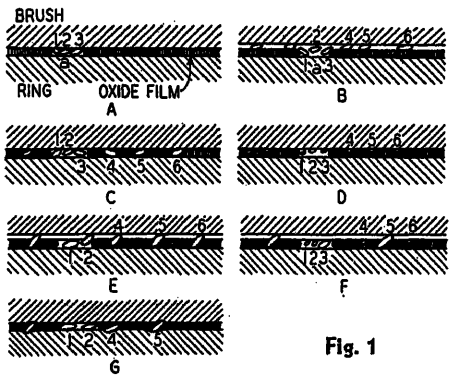



Fig. 1

this condition it is evident that these particles may form conducting bridges between the brush and the ring, and it is possible that the change in contact resistance observed with increasing current density may be caused largely by an increased number of particles acting as conducting bridges. However, the extremely short time required for decreasing the contact resistance when the current is increased suddenly, makes this possibility somewhat doubtful. It would further have to be assumed that when the current is interrupted these particles will gradually fall out thus permitting the oxide film to reform. This latter assumption is not at all contrary to observed data such as given in the papers presented.

By assuming that these loose particles have a bearing on the contact phenomena, it would seem relatively easy to explain the differences observed even in carbons having the same electric conductivity. A mere comparison of figures 1*D*, *E*, and *F*, under the assumption of relatively small particles of equal size in figure 1*D*, relatively large particles of equal size in figure 1*E*, and a combination of small and large particles in figure *F*, brings out very different conditions of current conduction. If the conditions of figure 1*D* apply, the particles may have little influence upon the contact resistance, while just the opposite might be expected with the large particles of 1*E*. Incidentally, the conditions shown in figure 1, *E* and *F* might explain some of the brush-wear data given in Hessler's paper. Differences might also be expected with the same 3 conditions of particles but under the assumption that the particles are not forced into the oxide film but merely ride on top of it. Another conceivable condition is that the graphite particles penetrate not only the oxide film but also the metal surface to a certain extent and that they lodge in the crevices of the metal ring surface as indicated in figure 1*G*. This might explain differences which have been observed with different finishes of the metal surfaces as well as differences found between ordinary cast material and other materials having a denser or harder surface structure. Finally, it seems possible that the graphite particles might dent the oxide film and force it into existing crevices of the ring without, however, penetrating it mechanically. In reality, the phenomena are probably even more complicated than indicated by any of the individual figures, as a combination of the various conditions shown in the figures may exist. As suggested in my brief discussion of Hessler's paper on "Electrical Brush Wear" (ELECTRICAL ENGINEERING, April 1936, page 406), the possibility of cuprous (red), low-resistance oxide forming in the neighborhood of the high temperature breakdown points may also enter into the phenomena. The abrasive effect of the ash particles in the carbons, previously referred to, and also the specific resistance of the carbons must as a matter of course be given due consideration.

Regardless of which of these factors are the most important under normal operating conditions, it would seem that the mechanical structure of the carbons as influenced by the number of graphite particles, their size, and the ease with which they become loose, is likely to be responsible for some of the differences observed in the contact resistance when different grades of carbons are operated on the same type of rings and under otherwise identical conditions.

**V. P. Hessler:** The tests of figures 8 and 9 were made at 50 amperes per square inch, of figures 10 and 11 at 120 amperes per square inch, and of figures 12 and 13 at 80 amperes per square inch. This information should have been given in the paper.

Baker's suggestion that the investigations be extended to include the effect of other gases, more brush grades, and other ring materials is in order. As suggested at the close of the paper it would be very instructive to repeat the investigations in the absence of oxygen. Perhaps a series of experiments of a similar nature, but designed to ascertain the conditions which produce electrical wear rather than abrasion would be most instructive. The cathode brush of figure 8 in the paper shows a large ratio of electrical wear to abrasion.

In every experiment performed by the author to date the anode metallic brush has always worn very much more rapidly than the cathode brush, whereas Baker has always observed the opposite effect. An extended conversation with Baker seemed to indicate that the only important variation in operating conditions was a difference in humidity. Some experiments will be performed with the lower humidity at the earliest possible date.

Baker's attempt to reconcile the action of a shirking brush on a slip-ring with the results of the paper illustrates a daily occurrence in a brush laboratory. The results of brush tests seem replete with inconsistencies when viewed from the standpoint of our present knowledge. However, it is hoped that many of these apparent inconsistencies will disappear with a complete understanding of brush phenomena.

Coover suggests that it would be interesting to obtain photomicrographs of metallic brush paths also. Only one of the slip-ring mechanisms was arranged for taking photomicrographs and it so happened that none of the metallic brush tests were made on this mechanism.

It is desirable to make the individual wear tests as long as possible, but whenever one test is extended over a longer period some other test must necessarily be deleted. The 24-hour period seemed to represent the best compromise. Actually some of the tests, in effect, were much longer than 24 hours. In figures 10 and 11 is change which was made in the operating conditions for 8 days.

May's theory that metal may be carried to the ring from the anode metallic brush has been considered as a possible explanation. The writer has planned to operate metallic brushes on a ring of some metal other than copper and study the paths carefully with the aid of microchemistry. The dissimilar metals should simplify the problem of detecting transferred materials. Of course, wear studies will have to be conducted simultaneously to ascertain whether the new material gives brush wear comparable to that with copper.

The tabulation of watts at the contact surface and wear made by Mr. May is very interesting. Previous studies made by the writer on wear indicate that there is no correlation between contact drop and wear, except in the case of a copper impregnated brush. This brush gave very similar wear and contact drop curves.

While the writer does not see any close connection between Hellmund's theory and the wear studies presented in the paper, it does relate to a very interesting observation made several years ago by a graduate student in the writer's laboratory. A very well developed "photograph" or blackened spot, had formed on a ring with a resulting high contact drop. With the hope of ascertaining the film resistance of the "photograph" the ring was stopped with the "photograph" under the brush and voltage-current data obtained. Then the ring was rotated until a normal ring surface was under the brush and the test repeated. The "photograph" showed by far the lower contact resistance and the voltage current characteristic was straight. From this the writer assumed that the black film consisted largely of carbon particles imbedded in the copper itself, but projecting through the oxide film, much as Hellmund has drawn this in figure 1*G*.

## Arc Characteristics

### Applying to Flashing on Commutators

**Discussion and author's closure of a paper by R. E. Hellmund published in the January 1937 issue, pages 107–13, and presented for oral discussion at the electrical machinery session of the winter convention, New York, N. Y., January 28, 1937.**

J. N. Jones (Westinghouse Electric & Manufacturing Company, East Pittsburgh, Pa.): The methods and data given in the paper make it possible to answer various

questions regarding flashing, and one practical example may be of interest. Originally most railway motors were operated on full line voltage of 600 volts, but several years ago 2 motors in series were advocated by Westinghouse engineers under certain railway operating conditions in order to improve flashing. It was felt at the time that such improvement would be accomplished by this, but the question could not be analyzed and it required several years of experience to prove the soundness of the proposed change. With the data now available, the analytical answer to this question can be given.

In the accompanying figure, the arc characteristics for 10 to 60 amperes at a

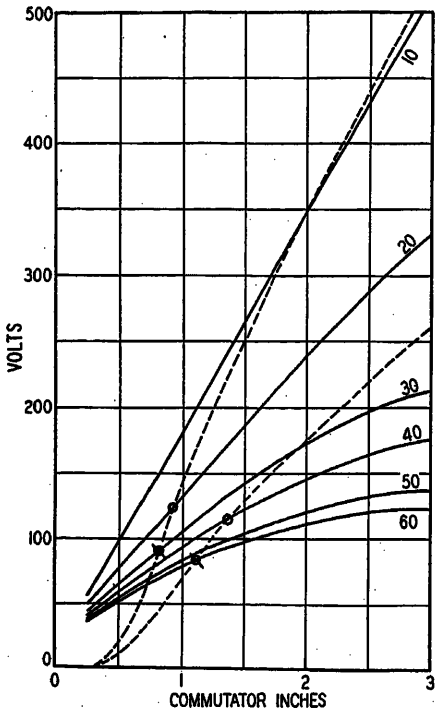



Fig. 1

speed of 2,200 feet per minute are given; the dotted lines indicate the voltage induced around the commutator, the upper curve applying to a 600-volt and the lower to a 300-volt machine. If we select a point of intersection on the 20-ampere curve of the high-voltage motor we find it to be at a distance of 0.93 inch from the zero line. The same motor operated from 300 volts would carry the same load with 40 amperes, and thus we have to find the intersection point for 40 amperes with the lower curve, This point is 1.38 inches from the zero line, which means an increase of 48 per cent and, correspondingly, a reduced tendency to flash. Similarly, the intersections of the 30-ampere curve with the high-voltage curve and of the 60-ampere curve with the low-voltage curve indicate an increase of 41 per cent. Practical experience has demonstrated that 300-volt motors are less subject to flashing in service, a fact which is somewhat in accord with the values indicated in these curves.

By a similar analysis of curves for a higher speed, 3,200 feet per minute, it was found that the distance from the zero line to the point of intersection of the 40-ampere, 300-volt curves was 44 per cent greater than that of the intersection of the 20-ampere, 600-volt curves. By a comparison of the 60-ampere, 300-volt and the 30-ampere, 600-volt points of intersection, the distance from the zero line of the first was 37 per cent greater than that of the latter.

For a speed of 1,100 feet per minute, the distance from the zero line to the 40-ampere, 300-volt point of intersection was found to be 52 per cent greater than that for the 20-ampere, 600-volt intersection. The corresponding distance for the 60-ampere, 300-volt point was found to be greater, by 46 per cent, than that for the 30-ampere, 600-volt.

From the results of these comparisons it would seem: (1) as the speed of the motors increases the advantage of having the motors in the series arrangement becomes slightly less but is still appreciable; (2) as the load becomes greater the advantage of the series connection over that of the full line voltage decreases.

**R. C. Mason** (Westinghouse Electric & Manufacturing Company, East Pittsburgh, Pa.): Without commenting on the interest and value to engineers of Hellmund's work, I would like to point out how some of his results can be explained in a general way by recent advances in our knowledge of gas discharges.

1. Figures 5 and 6 of Hellmund's paper are a little misleading where they show arc voltage increasing continuously from zero. Actually, as soon as an arc is drawn, a definite arc voltage develops, and the curves should start at that point. Even fairly high-speed cathode-ray oscillograms show that the voltage across a pair of opening contacts suddenly increases from a low contact drop to an arc drop of some 10 or 12 volts.

2. When the current through an arc of constant length decreases, the arc voltage changes in a manner which depends on the speed with which the current reduces: the arc voltage will be lower, the more rapidly the current decreases. In these experiments, however, where an arc is drawn by a moving commutator, an increase in arc length accompanies (causes) the decrease in current. While perhaps the losses from the arc may be influenced because air currents about the arc vary with commutator velocity, it seems that the predominant effect upon the arc voltage when the arc has reached a definite length and current must come from the speed with which the arc has been lengthened. How this may result can be seen by considering 2 extremes: suppose an arc for which the gradient in the positive column is 10 volts per centimeter has its length increased *extremely slowly* by one centimeter, while the current remains constant; the arc voltage will merely increase by 10 volts. If, however, the arc length could be *instantly* increased one centimeter, by the introduction of one centimeter of cold unionized gas, then the arc voltage would increase by the many thousand volts required to break down the one centimeter of cold gas. Of course, the latter extreme is never realized in practical cases of arcs on commutators, but the point is that whenever a new length of positive column is created, the voltage required to maintain any particular current in that length depends upon the temperature and state of ionization of the gas. If the arc lengthens quickly, the temperature and degree of ionization of the gas in the newer parts of the positive column lag behind those of the older parts; hence to maintain the arc, a higher gradient must be applied in the newer than in the older parts. If, however, the arc length increases gradually, the energy lost from the older parts of the positive column has time to flow into the newer parts, and not much increase in gradient arises. Thus, the arc voltage should increase with increased speed of drawing of the arc, just as shown in figure 7.

3. In the experiments described in the last part of the paper, the cathode or anode spots cannot actually move continuously over the commutator, because of the insulation between bars. Hence for advancement, new arc terminals must form. It is well known that a new cathode spot will not be established unless the electrode is at a potential considerably negative with respect to the adjacent arc stream, but it is perhaps not generally appreciated that likewise a new anode terminal will not form until the electrode is several volts positive. Figure 12*A* illustrates this very well; on the right side, no current flowed to the first bar from the shorted sector, the arc anode transferring directly to the second bar. In this case, it was necessary for the new electrode to be at least some 15 or 20 volts positive with respect to the adjacent positive column in order for the new anode to strike. The commutator bars are cold, while the gas in the arc column is at some 5,000 degrees or 6,000 degrees, so no matter how closely the arc stream hugs the commutator, always a transition region exists in which the gas temperature falls from the high value of the arc to the low temperature of the metal. Through reduction of electron mobility within the cold gas, the flow of current is so impeded that considerable voltage must be applied across this region in order to carry the full arc current and establish a new anode spot.

At a new cathode spot additional requirements, not well understood, must be met which demand even a higher voltage than at the anode. Thus in figure 12*B*, left, not even the voltage drop across 2 commutator bars, perhaps some 30 to 40 volts, was sufficient to transfer the cathode. In figure 12*C* and *D* the sudden breaks in the arc voltage give a measure of the voltage required to strike the new cathodes; these range from 30 to 175 volts, while even higher voltages in some cases caused no transfers.

**R. E. Hellmund:** The discussion contributed by Jones indicates how the data presented in the paper can be used to advantage to clarify certain practical questions.

Mason's reference to figures 5 and 6 of the paper is quite correct. These curves should start somewhat above the zero line if they are to represent arc voltages; they were extended to the zero line merely to indicate the starting current on which the curves were drawn. His other remarks are exceedingly interesting and give some very valuable explanations of the arc phenomena.

Penney's discussion indicates that with a roughness of 0.0003 the brushes may leave

the commutator a distance of one or two inches. Everybody familiar with railway practice knows that a figure much greater than the one given by Penney has often been allowed for the roughness of commutators, especially in some of the older motors. It therefore seems that a great deal of the commutator flashing in practice can be explained by commutator roughness, which supports the feeling I have had for some time that other causes, such as shocks caused by rail joints or mechanical vibrations of the motor as a whole, are of minor importance. The conclusion to be drawn from this is that commutator maintenance is possibly of even greater importance in reducing flashing in railway motors than any changes in the design of the motors. A review of the data given in the paper plainly indicates that flashing may occur with any motor design no matter what the field form of the motor may be. In railway work, space limitations make it practically impossible in the smaller motors to make the total distance between brushes more than

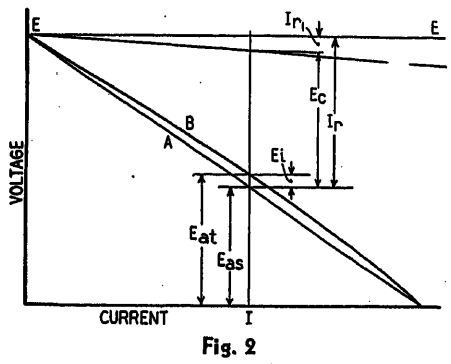



Fig. 2

5 or 6 inches, and since the total counter-voltage of the motor has to be induced within the distance between the brushes, the arc is likely to be drawn into the high-voltage region if the brush is off the commutator long enough.

Since it was not done in my paper, it may be well to call attention here to the fact that the transient arc characteristics as determined in the paper are not entirely independent of the circuit constants of the test arrangement. This may be illustrated by reference to the figure in this discussion. If a total voltage $E$ is impressed on the circuit, the ohmic drop in the circuit can be represented by the distance $Ir$ between the horizontal line $EE$ and the curve $A$. Curve $A$ must obviously be a straight line because the ohmic drop is proportional to the current. This simply means that with stable arc conditions the arc voltage $E_{as}$ is represented by the difference between the impressed voltage and the ohmic drop. If we consider, however, transient current conditions with a decreasing current, and if there is any self inductance in the circuit at all, a self-inductive voltage $E_i$ is induced, leading to a voltage $E_{at}$ for the arc voltage. This is the condition found in figures 5 and 6 of the paper. It is therefore evident that under transient conditions, the value $E_i$ will depend to some extent upon the inductance in the circuit. In a series motor, which is of the greatest practical importance in this study, conditions are different but the final results are somewhat similar. Instead of the large ohmic drop $Ir$, there is a small drop $Ir_1$, and in addition there is a counter electromotive force $E_c$ which is proportional to the current, at least as long as the motor is not saturated. The net result is that the sum of $Ir_1$ and $E_c$ is about equal to $Ir$, and the effect of any self induction is again represented by the value $E_i$. Under transient conditions the counter voltage may be influenced temporarily to some extent by the damping effects of the eddy currents in a solid frame portion upon the flux. Nevertheless, it is believed that the experimental data given in the paper are quite applicable to series motors, although it may be inadvisable to assume without further investigation that the same curves can be applied indiscriminately to entirely different conditions.

## Contact Drop and Wear of Sliding Contact

**Discussion and authors' closure of a paper by R. M. Baker and G. W. Hewitt published in the January 1937 issue, pages 123-8, and presented for oral discussion at the electrical machinery session of the winter convention, New York, N. Y., January 28, 1937.**

**R. E. Hellmund:** See discussion, page 602.

**V. P. Hessler** (Iowa State College, Ames): The results presented in this paper are very interesting and worthwhile as a step toward the ultimate goal of a complete understanding of sliding contact phenomena. The importance of the oxide film in contact drop phenomena seems to be definitely established by these and the former investigations of one of the authors. However, a large amount of experimental work will have to be done before the relative importance of the various factors involved in contact drop will be determined. For example, the oxide film alone does not explain the difference in contact drop obtained with the various grades of brushes. The difference might be attributed to abrasion but this seems hardly likely in view of the following simple experiment performed by the writer.

A pair of electrographitic brushes had been operated on a copper ring for several days with a current of 50 amperes per square inch. Then the ring was cleaned with fine carborundum paper and contact drops obtained simultaneously with the following results shown in table I of this discussion.

While the above indicates that abrasion does have an effect upon contact drop, the results were not nearly as pronounced as were expected. The abrasive paper must have cut through the oxide film, and the re-established film must necessarily have been of molecular dimensions considering the time required for an eighth of a revolution at 1,600 revolutions per minute.

Table I

| I | $E_+$ | $E_{av}$ | $E_-$ | |
|---|---|---|---|---|
| 50 | 0.68 | 1.57 | 0.85 | Before sanding. |
| 50 | 0.68 | 1.45 | 0.77 | After sanding lightly. |
| 50 | 0.67 | 1.40 | 0.73 | While sanding with 360 grit. |
| 50 | 0.69 | 1.48 | 0.80 | Running 2 minutes since sanding. |
| 50 | ..... | 1.20 | ..... | While sanding with 280 grit. |
| 50 | 0.66 | 1.42 | 0.76 | Running a few minutes since sanding. |
| 50 | 0.52 | 1.10 | 0.58 | While sanding with 280 grit. |

The authors suggest the possibility of a quasi-electrolytic action as a factor in ring wear, but show that the amount of material transferred is negligible compared to that in ordinary electrolytic action. In the case of brushes, the rate of wear is often not even proportional to the amount of current flow. With brushes not tracking the cathode metallic brush and the anode graphite brush always showed rates of wear independent of current density in the tests made by the writer. Of course, this does not apply to excessive values of current density.

The authors also suggest that, since there is less ring wear at the cathode section of the ring than at the zero-current point, material may have been picked up from some other part of the ring and deposited on the cathode section. It seems more logical to the writer to consider that the abrasion has been less at the cathode section than at the zero-current section. Very often a commutator will become threaded and the brushes dust under light loads, whereas these difficulties will all disappear under full load conditions. The same phenomena may be occurring in this synchronously operated ring.

The effect of operating sliding contacts in inert gases is indeed interesting. It will be another important step in advance when it is learned just why the presence of oxygen produces such a large increase in brush wear. The writer sincerely hopes that the authors will consider it worth while to repeat some of their experiments with a trailing brush to determine the importance of abrasion in this phenomena. It would also be interesting to analyse the gas in the tank for CO and $CO_2$ after a period of operation.

**R. M. Baker:** Hessler cites experiments in which he sanded slip rings while the brushes carried normal current, and found that the sanding operation resulted in only a small reduction in contact drop (contact resistance). It was inferred from this experiment that the oxide film is not an important factor in determining contact resistance. It must be pointed out, however, that quite different results would have been obtained if the experiment had been performed with a few milliamperes instead of normal current flowing in the contact. With normal current flowing through the contact, the film was already broken down to such an extent that sanding the ring had little effect. Sanding the ring with very low current flowing in the contact will some times result in a 1,000-to-one change in contact resistance.

It was unfortunate that the authors used the word "electrolytic" in describing the material transfer indicated in figure 5, for this word indicates the existance of an electrolyte. It was thought more likely that the material was transported by gaseous metal ions produced in the contact by vaporization, or some other process. The unequal wear might occur as Hessler and several others have suggested simply by nature of the fact that the abrasive effect of the brush

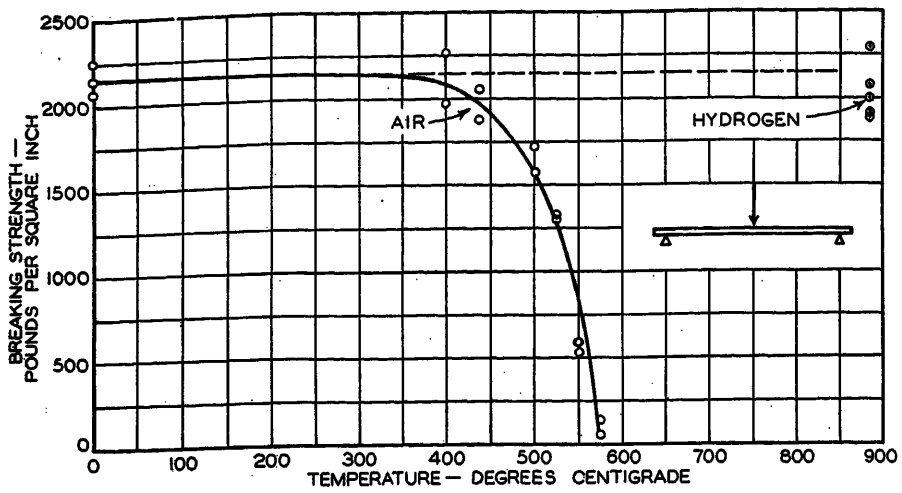



**Fig. 1. Effect of oxidation on the strength of carbon material**

is different over different parts of the rings, depending upon the amount and direction of the current flowing. There are 2 facts, however, which indicate very strongly that there is actually a transfer of material from the ring to the brush and vice versa. First, the polarity at which rapid ring wear occurs is correct for material transfer by positively charged metal ions; secondly, the variation in the wear curves is very nearly proportional to the current. If the results are to be explained on the basis of abrasion, it is necessary that the abrasion be not only dependent upon the direction but also upon the magnitude of the current.

Hessler mentions the fact that the brush wear data which he has obtained for metal graphite brushes cannot be explained by the picture of material transfer given above. This is to be expected, because brush wear is hundreds of times more rapid than ring wear and the small component produced by material transfer in the contact would never be noticed. This also raises another possible point of question which should be straightened out. Since the brush wears so rapidly, it is unlikely that much of the copper picked up off the ring would ever be redeposited. Thus, if copper is deposited on some part of the ring surface it probably is copper originally included in the body of the brush.

Some experiments with trailing brushes in an oxygen-free gas will be made as suggested by Hessler. It is doubtful, however, if such tests will give any evidence as to the process whereby brush wear is reduced upon going from air operation to operation in some oxygen-free atmosphere.

The authors have talked often about making an experiment to determine the amount of carbon monoxide and carbon dioxide given off by brushes during operation in air or in oxygen but have never found time to make the experiment. Such an experiment would furnish interesting information.

Hellmund has rightly brought out the fact that investigators of carbon brush problems have neglected to consider the effect of the carbon or graphite particles which are continuously being set free in the contact through the process of brush wear. If one assumes that all the brush wear results from particles 0.0001 inch in diameter being torn out of the brush face, one calculates that, for normal brush wear, about 50 to 100 particles are liberated from each square inch of brush area for each foot of travel. This gives some idea of the number of particles released in the contact during normal operation in air. It is surprising when one realizes that on the above assumption a brush one square inch in area, operating on a ring with a speed of 5,000 ft. per minute, would give off half a million particles in one minute.

It is not known just how these particles leave the contact or what part they play during the time they are in the contact. Hellmund makes a number of interesting suggestions, and following these, an investigation will be undertaken by the authors to determine experimentally the size and number of the particles given off by different brushes.

Hellmund suggests that the roughness of the voltage records (figure 2 of paper) for the negative polarity might be explained by the movement or disappearance of loose carbon particles in the contact. It will be seen, however, by a comparison of alternate periods of the voltage wave (figure 2 of paper) that the variations are a function of the ring position and must therefore be due to some condition existing on the ring surface rather than in the brush face. This same effect is even more noticeable during d-c operation where the voltage drop record repeats almost exactly over successive revolutions when 3 or 4 revolutions are observed on one oscillogram.

Hellmund mentions an earlier article in which the authors suggested that oxidation of the brush material immediately adjacent to the contact resulted possibly in a weakening of the brush structure and the high rate of brush wear commonly observed in air. Further evidence along this line is given by the curves of figure 1 of this discussion.

To test the weakening effect produced in a brush material by exposing it to various temperatures in air, the following experiment was made. Samples of an electrographitic lamp-black, $\frac{1}{2}$ inch wide by 3 inches long by $\frac{1}{16}$ inch thick, were subjected to various temperatures for 20 hours in an electric furnace. These samples were later subjected to a breaking test with the results indicated in figure 1. The strength recorded is the modulus of rupture in pounds per square inch.

It will be seen that in air the material began to loose its strength around 350 degrees centigrade and had zero strength around 570 degrees centigrade. Even the samples which had zero strength, still retained essentially their original size and shape and it seemed as if the weakening had occurred by a surface oxidation of the individual particles of the brush to weaken the bonds until the sample was just ready to fall apart. In hydrogen, similar samples were heated up to 880 degrees centigrade with practically no weakening. This is in line with previous arguments and is a little more evidence that oxidation of the brush material adjacent to the contact is an important factor determining the rate of brush wear in air.

In closing it should be mentioned that R. Holm of the Siemens Company in Berlin made experiments some years ago which demonstrated some of the results given by figure 2 in the paper. A copper ring was operated with a low value of direct current until the contact resistance was high. The ring was then stopped and part of the surface was subjected to a heavy current. Afterward the ring was allowed to run with only a small current flowing while the contact drop was observed with the oscillograph. The variation of contact drop around the ring showed that the section of the ring surface which had been subjected to the heavy current continued for some time to offer a much lower resistance to the flow of current than did other sections of the ring surface. The results of this experiment were never published but were communicated verbally to one of the authors during his visit to Berlin in 1932.

## Self-Regulated Compounded Rectifiers

**Discussion and authors' closure of a paper by W. Melvin Goodhue and R. Burton Power published in the November 1936 issue, pages 1200–5, and presented for oral discussion at the electrical machinery session of the winter convention, New York, N. Y., January 28, 1937.**

**F. N. Tompkins** (Brown University, Providence, R. I.): The authors are to be congratulated for producing such a timely and interesting paper.

Since little mention was made of a single-phase full-wave rectifier working in the manner described in the paper, it was thought worth while to set one up in the laboratory. It was found to give results comparable with those given in the paper. For instance, with a straight rectifier, i.e., not self-regulated nor compounded, when the input voltage was varied from 150 to 250 volts the output voltage varied from 102 to 178 volts. With the input voltage held constant at 230 volts and the load varied from zero to full load, the output voltage varied from 184 to 159. With the rectifier self-regulated but not compounded, a variation of input voltage from 150 to 250 gave a change of output voltage from 97 to 119 volts. When the input voltage was held constant at 230 volts a variation of load from zero to full load gave an output voltage change from 119 to 115 volts. It is quite possible that with changes in the apparatus

used even better results would have been obtained. These tests, besides indicating that the circuit may well be used with single-phase input, pointed out several facts which either were not stressed or were not mentioned by the authors.

The current transformer used in the 3-phase arrangement seems to be of special design, being for 3-phase operation. Three common single-phase current transformers should not be used since they would be working into a half-wave rectifier and would have no secondary load every alternate half cycle. This would lead to saturation of the cores and a high voltage drop across the primaries. In the single-phase compounded rectifier, as set up in the laboratory, it is necessary to use a current transformer with a center tap in order that the current compounding may be supplied from a full-wave rectifier. It was also found to be advisable to filter the output of this rectifier for best results, a choke and condenser being used for this purpose.

The ratio of the main transformer must be carefully chosen when designing a rectifier of this kind. To secure either voltage compensation or compounding, it is necessary to operate the rectifier at some lower voltage than would normally be given by the chosen transformer ratio. This is necessary in order that the regulating voltages from the drop wire across the output and from the current-transformer rectifier may have control of the grids of the tubes. The amount of voltage below normal at which the rectifier unit must operate depends upon the amount of voltage regulation desired.

In the paper small lamps are shown in the grid circuits acting as protective resistors. In the single-phase arrangement it was found advisable to use much higher values of resistance than is represented by these lamps, 5,000 ohms being a good value. The grids should not take any more current than is necessary.

**L. A. Kilgore** (Westinghouse Electric & Manufacturing Company, East Pittsburgh, Pa.): The authors describe a method of automatically controlling the voltage of grid-controlled rectifiers, which utilizes the output voltage of the rectifier to control the grids. The authors show a smoothing inductance which takes out part of the pulsation of output voltage. If the smoothing action is not complete, the grid picks up when the output voltage is at the minimum point. Hence, it attempts to regulate for a constant minimum voltage. The difference between the average and minimum voltage will be the function of the load current, load-circuit inductance, and resistance. The authors describe a means of compounding which takes care of the change due to load current. The writer would like to ask whether or not they would expect changes in average voltage if the character of the load circuit changed, especially if the load inductance changed.

If the ripple in the output voltage was completely filtered out, then any slight variations in the critical voltage of the grids would cause wide variations in the firing of individual anodes and cause serious unbalance of load. It would seem that to keep the same accuracy of firing, the ripple voltage must be of the same order of magnitude as the sine wave grid voltages which have been previously used for controlling the firing of grids. If this is true, nothing is gained over the conventional method of impressing grid voltages from a grid transformer, and it has the disadvantage of being dependent on such factors as the inductance of the load circuit. The writer would appreciate the authors' comments on these points for it may be that some of the functions of the apparatus described have been misunderstood.

When considering the control of rectifier voltage by grids, whether automatic or manual, it should be observed that any reduction of voltage is accompanied by a nearly proportional reduction in power factor, and an increase in harmonics. This fact somewhat limits the general application of such control, but the writer feels that there will be numerous applications where the automatic control of rectifier voltage will be used. Several automatically regulated rectifiers have been built, one using a conventional current regulator, such as might be used on a rotating machine. Another rectifier using voltage and current compensation was found to give very flexible control of the regulation characteristics.

**Didier Journeaux** (Allis-Chalmers Manufacturing Company, Milwaukee, Wis.): The authors are to be given credit for presenting a method of rectifier control of sufficient interest to make their readers desirous of obtaining additional information on the details of the process of operation of their system. In particular, curves would be desirable showing the different characteristics obtained by varying the voltage of the bias battery and the tap of the potentiometer, and by maintaining the tubes in an oil bath at different constant temperatures. Oscillograms of the input and output voltages, of the d-c load current and of the grid voltage during steady state operation and during transients would also be of assistance in obtaining an insight into the action of the grids. The omission of a d-c load-smoothing inductance in figure 7*b* appears to be inadvertent.

While the results reported by the authors are quite interesting, it is necessary to bear in mind the limitation to which the system is subject. In particular, the action of the grid control relies on the curvature of the grid characteristic and is of extreme sensitivity. This renders the system easily disturbed by any irregularity in the action of the tubes to the extent that, in some of the circuits, tubes must be selected and perhaps also matched to give reliable results. If the grid characteristic is subject to variations, the output voltage or current will receive the same variations amplified in a constant ratio. This would probably render the regulator entirely inapplicable to the control of rectifiers of the mercury-pool type, for which mechanical regulators of the rocking sector type have been found entirely satisfactory. Such regulators have been used with great success in this country and abroad for controlling constant voltage, compounded, and constant current rectifiers, the latter being utilized in some large electrolytic plants. While rocking sector regulators have not been used on currents requiring regulation through a load range including short circuits, they are perfectly adapted for that purpose. By the addition to the regulator of a high-speed relay, regulation could be maintained through suddenly applied short circuits within such limits and at such speeds as to meet the requirements of most practical applications.

**C. L. Dawes** (Harvard University, Cambridge, Mass.): During the past few years it has become increasingly evident that ionic devices were certain to replace relays, certain types of rotating machinery and many types of regulating devices. For example, in new substation installations, the mercury-arc rectifier has virtually superseded rotating machinery in the conversion of alternating to direct current. Because of the absence of rotating elements, windings and iron cores, such rectifiers are inherently more efficient, especially so at light load, and are much lighter than equivalent rotating machines. Moreover, because the ions constituting the rectifying medium have insignificant inertia, and respond with extreme rapidity to both electric and magnetic fields, it is possible to obtain characteristics, and to control current and voltage in a manner which is impossible with rotating machinery. This paper by Goodhue and Power is an excellent illustration of some of the results which can be obtained with such ionic devices.

I am first calling attention to the method of grid control which they employ as is illustrated by figures 1*a*, 1*b*, and 7*a* and 7*b*. The usual method of grid control is to apply an alternating electromotive force to the grid and to control the instant of firing either by shifting the phase of this electromotive force, or by changing its magnitude. The authors obtain greater sensitivity, less effects from temperature, and more positive action by connecting all the grids together and applying a direct-current voltage to them. This electromotive force is supplied jointly by a constant source of electromotive force, such as a battery, and a potentiometer connected to the d-c system supplied by the rectifier. As the authors state, the regulator operates so rapidly that the pointer of a d-c voltmeter shows no noticeable flicker with large and sudden changes in input voltage.

By the addition of current compounding a wide range of voltage-current characteristics may be obtained, from almost any desired degree of cumulative compounding to almost any degree of differential compounding as shown by figure 3. Also constant-current characteristics and characteristics combining constant-current to the limit of the rectifier operation and then through nearly constant potential to zero current all may be obtained merely by suitable adjustments of the shunt and series regulating resistances as shown by figure 4.

Hence it appears that these methods offer possibilities in industrial motor control, not readily obtainable with the usual d-c sources. As pointed out by the authors, by the use of the characteristics of figure 4 motors may be started with any desired value of constant torque and brought smoothly up to rated speed. All starting equipment is eliminated together with the pulsations in starting current caused by the intermittent closing of contactors. The method makes possible by simple means the precise control of many processes which control heretofore was only possible by

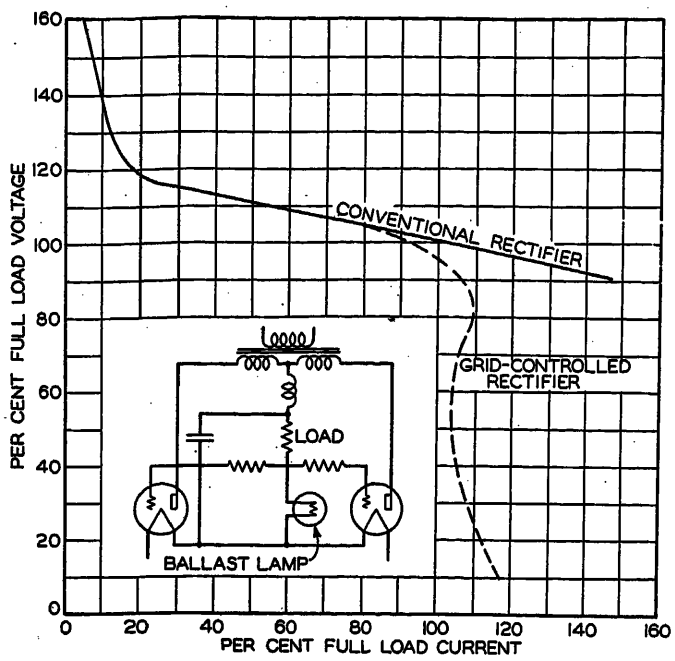



Fig. 1

means of complicated and cumbersome electromagnetic control equipment. As an example, if it were desired to maintain the speed of a motor constant it could be separately excited and a direct-current magneto connected to the shaft. The terminals of the magneto would be substituted for the potentiometer $S$, figures 1*a*, 1*b*. Any change in speed of the motor would change the electromotive force applied to the grids, and the electromotive force at the motor terminals would change correspondingly. If compensation for the small effects of temperature on the critical grid voltage were desired, a slight degree of current compounding could be introduced, using the connections of figure 1*b*. There are many other applications of such automatic control such as maintaining the correct distances in alignment processes, controlling temperature and pressure, etc.

Heretofore constant direct current has been obtained by means of the constant-current transformer supplying constant single-phase current to single-phase rectifiers. As shown by figure 4 the methods developed by the authors make it possible to obtain such constant direct current from a polyphase rectifier, with advantages over the constant-current transformer method. The moving coil with the accompanying mechanism is eliminated. The constant-current transformer cannot maintain constant current during sudden changes of load. With the moving coil in any fixed position the current locus is a circle. Hence the coil must move to maintain constant current, and, owing to the inertia of the mechanical system, considerable time is required for readjustment of the position of the coil. With the system shown by the authors, response to load changes is practically instantaneous. Moreover, their system constitutes a balanced 3-phase load whereas the single-phase, constant-current transformer produces unbalancing in 3-phase, systems which under some conditions may be objectionable.

To my mind this paper is valuable, not only in showing the definite characteristics that are obtainable with a controlled mercury-arc rectifier, but it also shows the flexibility that is obtainable by means of ionic control devices and it opens up wide possibilities in the field of industrial power applications.

**Reuben Reiter** (Harvard University, Cambridge, Mass.): The data presented in the curves of this paper show that the maximum power controlled by the authors in their experiments was of the order of 2 kw. It is desirable to know the economics of this method of control when applied to much larger blocks of power. The dollars and cents saved by this method over other existing methods will determine its present value.

Would it not be possible to economize on the initial cost of the control installation by employing a single phase for control rather than 3 phases. The system shown by the authors employs 3-phase transformers and requires 3 rectifying units to supply the d-c control voltage. The method is a balanced one, but is it necessary for the ordinary installation.

**G. H. Rockwood** (Bell Telephone Laboratories, Inc., New York, N. Y.): The compounding circuits suggested by the authors are of considerable interest since they permit of cumulative compounding so conveniently. As the authors suggest differential compounding makes possible the construction of a rectifier which may be used for d-c motor control, or one the output of which may be short-circuited without damage to tubes or associated equipment. Because of the convenience of differential compounded circuits it seems pertinent to call attention to another type of circuit which makes possible differential compounding in a cheap and simple manner. The circuit for a single-phase rectifier is shown. In this circuit the load current is passed through a series resistance, the drop across which supplies the grid excitation for the rectifier tubes. If this series resistance is a nonlinear device such as a tungsten-filament ballast lamp, the voltage drop across it even at full-load current may be made small enough so that the grids have very little negative bias, but for overload currents the grid bias rises rapidly. Because of the curvature of the grid characteristics of negative grid tubes, a small grid bias causes practically no change in output of the rectifier. Consequently, the load-regulation characteristics for the conventional rectifier and the differentially compounded grid-control rectifier are substantially identical except in the overload region. It will be observed from the figure that the rectifier may be short-circuited without having the load current rise to excessive values. It should be added that the rectifier operation is stable even under short circuit conditions.

**Myron Zucker** (Detroit Edison Company, Detroit, Mich.): The authors are to be commended for trying to apply the inherent speed of electronic equipment to work-a-day jobs. Such development, especially toward simplification, is needed if industry is to profit by electronics. Despite the quick action theoretically obtainable with electronic regulators and controllers almost all regulating work can still be done more economically by other means. Even in such a wide-open field as the high-speed regulation of distribution circuits to eliminate lamp flicker, no satisfactory regulator has yet been developed: it is still necessary to resort to the "brute force" method of making every element in the circuit oversize. As long as transformer capacity and copper come cheaper than tubes, there can be no quarrel with the present method of handling the situation. Perhaps a continual assault on the regulation problem will some day produce more refined solutions.

However, despite the desirability of the study, the authors' solution seems to be limited to certain special applications. Several factors seem to make it unsuitable for commercial work.

The first control scheme described in the paper is the most attractive because of its simplicity. It depends on balancing the output voltage of the rectifier against a battery, to energize the grids. This has 2 disadvantages:

1. An ordinary battery is not as reliable a long-time voltage standard as is commonly considered, so that—especially with the sensitive differential principle used in the grid circuit—erratic operation is likely to occur. How much current—instantaneous and average—and in which direction—was drawn through the battery?

2. Ripple is demanded in the output voltage. Although too much is undesirable, it is obvious that too little would be even worse. In the extreme case of no ripple, the average voltage would be obtained from a series of "full on" operations followed by all tubes being entirely "off" for several cycles.

It would help if the authors would tell how much ripple they have found desirable in their tests, and also whether they have run any tests for extended periods of continuous operation. Also, what magnitudes of battery voltage was used? How do the values depend on load, voltage, and the range covered by these? What are the quantitative conditions for figure 2, the curve showing perfect regulation? Can this curve be reproduced at will for various

loads and voltages? Once the proper adjustment has been made for a certain voltage-load characteristic with a given supply voltage, will a similar curve be obtained for a different value of supply voltage?

It seems that the ripple might be reduced by placing filters on the load side of the control potentiometer *S*. Have the authors tried this? Since a certain minimum of

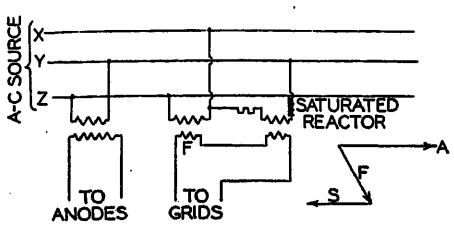



Fig. 2

ripple is required for control, is it not true that the ripple is worse with this type of control than with other types unless such filter can be used?

Use of tubes that "fire" with negative grid voltages is suggested by the authors. This might better some of the curves and permit use of weaker grid circuits (or ease the battery service), but would increase the chances of erratic operation. These "negative grid" tubes have a tendency toward random firing even with the best of grid excitation; it might be too much to expect them to give good service on the slim margin provided by voltage balancing.

It might be suggested that similar curves including compounding have been obtained in a more reliable way by a-c excitation. For instance the circuit shown in the diagram will give very close regulation. "Compounding" can be added with phase adjustable, giving a wide range of characteristics available. Such a control circuit has been applied to rectifiers and to excitation of an alternator. In the latter case, an added feature is that overspeed may be made to remove excitation and trip the main alternator circuit breaker. This type of circuit does what the authors set out to do—control without auxiliary tubes—and at the same time provides a definite, predictable voltage to the main grids.

**W. M. Goodhue:** Tompkins reports verifying the circuits given in the paper with a single-phase circuit in his laboratory. The authors appreciate the interest which he shows, particularly in view of the difficulties encountered in a different laboratory not having equipment specially designed for this new circuit. For example, the amount of smoothing inductance must be co-ordinated with the rectifier circuit in order to obtain a specified uncompensated characteristic.

The current transformer is stated in the paper to be polyphase. It would naturally follow that, with a single-phase set, transformers with the center tap would be employed. In filtering the pilot rectifier, it should be remembered that too much grid filtering will introduce time lag, and Tompkins perhaps uses grid filtering to compensate a long commutation period in the main rectifier.

In all grid-controlled rectifiers and inverters it is usual and essential to employ a main transformer turn ratio giving a maximum d-c voltage greater than the operating voltage. Even in a d-c dynamo, the shunt-field coils are designed for 80 per cent or so of full voltage, the remainder being absorbed in the field rheostat.

The value of grid resistance to be used depends on the choice of tubes, and must be co-ordinated with potentiometer resistances. Tompkins may have used a different type of tube than the authors. Also, the value of resistance is not critical.

L. A. Kilgore asks whether the authors would expect any change in average voltage if the load *inductance* is changed. This condition is peculiar in that *load* inductance, unlike the smoothing inductance, is outside of potentiometer *S*. This tends to *increase* the *voltage* ripple across potentiometer *S*, and hence the average voltage. This effect may perhaps be overcome by the insertion of condenser-resistance filtering in the contact *S* lead, in place of smoothing inductance in the power circuit.

The question of the accuracy of firing does require expounding. Inspection of curves, such as figure 2, shows *extraordinary accuracy* all out of proportion to any results obtainable with *static* grid circuits having similar magnitudes. Protective devices were employed in these experiments and would have shut down the equipment if serious anode unbalance ever occurred. No shutdown due to unbalance occurred, showing that this effect was not serious. The peak current equals the load current, so that only firing-time unbalance need be considered. Kilgore neglects the fact that unbalanced firing would produce an *unbalanced ripple*. The resulting regulator action would automatically restore balance immediately. In other words, failure of a tube to fire at the appointed time causes the ripple to continue dipping *beyond* the appointed time with accelerating downward slope, forcing the tube to fire close to the appointed time.

Therefore, ripple voltage in this circuit may be much smaller than the sine-wave voltages usually employed in grid circuits. Of course, if *complete filtering* is desired, it can be added in the d-c load itself *beyond the potentiometer S*, without depriving the grid circuit of ripple.

With large ripple, compounding would still work, and high voltage sets (250 volts up) would have a small *per cent* ripple and hence regulate. The authors agree with Kilgore that the advantages of grid control far outweigh the reduction in power factor.

Didier Journeaux suggests oscillograms for the purpose of understanding the grid action. Different states of operation are possible, all satisfying the equations of the paper and giving the regulator action. The extraordinary accuracy (figure 2) compared with the small ripple voltage operating the grids would require special experiments to understand. Artificial variation of critical voltage of one tube must be introduced.

Therefore, the number of oscillograms and amount of research would be so large as to properly belong in a second paper on the subject.

The omission of smoothing inductance in figure 7*b* was probably due to the custom of combining interphase transformer and smoothing inductance by the use of a high-leakage interphase transformer.

The characteristics varying the potentiometer taps and bias battery are shown in figures 3, 4, and 6. Only slight improvement with oil bath may be expected, since other factors such as per cent ripple still vary with current.

The question of tube irregularity and grid variations has been considered in answer to Kilgore's discussion. The grid control does not rely on the curvature of the grid characteristic. The authors wish to thank Journeaux for calling attention to the fact that mechanical regulators can possibly be designed for high speed, where the grid current to be controlled is small. However, such regulators are limited economically to large size rectifiers.

G. H. Rockwood has a very interesting differential-compounded rectifier. It seems to depend directly on the grid critical voltage and hence be subject to wide variations with temperature and supply voltage. In the dotted curve portion, the current varies considerably, while the authors' characteristics are linear (figure 4) with nearly constant current. This is because the use of a bias battery in the authors' circuit reduces the per cent of variation due to critical grid voltage. For example, assume a critical grid voltage of 5, which varies say one volt, and a battery of 90 volts. For Rockwood's circuit, 1 volt in 5 is 20 per cent variation; for the authors' circuit, 1 volt in 90 is 1.1 per cent variation. With a 180-volt battery, the variation is only 1 volt in 180 or 0.55 per cent. Thus, the use of a bias battery or its equivalent is essential in any d-c controlled rectifier circuit to eliminate grid variations. The use of a tungsten-ballast filament introduces time lag, especially for currents of 5 or more amperes; this lag is minimized by operating smaller filaments in parallel. The power loss in the ballast probably equals the tube loss, limiting application to small equipment, where first cost rather than efficiency is important. Of course, voltage regulation and cumulative compounding are not obtainable.

C. L. Dawes offers a very illuminating discussion of the industrial applications of the new circuit, and also the principles of operation. As he states, the moving-coil type of constant-current transformer is practically helpless during a rapid change, and reverts to an inferior circle-diagram characteristic. When the moving coil is near the stationary coil, the dynamic charateristic is especially inferior, the short-circuit current being several times the operating current, because the reactance is low. The authors feel with Dawes that the flexibility of grid control methods is enhanced by the new circuit.

Reuben Reiter evidently wishes the authors to discuss economics of this circuit. With large blocks of power the following relations exist:

1. Entire control-circuit kva and power loss is negligible. No phase shifters are necessary. Therefore, the expense of control equipment, both initial cost and operating cost, is very small compared to the main equipment.

2. Other methods of obtaining constant current from a constant-potential source are expensive, such, for example, as moving-coil transformers, monocyclic networks.

3. In addition, the dollars and cents problem involves other factors introduced in connection with the purpose of the equipment, the facilities available, and the financial nature of the application. Obviously, too general statements are misleading.

Reiter also suggests a single-phase control with polyphase power. To avoid throwing the power anodes out of balance, considerable filtering of the pilot rectifier may be necessary, with resulting time lag. Initial cost is usually vital in small installations. For these, the *entire power equipment* may be single-phase, the pilot rectifier may consist of a *cheap full-wave radio tube* (type 83, 83*v*, or 80), and the current transformer of inexpensive power-pack construction.

## Dyadic Algebra Applied to 3-Phase Circuits

August 1936 issue, pages 876–82.

## Complex Vectors in 3-Phase Circuits

December 1936 issue, pages 1356–64

**Discussion of 2 papers by A. Pen-Tung Sah published in the August 1936 and December 1936 issues and presented for oral discussion at the tensor analysis session of the winter convention, New York, N. Y., January 26, 1937.**

Giuseppe Calabrese (The New York, N. Y. Edison Company, Inc.): When new methods of analysis are applied to any branch of science, the first step taken is that of explaining well-established facts with the new methods. In this respect, and in connection with Sah's papers, perhaps, it may be of some interest to derive the formula of the force between 2 elements of conductors carrying currents, in the light of the theory of dyadics, and to show how this force may be visualized as being proportional to the direct product of a vector by an antiself-conjugate dyadic.

With reference to the figure below, let $\dot{I}$ and $\dot{I}_1$ indicate the magnitudes and space directions of the currents flowing in the 2

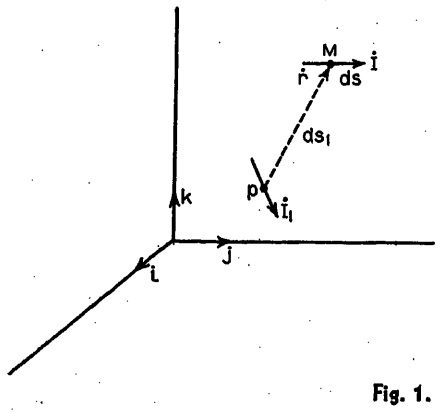



Fig. 1.

elements $ds$ and $ds_1$ of the 2 conductors located respectively in $M$ and $P$. Let $\dot{r}$ be the vector $PM$ positive from $P$ to $M$.

The force $\dot{F}_0$ exerted on the element $ds_1$ of the conductor carrying the current $\dot{I}_1$ by the element $ds$ of the conductor carrying the current $\dot{I}$ is given by (the dot on the letters $\dot{I}$, $\dot{I}_1$, $\dot{r}$, $\dot{F}_0$, is used to indicate vector quantities. The same letters without any additional sign indicate scalar quantities:

$$\dot{F}_0 = \frac{K\,ds ds_1}{r^3}\,\dot{I}_1 \times (\dot{r} \times \dot{I}) \qquad (1)$$

where $K$ is a constant depending upon the physical nature of the medium interposed between 2 elements.

From vector analysis, it is known that the vector $(\dot{r} \times \dot{I})$, when used in cross multiplication, is equal to the anti-self-conjugate dyadic $(\ddot{I}r - \dot{r}\ddot{I})$ in direct multiplication, used as a prefactor or post-factor, depending on whether $(\dot{r} \times \dot{I})$ is used as a prefactor or post-factor. The expression (1) of the force $\dot{F}_0$ may, therefore, be rewritten as follows:

$$\dot{F}_0 = \frac{K\,ds ds_1}{r^3}\,\dot{I}_1 \cdot (\ddot{I}r - \dot{r}\ddot{I}) \qquad (2)$$

That is, the electromagnetic force exerted on an element $ds_1$ of a conductor carrying the current $\dot{I}_1$, by the element $ds$ of a second conductor carrying the current $\dot{I}$, is proportional to the direct product of the current vector $\dot{I}_1$ into the anti-self-conjugate dyadic $(\ddot{I}r - \dot{r}\ddot{I})$. It will be recalled now, and it is apparent from equation 2 that the direct product of a vector by an anti-self-conjugate dyadic lies in the plane common to the antecedents and consequents of the dyadic. It will be recalled also (or it may be proved directly by expanding the dot product $\dot{F}_0 \cdot \dot{I}_1 = \frac{K ds ds_1 r}{r^3}\,\dot{I}_1 \cdot (\ddot{I}r - \dot{r}\ddot{I}) \cdot \dot{I}_1 = 0$) that the direct product of a vector by an anti-self-conjugate dyadic is perpendicular to the vector. Once these 2 rules are recalled, the space position of the force $\dot{F}_0$ is immediately visualized from equation 2. $\dot{F}_0$ lies in the plane of $\dot{r}$ and $\dot{I}$ and is perpendicular to $\dot{I}_1$. From (2), the 2 components of the force $\dot{F}_0$ along $\dot{r}$ and $\dot{I}$ may also be readily computed respectively at:

$$\frac{K ds ds_1}{r^3}\,(\dot{I}_1 \cdot \dot{I})\dot{r} \quad \text{and} \quad \frac{K ds ds_1}{r^3}\,(\dot{I}_1 \cdot \dot{r})\dot{I} \qquad (3)$$

Furthermore the 3 space vector $\dot{I}$, $\dot{I}_1$, $\dot{r}$ may be expressed in terms of any arbitrarily chosen orthogonal system $ijk$ as follows:

$$\dot{I} = xi + yj + zk$$
$$\dot{I}_1 = x_1 i + y_1 j + z_1 k$$
$$\dot{r} = r_1 i + r_2 j + r_3 k$$

Correspondingly the dyadic $(\ddot{I}r - r\ddot{I})$ in nonion form becomes:

$$(\ddot{I}r - r\ddot{I}) = (r_2 x - r_1 y)(ij - ji) + (r_3 x - r_1 z)(ik - ki) + (r_3 y - r_2 z)(jk - kj)$$

From which:

$$\dot{F}_0 = \frac{K ds ds_1}{\sqrt{r_1^2 + r_2^2 + r_3^2}} \times [\{y_1(r_1 y - r_2 x) + z_1(r_1 z - r_3 x)\}\, i + \{x_1(r_2 x - r_1 y) + z_1(r_2 z - r_3 y)\}\, j + \{x_1(r_3 x - r_1 z) + y_1(r_3 y - r_2 z)\}\, k] \qquad (4)$$

By means of either (3) or (4), the electromagnetic force between 2 elements of conductors carrying currents may be calculated. In the practical applications, if the expressions (3) are used, the vectors $\dot{I}$, $\dot{I}_1$, $\dot{r}$ may be decomposed in such a manner, or if using equations 4, the systems $ijk$ may be so chosen as to reduce the necessary calculations to a minimum.

The forces on finite lengths of conductors are calculated by means of appropriate integrations.

Of course the same conclusions may be reached, without much difficulty, from equation 1 by expanding the triple vector product according to the rules of vector analysis, without any knowledge of dyadics.

K. L. Wildes (Massachusetts Institute of Technology, Cambridge): The authors of this group of papers have shown remarkable genius in the application of 2 closely related branches of mathematics to electric-circuit problems. The method of Sah is limited to 3-phase, or 3-branch circuits, since it is based upon the 3-dimensional vector analysis of Gibbs. I am inclined to agree with Sah, however, that the better initial approach to the whole subject of "higher circuit analysis" is through the vector algebra rather than the tensor algebra.

During the term just closing at MIT I have been presenting, as a part of one of my graduate courses in electric power-circuit theory, this vector algebra method of solving 3-phase unbalanced circuits. From this experience it is my opinion that the best pedagogical approach to this whole matter is, first, to study thoroughly the elements of vector algebra and linear vector functions, as developed by Gibbs and Wilson. This would be followed by a study of Sah's first paper in which the application is made to instantaneous 3-phase voltages or currents as phase components of a 3-dimensional vector. This paper also develops the simpler operations with impedance and admittance dyadics. Then, just as we usually go from the study of instantaneous values of alternating quantities to the complex representation, we proceed to Sah's second paper, in which we find the vector method applied to currents and voltages in the complex form. This transition is not difficult because the differences between vectors whose components are instantaneous values and those whose values are complex are practically the same differences as those which exist between single-phase quantities.

The final, and perhaps the most difficult step in the application of this method to the solution of circuits, is the development of the technique of solving equations once they are written. This technique involves great ingenuity, as well as a great deal of experience in handling vector equations. Many of these applications and ingenious methods of solving vector equations have been worked out by Sah, and it is my hope that these will soon be made available in future papers, or preferably in the form of a book.

Since this method is a direct competitor of the method of symmetrical components in solving unbalanced 3-phase circuits, it may be in order to make a comparison of these 2 methods. It has been our experience that circuits involving balanced impedances, except at a single point, or

possibly 2 points of unbalance, are more easily solved by the method of symmetrical components, while circuits possessing impedances of considerable unbalance are probably solved with about the same ease by the new method as with symmetrical components. There is probably some degree of complexity at which the vector method of solution becomes easier than the component method. This is especially true if some systematic, or perhaps mechanical method, of aiding the solution to the equations can be developed. The technique of understanding and using the method of symmetrical components is certainly much simpler than the new method, and would be, I should say, a prerequisite to studying it. For example, in the paper dealing with complex vectors the zero-sequence, positive-sequence, and negative-sequence components of a vector representing a set of voltages are found by dotting this vector with the isoclinic or zero-sequence vector $u$, the positive-sequence vector $f$ and the negative-sequence vector $b$, respectively. In our class work we have duplicated the symmetrical-component solutions of circuits with impedances unbalanced at one point in terms of the new vector *notation* simply to become acquainted with this notation. We have then proceeded to solve the same problems by not only a notation, but a *process*, which characterizes Sah's work.

A careful study of this vector method not only has merits of its own, but forms an excellent foundation for the understanding of tensor algebra which is the subject of the papers by Kron, Boyajian, and Bewley.

In conclusion, I cannot refrain from saying that I have great admiration for the fundamental development of these methods of analysis by Sah and Kron. The time for evaluating their contribution has not yet arrived, but it is the responsibility of the electrical engineers and the professors of electrical engineering in the colleges to give attention to these methods and to come to a sound evaluation of their utility within the next 2 or 3 years. Not until many problems have been worked out to final numerical results can we say definitely whether the new methods are capable of organizing and clarifying large classes of problems, or whether, in general, the use of these methods makes the problems more obscure and more difficult of solution. I am personally enough interested to attempt to find the answer to this question.

**Joseph Slepian** (Westinghouse Electric & Manufacturing Company, East Pittsburgh, Pa.): The 2 papers by Sah are to be commended for the interesting material they present, and the temperate tone used by the author in estimating the value of his results. In all cases, the arbitrary character of certain assumptions are plainly stated. The definition of a scalar as having magnitude but no direction, and a vector as having magnitude and direction is in agreement with all previous usage. If any fault is to be found, it is that the mathematical terminology is a form which seems to be passing out of use. The dyadics of Gibbs are perhaps in the same class as the quaternions of Hamilton, namely, seldom used in modern mathematical works. It is an interesting evidence of the rapidity of progress in mathematics that the reference book, used by Sah, reference 1 in his first paper, is only 12 years old.

The first section describing "Three Phase Impedance as an Entity" makes it quite clear, by leaving out all irrelevant notions, that the impedance may be regarded as an entity, with 9 components in the 3-phase case, without requiring it to be a tensor, dyadic, or anything other than a set of numbers describing an electrical system.

The next section introduces the dyadic notation with the pairs of unit vectors occurring as symbols. Strangely enough, these double unit vector symbols occur nowhere else in the paper. I think this is the best evidence of their unnecessary and irrelevant quality.

As Sah states, the geometrical representation which he gives to a 3-phase set of currents or voltages, namely, an ellipse with center at a fixed origin, and a specified initial point on the ellipse, is in a certain sense arbitrary. But so too is the geometrical representation of a single aternating quantity as a vector in a plane. But in this latter case, all the arithmetic calculations we make with single-phase quantities correspond to simple geometric operations upon their corresponding vectors. Thus the addition of 2 single-phase quantities corresponds directly to the vector addition of their corresponding vectors. It is these correspondences which make the vector representation of single-phase quantities so valuable.

But unfortunately, not quite so good a case can be made out for Sah's ellipse representation of 3-phase quantities. The ellipse corresponding to the sum of 2 sets of 3-phase quantities is not related in any so obvious or suggestive a manner to the ellipses corresponding to the individual sets of 3-phase quantities. However, certain calculations, made with 3-phase quantities do have simple, geometrical equivalents in Sah's representation. The 3 symmetrical components are represented by 2 circles and a line which have very simple relationships to the ellipse as Sah shows. Similarly, changing from delta to wye components or vice versa, corresponds to simple operations upon the representative ellipse.

In his second paper, Sah generalizes from the notion of a vector with real components to that of a vector with complex components, and shows well the value of these ideas in application to 3-phase alternating quantities. The mathematics is all good and valid. It seems to me, however, that it might be put into more attractive form by generalizing from the real space to the "unitary" space with complex components, now used so extensively in quantum mechanics.

In vector analysis in real Euclidean space, a fundamental scalar is the product of two vectors defined as

$$X \cdot Y = x_1y_1 + x_2y_2 + x_3y_3$$

with obvious significance to the notation. This expression must be generalized to meet the case where $x_1$, $x_2$, $x_3$, $y_1$, $y_2$, $y_3$, may be complex numbers instead of only real numbers. Now it is not necessary in making the generalization, to use precisely the same formula as for the case of reals, but it is sufficient, to use a formula for the case of complex components which will reduce to the above formula when the components become real. Thus we may define for the scalar product, instead of the above expression, which Sah uses, the following:

$$X \cdot Y = x_1^*y_1 + x_2^*y_2 + x_3^*y_3$$

where $x_1^*$, $x_2^*$, $x_3^*$ are the conjugates of $x_1$, $x_2$, $x_3$. Obviously when $x_1$, $x_2$, $x_3$ are real this expression reduces to the preceding one.

The definition of the scalar product in this way, by a Hermitian instead of a quadratic form, has many advantages. By this definition, the scalar product of a vector by itself is the square of its length or magnitude as Sah defines it, and is never negative, and is zero only when all the components of the vector are zero. If we call 2 vectors mutually perpendicular when their scalar product thus defined is zero, then no vector is perpendicular to itself. In 3-dimensional complex space a set of no more than 3 mutually perpendicular unit vectors can be found. If $I$, $J$, $K$, are any 3 such mutually perpendicular unit vectors, and if $X$ is any vector, then $X = (I \cdot X)\ I + (J \cdot X)\ J + (K \cdot X)K$ if this definition of scalar product is used.

Vector space with complex components and with this definition of the scalar product is much used in quantum mechanics. It is called unitary space, and has many properties similar to those of Euclidean space. A good account of unitary space is given in Weyl's "Group Theory and Quantum Mechanics."

With this definition of scalar product, the unit vectors $u$, $f$, $b$ in Sah's paper, which represent unit symmetrical components (divided by $V\bar{3}$) become mutually perpendicular. The transformation to symmetrical components becomes a "unitary" transformation which may be regarded as a generalization of the "orthogonal" transformation in real space, that is a rigid rotation of orthogonal axes.

**Irven Travis** (University of Pennsylvania, Philadelphia): The statements in this discussion are restricted to *linear* networks. In such networks the calculation of the currents resolves itself into the calculation of the values of the $I$'s in a set of equations of the form

$$\left.\begin{aligned} Z_{11}I_1 + Z_{12}I_2 + \ldots + Z_{1n}I_n &= V_1 \\ Z_{n1}I_1 + Z_{n2}I_2 + \ldots + Z_{nn}I_n &= V_n \end{aligned}\right\} \quad (1)$$

Methods of evaluating the $Z$'s in a particular problem are well known. If the calculation of the $I$'s is to be rendered simpler than seems to be indicated by these equations some scheme must be devised to circumvent the indicated algebraic work. Any such scheme, however, must ultimately express the $I$'s in terms of the $V$'s; or at least certain known functions of the $I$'s in terms of certain known functions of the $V$'s. Methods for accomplishing this have been variously described as vector, tensor, dyadic, matrix, etc, methods. It seems that the success of any of these schemes for simplification must depend upon special properties of the array

$$\left.\begin{aligned} Z_{11}Z_{12} \ldots Z_{1n} \\ Z_{n1}Z_{n2} \ldots Z_{nn} \end{aligned}\right\} \quad (2)$$

(Conventional bars are not placed on this array nor is any name assigned to it lest

the writer's position be prejudiced.)

If the array (2) has special properties, as for example symmetry, *any* system designed to take advantage of these properties will meet with success. It the array has no special properties the various schemes suggested amount to statements of the same problem in terms of different notations and no particular advantage accrues to any one.

In January 1933, it was suggested to the writer by Carl Chambers, then a graduate student at the Moore School, that the Stokvis-Fortescue transformation could be expressed in matrix form more simply than in terms of the "sequence operators" used in Fortescue's 1918 paper. A matrix formulation for 3-phase circuits was developed, in which the matrix

$$\frac{1}{3}\begin{Vmatrix} 1 & 1 & 1 \\ 1 & a & a^2 \\ 1 & a^2 & a \end{Vmatrix} \qquad (3)$$

and its inverse

$$\begin{Vmatrix} 1 & 1 & 1 \\ 1 & a^2 & a \\ 1 & a & a^2 \end{Vmatrix} \qquad (4)$$

play an important part. After having been used in mimeographed form in the senior machinery course at the Moore School for 3 years this method of presenting symmetrical components was included in section 3 of the "Electrical Engineer's Handbook," Pender-DelMar, John Wiley and Sons, 1936. I was very much interested in Sah's paper as several of his expressions from the vector viewpoint are in complete agreement with similar expressions obtained from the matrix viewpoint.

However, neither the vector nor the matrix presentation has any virtue other than neatness of notation and clarity of expression. Any simplification in actual calculation of any given problem must be due to symmetry in the impedance matrix of the system. If there is no symmetry there can be no simplification.

From a pedagogical view point it is highly desirable to use some scheme which systematizes an analysis and correlates all calculations of a given class. Special cases are given added clarity if they appear as special cases of a general formulation rather than as isolated and unrelated problems. It is in this aspect and not in reduction in actual labor of calculation that tensors and matrices are of value in electrical engineering.

C. E. Rose (Federal Emergency Administration of Public Works, Washington, D. C.): Believing that the following discussion of the article, entitled, "Dyadic Algebra Applied to 3-Phase Circuits," by A. Pen-Tung Sah, which appeared in the August issue of ELECTRICAL ENGINEERING, may be helpful to others interested in the applications of dyadics and tensors to the solution of electrical problems, I submit the following:

A dyad is nothing more or less than the product of 2 vectors written as $AB$, and the symbolic sum of a number of dyads is a dyadic.

A matrix is a system of related but independent quantities whereas a determinant is either a real or complex number, or zero.

Therefore equation 28*d*, page 881 in this article is presented incorrectly, due probably to a typographical error. It is written as:

$$(\sqrt{3}u \times Z_m)_{2s} = j\begin{Vmatrix} -2.20 & -3.42 \\ 7.90 & 2.12 \end{Vmatrix} + j\begin{Vmatrix} 2.12 & 1.46 \\ 1.30 & 0.08 \end{Vmatrix} + j\begin{Vmatrix} -2.20 & -1.54 \\ -5.70 & 0.08 \end{Vmatrix}$$

the right-hand side of which is expressed as the sum of 3 dyadics of rank 2, whereas it should have been written as:

$$(\sqrt{3}u \times Z_m)_{2s} = \begin{vmatrix} -2.20 & -3.42 \\ 7.90 & 2.12 \end{vmatrix} + \begin{vmatrix} 2.12 & 1.46 \\ 1.30 & 0.08 \end{vmatrix} + \begin{vmatrix} -2.20 & -1.54 \\ -5.70 & 0.08 \end{vmatrix} = -11.66$$

because it is the sum of 3 determinants of rank 2, and involves neither a matrix nor a dyadic and is numeric only.

Again, equation 19, page 880, is written as:

$$Y = \begin{Vmatrix} y_{aa} & y_{ab} & y_{ac} \\ y_{ba} & y_{bb} & y_{bc} \\ y_{ca} & y_{cb} & y_{cc} \end{Vmatrix} = Z^{-1} = \frac{1}{D}\begin{Vmatrix} (z_{bb}z_{cc} - z_{bc}z_{cb}) \cdots\cdots\cdots\cdots \\ \cdots\cdots\cdots\cdots\cdots\cdots\cdots \\ \cdots\cdots\cdots\cdots (z_{aa}z_{bb} - z_{bb}z_{ba}) \end{Vmatrix}$$

It is not necessary when writing a tensor equation, which contains only electric tensors, to define the voltages under consideration, as covariant tensors which they are, but when once a convention has been established as it is in this article by equation 1, page 876, which is written as:

$$e_a = z_{aa}i_a + z_{ab}i_b + z_{ac}a_{ac}i_c, \text{ etc.}$$

and which properly defines the voltages as a covariant tensor of rank 1, and the impedances as a covariant of rank 2, then it is thought that the admittance $Y$ would be better defined as a contravariant tensor of rank 2, because this corresponds to reality in which case we would write:

$$Y = \begin{Vmatrix} y^{aa} \cdots\cdots\cdots\cdots\cdots\cdots \\ \cdots\cdots\cdots\cdots\cdots\cdots\cdots \\ \cdots\cdots\cdots\cdots\cdots\cdots y^{aa} \end{Vmatrix} = Z^{-1}$$

The matrix $Z^{-1}$, which is the inverse of matrix $Y$ is obtained from it by replacing each element of the $Y$-matrix by its cofactor, with the superscrips changed to subscrips and permuted once, divided by the determinant of the $Y$-matrix because

$$Y^{ik} = Z_{kl}{}^{-1}$$

namely it is a skew-symmetric tensor, and is nothing more than the vector product of 2 generalized vectors. Thus if we write vectorially:

Vector $A$ times vector $B = A \cdot B + A + B$, the last term is really a skew-symmetric tensor of rank 2, which is written in tensor form as:

$$A_{ik} = A_{kl}$$

The simplest matrix which we encounter is the co-ordinate of a point in 2-dimensional space as $(X, Y)$.

The "scalar of the second" used in this article is simply

$$\phi_2 = (\phi_s)_2 = A_{11} + A_{22} + A_{33}$$

in which $A_{11} \ldots A_{33}$ are the elements of the principal diagonal of the inverse for the matrix under consideration. The matrix:

$$\begin{Vmatrix} 0 & -1 & 1 \\ 1 & 0 & -1 \\ -1 & 1 & 0 \end{Vmatrix}$$

which appears several times in this article is nothing more or less than:

$$\begin{Vmatrix} ii & ij & ik \\ ji & jj & jk \\ ki & kj & kk \end{Vmatrix}$$

obtained by combining the 3 unit vectors, 2 at a time, into dyads multiplied by $-1$.

Professor Gibbs, part of whose theorems A. Pen-Tung Sah employed, proved that a dyadic $\phi$ possessed 3 scalar invariants; namely

$$\phi_1 = a_{11} + a_{22} + a_{33}$$
$$\phi_2 = A_{11} + A_{22} + A_{33}$$
$$\phi = \begin{Vmatrix} a_{11} & a_{12} & a_{13} \\ a_{21} & a_{22} & a_{23} \\ a_{31} & a_{32} & a_{33} \end{Vmatrix}$$

A transpose is a dyadic, or matrix, which is obtained by interchanging rows and columns. The simplest definition of a tensor is, I believe; that if the 9 quantities:

$$\begin{Vmatrix} a_{11} & a_{12} & a_{13} \\ a_{21} & a_{22} & a_{23} \\ a_{31} & a_{32} & a_{33} \end{Vmatrix}$$

possess the property that when written as

$$\sum_{ik} a_{ik}a_ib_k = a_{11}a_1b_1 + a_{21}a_1b_2 + a_{13}a_1b_3 \ldots$$

is invariant to any arbitrary rotation of the Cartesian co-ordinate system, wherein $A$ and $B$ are any arbitrarily chosen vectors, then this last matrix presented above is a tensor. This definition also yields a simple method to test for the existence of a tensor by subjecting it to a rotation and if, after simplifications, it returns to the identical original form we know that it is a tensor.

# An Analysis of the Shaded-Pole Motor

**Discussion and author's closure of a paper by P. H. Trickey published in the September 1936 issue, pages 1007-14, and presented for oral discussion at the induction machinery session of the winter convention, New York, N. Y., January 27, 1937.**

Selby Haar (Board of Transportation, City of New York, N. Y.): Emphasis has been laid on the small rating of the usual shaded-pole motor. Have you ever observed with these motors that the current at fractional loads is less than at no load?

G. G. Veinott (Westinghouse Electric & Manufacturing Company, Springfield, Mass.): Trickey has presented an illuminating analysis of a type of motor of great commercial importance, and his analysis is probably the first of its kind ever presented before AIEE on this important

motor. The "shading principle," that is the action of a short-circuited coil placed around a portion or all of a magnetic circuit, is a familiar one; it is used in damper or amortisseur windings of synchronous machines, it is used in watt-hour meters, a-c contactors and in many other places.

Once when studying damper windings, I discovered some fundamental equations of the damped magnetic circuit which were most helpful quantitatively and qualitatively. So far as I know, these equations and concepts are original and I am now publishing them for the first time because of the light they throw upon the principle of the shading coil.

The conventional method for analyzing a damped magnetic circuit is to compute the current induced in the damping coil by the changing flux and subtract the magnetomotive force due to this current from the primary-exciting magnetomotive force, obtaining a resultant magnetomotive force; from this resultant magnetomotive force is calculated the flux, which in the case of an a-c supply, is assumed to be proportional to and in phase with this resultant magnetomotive force.

A-c circuits containing resistance and inductance could be solved in an analogous manner by computing the voltage induced in the inductance, subtracting it from the impressed voltage, obtaining a resultant voltage; the current would then be proportional to, and in phase with this resultant voltage. It has been found more convenient to analyze such circuits by introducing the concent of reactance, which might be termed a "quadrature resistance." The method of analyzing a damped magnetic circuit which I am about to outline is exactly analogous to the conventional method of treating a-c circuits; in it I introduce a concept of what might be termed "quadrature reluctance" since, in the magnetic circuit, it bears the same relation to reluctance that inductive reactance does to resistance in an electrical circuit.

The fundamental equation for the instantaneous value of flux in a magnetic circuit of reluctance $\mathcal{R}$ excited by a sine-wave magnetomotive force, $m = M_m \sin \omega t$, and interlinked by an electrical circuit of $N$ turns having an ohmic resistance of $r$ ohms and no leakage inductance, can be shown to be

$$m = \phi\mathcal{R} + \frac{4\pi n^2}{r \cdot 10^9}\frac{dq}{dt} = M_m \sin \omega t \qquad (1)$$

Now let,

$$\frac{4\pi n^2}{r \cdot 10^9} = \mathcal{L} \qquad (2)$$

Then equation 1 becomes

$$m = \phi\mathcal{R} + \mathcal{L}\frac{d\phi}{dt} = M_m \sin \omega t \qquad (3)$$

The fundamental equation of an a-c circuit containing resistance and self-inductance is

$$e = Ri + L\frac{di}{dt} = E_m \sin \omega t \qquad (4)$$

Equations 3 and 4 are seen to be identical in mathematical form. Since these differential equations are identical in form, the solutions must also be identical in form and therefore, we may write at once (or solve equation 3 if we wish)

$$\phi = Ce^{-\frac{\mathcal{R}}{\mathcal{L}}t} + \frac{M_m}{\sqrt{\mathcal{R}^2 + (\omega\mathcal{L})^2}} \sin(\omega t - \theta) \qquad (5)$$

or, neglecting the transient term, the root-mean-square value of flux is

$$\Phi = \frac{M}{\sqrt{\mathcal{R}^2 + (\omega\mathcal{L})^2}} \qquad (6)$$

and the flux $\Phi$ lags behind the exciting magnetomotive force by an angle

$$\theta = \cos^{-1}\frac{\mathcal{R}}{\sqrt{\mathcal{R}^2 + (\omega\mathcal{L})^2}} \qquad (7)$$

Thus, it can be seen that a damper coil affects a magnetic circuit the same way self-inductance affects an electric circuit, even so far as transient effects are concerned. That is to say, in a-c magnetic circuit, a damper or shading coil reduces the effective a-c component of flux and causes this flux to lag behind the exciting magnetomotive force.

Nearly all elementary text books refer to the Ohm's law of the magnetic circuit. Likewise, all a-c textbooks extend the Ohm's law of the d-c circuit to the a-c circuit by using a "quadrature resistance" or reactance in combination with resistance. None of them, apparently, extend the "Ohm's law of the magnetic circuit" to damped magnetic circuits excited by alternating current. I would propose to do so by introducing a few new terms which I list below; those terms in *italics* are of my own invention.

Thus, the angle of lag of the flux in a shading coil, behind the flux in the unshaded portion is

$$\theta = \cos^{-1}\frac{\mathcal{R}}{\sqrt{\mathcal{R}^2 + (\omega\mathcal{L})^2}} \qquad (7)$$

$$= \cos^{-1}\frac{\mathcal{R}}{\sqrt{\mathcal{R}^2 + \left(\frac{8\pi^2 n^2 f}{r \cdot 10^9}\right)^2}} \qquad (8)$$

Moreover, in a damped magnetic circuit, the ratio of the damped flux, to that which would exist with no damping is given by the equation

$$\cos\theta = \frac{\mathcal{R}}{\sqrt{\mathcal{R}^2 + (\omega\mathcal{L})^2}} \qquad (9)$$

Equation 9 might be called the damping factor.

The foregoing analysis has been given because of the light it throws on the principle of the shading coil. It does not contradict any point of Trickey's analysis but will, I hope, help to explain how a shading coil reduces the flux and causes it to lag behind its magnetomotive force producing in effect a sort of makeshift rotating field in a shaded pole motor.

It is to be noted that this method of analysis automatically eliminates one variable, namely, the current in the shading coil. Perhaps, by using this concept, Trickey could reduce his analysis to 3 simultaneous equations, instead of 4 as he now has. This is merely offered as a suggestion which may or may not be of value.

Trickey has compared the performance of the shaded pole motor with the split-phase motor with no starting switch. In the light of the foregoing analysis, an interesting comparison can be made between these types of motors. In both types there are 2 magnetic fields set up approximately 90 degrees apart in space. In both motors these fields are displaced slightly in time. In both motors these fields are each set up as a result of the same single-phase electromotive force. In both types of motors, it may be said, there are 2 magnetic circuits. But herein lies the difference: in the split-phase motor there are 2 magnetomotive forces displaced in time phase from each other acting on similar magnetic circuits, so the fluxes are displaced by the same phase angle as the magnetomotive forces; in the shaded-pole motor there is only one magnetomotive force acting upon 2 magnetic circuits in parallel and the phase displacement in fluxes is due to dissimilarity in the magnetic circuits. Thus, it is scarcely to be wondered that the performance of the 2 types of motors should be similar.

**P. H. Trickey:** It is quite possible for a shaded-pole motor to have less input under load than at no load. In fact, the losses of shaded-pole motors very often decrease with load. If the motor is highly saturated, this will sometimes result in an actual decrease in watts input in going from no load to full load.

Veinott's discussion is very interesting, and it seems to me to have possibilities in handling the difficulties of shaded pole circuits. In this case of the shaded pole motor, if it will result in the reduction in the number of variables from 4 to 3 even at the expense of adding another constant or two, it will probably make possible a much more satisfactory solution.

| Electric Circuit | | Magnetic Circuit | |
|---|---|---|---|
| Electromotive force | $E$ | Magnetomotive force | $M$ |
| Current | $I$ | Flux | $\Phi$ |
| Resistance | $R$ | Reluctance | $\mathcal{R}$ |
| Inductance | $L$ | *Delayance* | $\mathcal{L}$ see equation 2 |
| Reactance | $X = 2\pi fL$ | *Retardance* | $x = 2\pi f\mathcal{L}$ |
| Impedance | $R + jX$ | *Hindrance* | $\mathcal{R} + jx$ |
| | or $\sqrt{R^2 + X^2}$ | | or $\sqrt{\mathcal{R}^2 + x^2}$ |
| Conductance | $\left(G = \frac{R}{R^2 + X^2}\right)$ | Permanence | $\left(\mathcal{P} = \frac{\mathcal{R}}{\mathcal{R}^2 + x^2}\right)$ |
| Susceptance | $B = \frac{X}{R^2 + X^2}$ | *Accordance* | $\left(\mathcal{B} = \frac{}{\mathcal{R}^2 + x^2}\right)$ |
| Admittance | $Y = G - jB$ | *Acceptance* | $(y = \mathcal{P} - j\mathcal{B})$ |

# The Tensor—A New Engineering Tool

August 1936 issue, pages 856–62

# Tensor Algebra in Transformer Circuits

November 1936 issue, pages 1214–19

# Tensor Analysis of Multielectrode-Tube Circuits

November 1936 issue, pages 1220–42

**Discussion of papers by A. Boyajian, L. V. Bewley, and Gabriel Kron published in the August 1936 and November 1936 issues and presented for oral discussion at the tensor analysis session of the winter convention, New York, N. Y., January 26, 1937.**

**W. E. Byrne** (nonmember; Virginia Military Institute, Lexington): One of the best ways in which to find out what is contained in a newly organized theory is to teach the material. During the first term of this school year I have given a course one hour a week on vector analysis, polyadics, matrices and tensors to a small group of students and instructors. As an application of these mathematical topics I took up the first 2 papers of Kron (*General Electric Review*, 1935). Naturally such applications are not as general as the basic mathematical theory since the connection matrices are specialized, in that the elements are merely $-1$, $+1$, and 0. Kron and others working in this field are to be commended for developing such powerful and general methods of attacking problems of electrical engineering. It is interesting to note that engineers and mathematicians promise to have more and more in common in the future.

**M. G. Malti** (Cornell University, Ithaca, N. Y.): If we look back to the early records of the use of the algebra of complex numbers in connection with electrical-engineering problems we would find that the problems of those days (early twentieth and late nineteenth century) are just as readily solvable with as without the use of complex numbers. The introduction of complex numbers into engineering paved the way for a deeper, more comprehensive and more forceful analysis of these and later problems.

I shall go a step further and state that most of the early problems were too simple to require more than the mere algebra of complex numbers. The application of the theory of functions of complex variables to electrical-engineering problems was unheard of in those days. Now, within the life span of those who witnessed the first introduction of the algebra of complex numbers, we see a rather common use of the theory of fuctions of complex variables in connection with operational analysis, Laplace and Fourier Transforms, etc.

There was little sympathy and no understanding shown to those select few who used the albegra of complex numbers in the early days. Little sympathy is shown now to those who talk of Laplace transforms and contour integration and downright opposition to those who dare mention tensors.

It is undoubtedly true that our present engineering problems do not call for tensor analysis. But who can predict that the engineers of the future will not need tensor analysis to solve their problems? Any engineer who 30 years ago dared make the statement that engineers would have to become thoroughly acquainted with mathematical works on functions of complex variables to solve their knotty theoretical problems of network analysis would have been laughed at. But here we are today using these works most effectively in circuit analysis.

I make these statements more to express a point of view than to support one faction or another. We all agree that it is impossible to guess what the problems of the future will be and what type of analysis these problems will require. Hence it behooves us to view with sympathy and understanding all work of an advanced nature in the hope that, if it is not immediately useful, it might prove to be so in the future.

**M. F. Gardner** (Massachusetts Institute of Technology, Cambridge): The linear algebraic transformation expressing the element currents $i^k(t)$ in terms of the loop currents $i^\alpha(t)$ in a connected network is

$$i^k(t) = C_\alpha{}^k i^\alpha(t) \tag{1}$$

in which $C_\alpha{}^k$ is the connection matrix, and in which the $k$ and $\alpha$ run over the elements and loops, respectively.

The linear equations expressing the envarience of the total instantaneous power $p(t)$ under transformation from element variables $[i^k(t)$ and $v_k(t)]$ to loop variables $[i^\alpha(t)$ and $\bar{v}_\alpha(t)]$ is

$$p(t) = v_k(t) i^k(t) = v_\alpha(t) i^\alpha(t) \tag{2}$$

If the voltages and currents are sinusoidal—and only steadystate relations are of interest— the $i$'s of equation 1 can be replaced by their complex amplitudes. With the $i$'s of (2) replaced by their complex amplitudes, the $v$'s must be replaced by the conjugates of their complex amplitudes. The $p$ is then replaced by the so-called "vector power." This use of conjugate complex amplitudes works satisfactorily for this particular case—the steady state with sinusoidal functions or sums of sinusoidal functions.

Barnes (of Tufts College) and I have noted that the use of conjugate complex amplitudes in this way does not carry over to the case of transients, which involve nonperiodic functions. Since we have not seen a satisfactory statement in the literature of a generalization to cover such cases, we shall indicate one here.

Before we can state the essential idea of this extension it perhaps will be helpful to make a few preliminary remarks about the Laplace transformation (hereafter abbreviated $L$-transformation) by which the extension will be made.

Let $s = \sigma + j\omega$ be a complex variable corresponding to the real variable $t$. Then a general time function $f(t)$ can be transformed into its corresponding generalized frequency function $F(s)$ if $f(t)$ is given and is such that the following definite integral is absolutely convergent,

$$\int_0^\infty f(t) e^{-st} dt = F(s) \qquad c_a < \Re(s) \tag{3}$$

This integral defines $F(s)$ for that part of the complex $s$-plane wherein the real part of $s$ is sufficiently great to insure the integral having a finite value.

If, on the other hand, $F(s)$ is the function known and the corresponding $f(t)$ is unknown, (3) becomes an integral equation, but its solution is given by the integral

$$\frac{1}{2\pi j}\int_{c-j\infty}^{c+j\infty} F(s) e^{ts} ds = f(t) \quad 0 < t \quad c_a < c \tag{4}$$

This is a line integral in the complex plane. The path of integration is a straight line paralleling the axis of imaginaries and lying in that part of the $s$-plane in which $F(s)$ is defined.

The integrals of (3) and (4) constitute, respectively, the direct $L$-transformation and its inverse. Further, an $f(t)$ and its $F(s)$ constitute an $L$-transform pair and can be written as

$$f(t) \qquad F(s) \tag{5}$$

For application of these ideas in the present discussion it is necessary to know that, given 2 $L$-transform pairs

$$\left.\begin{matrix} f_1(t) & F_1(s) \\ f_2(t) & F_2(s) \end{matrix}\right\} \tag{6}$$

the pair which results when the 2 *time* functions are multiplied is

$$f_1(t)\, f_2(t) \frac{1}{2\pi j}\int_{c_1-j\infty}^{c_1+j\infty} F_1(w) F_2(s-w) dw$$

$$\left.\begin{matrix} c_{a_1} < c_1 \\ c_{a_2} < \Re(s-w \end{matrix}\right\} \tag{7}$$

For interpretation of this it is helpful to have also the pair which results when the 2 *frequency* functions are multiplied. This pair is commonly found in engineering literature. It is

$$\int_0^t f_1(\tau) f_2(t-\tau) d\tau \qquad F_1(s)\, F_2(s) \tag{8}$$

Pairs (7) and (8) can be abbreviated by introducing the notation

$$f_1(t)\, f_2(t) \qquad F_1(s) * F_2(s) \tag{7a}$$

$$f_1(t) * f_2(t) \qquad F_1(s)\, F_2(s) \tag{8a}$$

In (7) the integration in the complex $w$-plane is along a straight line paralleling the axis of imaginaries and lying in that part of the $w$-plane in which $F_1(w)$ is defined. In (8) the integration is along the positive time axis. In both integrals the functions are said to be convolved. In (8) the $f_2$ function is "folded" before multiplication by the $f_1$ function. In (7) the $F_2$ function is rotated by 180 degrees and shifted by the amount $s$ before multiplication by the $F_1$ function. Various forms of the convolution integral for functions of real variables shown in (8) are referred to in the engineering literature as Borel's integral, Duhamel's integral, and the superposition integral. For frequency functions, the counterpart of this superposition-type in-

tegral is the complex convolution integral appearing in (7).

Applying these ideas now to the original equations 1 and 2, each member is transformed by use of (3), i.e., each member is multiplied by the exponential $e^{-st}$ and integrated from 0 to $\infty$. Equation 1 transforms to

$$I^k(s) = C_\alpha{}^k \hat{I}^\alpha(s) \qquad (9)$$

Equation 2 presents cases of time-function products. In their transformation (7*a*) is used. The result is

$$P(s) = V_k(s) \quad I^k(s) = v_\alpha(s) * \hat{I}^\alpha(s) \qquad (10)$$

Each typical term in (9) and (10)—instead of being a function of $t$ as in (1) and (2)—is a function of $s$. The currents, voltages, and power involved may be any functions of time, provided only that they are $L$-transformable by (3). When it is necessary to return to functions of time, the inverse transformation (4) is used.

It should not be concluded from what has been said here that in practical work it is advisable, even though possible, to replace the simple operation of multiplication by the complicated operation of convolution (*). But in theoretical work it may be very convenient to make this replacement, especially when it is not necessary to actually carry out the indicated convolution.

Summarizing, for theoretical work utilizing tensor or matrix notation a scheme is provided for handling general time functions by means of their $L$-transforms much as sinusoidal functions are now treated by means of their complex amplitudes. The condition remaining which these time functions must fulfill is that they be $L$-transformable. In addition to furnishing a generality needed for theoretical work, the transform method provides a compact symbolism which fits conveniently into the tensor or matrix scheme of notation.

**W. H. Ingram** (nonmember; New York, N. Y.): On page 1220 the author mentions a "first generalization theorem" and says that by the use of the notation advocated the behavior of the most complex systems are "described' by the application of the theorem to equations of motion governing the simplest of all systems, namely, that of one degree of freedom.

This should be a theorem of great importance, as its statement and the italics used would suggest, but on examination it would appear to be merely a statement that from the equation $e = Zi$ governing a simple system we can deduce the equation $e_n = Z_{nm}i^m$ for a more complex system although, presumably, the fact that the ordinary equation

$$e_n = \Sigma Z_{nm} i_m$$

rests in some way on the simpler one is not claimed as requiring the new theorem.

If this is the generalization claimed, we are brought immediately to the question of what a tensor is and what bearing the concept of a tensor has on the solution of network, machine and vacuum-tube problems.

To begin with, a tensor has no meaning except in reference to, or conjunction with, *admissible co-ordinate systems*. Not all co-ordinates used by electrical engineers come under this head: the co-ordinates used by Blondel and Park, among others, in the theory of electrical machines, do not. To prove this, take, for example, the expression

$$ds^2 = g_{ij} dq^i dq^j$$

called the Riemannian *metric* in certain geometrical interpretations of dynamics and connected with the kinetic energy. The coefficient $g_{ij}$ is a tensor because of the fact that

$$g_{ij} = g_{\alpha\beta}{}^* \frac{\partial q^\alpha}{\partial q^i} \frac{\partial q^\beta}{\partial q^j}$$

*when* the $q$'s with Latin superscripts and those with Greek form 2 admissible co-ordinate systems. Given the first system, a second can always be obtained by a linear transformation, that is, of the form

$$q^i = b_j{}^i q^{*j}$$

as a matter of fact, an infinite number of admissible systems exist in this case.

However, in the theory of electrical machinery, transformations of the form

$$dq^i = \beta_\alpha{}^i dx^\alpha$$

occur where the $dx$'s are the differentials of quasico-ordinates and where the right-hand side is a not completely integrable Pfaffian so called, that is, the right-hand side is not a complete differential. Substitute this last equation into the formula for the metric and we obtain

$$ds^2 = g_{\alpha\beta}{}^* dx^\alpha dx^\beta$$

so that

$$g_{ij} = g_{\alpha\beta}{}^* \frac{\partial \dot{x}^\alpha}{\partial \dot{q}^i} \frac{\partial \dot{x}^\beta}{\partial \dot{q}^j}$$

where $\dot{x}$ is the total derivative of $x$ with respect to the time or any other parameter. This last expression is *not* in agreement with the rule for the transformation of a covariant tensor of the second order. Hence the $x$'s, which include the co-ordinates introduced by Blondel and which are indispensable in the theory of electrical machinery, do *not* form an admissible co-ordinate system.

The functions $\beta_1{}^i, \beta_2{}^i \ldots \beta_n{}^i$ are regarded by geometers as the components of a covariant vector, in the manifold of the $q$'s, tangent to a congruence of the curves defined by the equations

$$\frac{dq^1}{\beta_i{}^1} = \frac{dq^2}{\beta_i{}^2} = \ldots = \frac{dq^n}{\beta_i{}^n}$$

and the $dx$'s, given by $dx^i = \alpha_j{}^i dq^j$, may be interpreted as the differential co-ordinates of a neighboring point in the associated space of the tangents mentioned and forming a Cartesian reference system. A different system of congruences chosen in the $q$-space gives a different associated space and this is also so in general when there is a metric defining the associated space.

In the present case the metric in question would be $g^*$, the $x$'s referring to arcs of the congruences, and the associated space is Riemannian. But no tensor discussion involving this space is possible except when based upon the underlying $q$-system of co-ordinates. In other words, no tensors occur in, or can enter, the theory of any commutator machine until the latter is regarded as a transform of a slip-ring machine and then only with reference to the true co-ordinates involved.

When the commutator machine has fewer degrees of freedom, certain $dx$'s are identically zero and the theory of nonholonomic metrical subspaces comes in. (Vranceanu, "Les espaces non-holonomes," Paris, 1936 page 18.)

The question has been suggested: can tensors enter the congruence space via the asymmetric "coefficients of affine connection" of ultra Riemannian geometry and, if so, has that fact any bearing on the theory of electrical machines and circuits? It is known (Eisenhart, "Non-Riemannian Geometry," page 14) that the paths of the manifold corresponding to geodesics of a Riemannian space are given by the curves defined by the equation

$$\dot{q}^j(\ddot{q}^i + \Gamma^i{}_{kl}\dot{q}^k\dot{q}^l) - \dot{q}^i(\ddot{q}^j + \Gamma^j{}_{kl}\dot{q}^k\dot{q}^l) = 0$$

where

$$2\Gamma^i{}_{jk} = L^i{}_{jk} + L^i{}_{kj}$$

provided $L^i{}_{jk}$ transforms according to the fundamental equation

$$\frac{\partial^2 q^i}{\partial \bar{q}^\alpha \partial \bar{q}^\beta} + L_{jk}{}^i \frac{\partial q^j}{\partial \bar{q}^\alpha} \frac{\partial q^k}{\partial \bar{q}^\beta} = \bar{L}_{\alpha\beta}{}^\gamma \frac{\partial q^i}{\partial \bar{q}^\gamma}$$

Now we cannot take

$$L^r{}_{jk} = g^{*rs}\Lambda_{jk,s}$$

as has been done (Kron, "Non-Riemannian Dynamics of Rotating Electrical Machinery," *Journal of Mathematics and Physics*, volume 13, 1934, page 156) for the $x$'s would appear in place of the $q$'s in this last equation and the existence of the derivatives $\partial x^i/\partial \bar{x}^\alpha$ cannot be established. A search for a more suitable "coefficient" might be in order if no metric were available, but in the theory of electrical machines and circuits a metric is always at hand and the geometry of the dynamics of electrical machinery and circuits is in fact ordinary Riemannian, as I have remarked elsewhere (*Bulletin* of the American Mathematical Society, September 1934, page 666). This, I gather, is also the opinion of Synge ("Tensorial Methods in Dynamics," University of Toronto Press, 1936).

The author calls $C_m{}^\alpha$ a "transformation tensor." The transformations involved are of such a special kind that the name used may be misleading. Consider the system of seven variables $x_1, x_2 \ldots x_7$ upon which 2 conditions are imposed, say the conditions that the equations $x_1 - x_2 + x_3 - x_5 = 0$ and $x_2 - x_3 + x_4 - x_7 = 0$ be satisfied. We can solve these equations for 2 of the variables, say $x_6$ and $x_7$. The remaining variables may be thought of as the independent ones and we may wish to designate them by special letters, say $y_1, y_2 \ldots y_5$. Hence we may write $x_1 = y_1$, $x_2 = y_2$, $x_3 = y_3$, $x_4 = y_4$, $x_5 = y_5$, $x_6 = y_1 - y_2 + y_3$, $x_7 = y_2 - y_3 + y_4$. The matrix of this "transformation" (it will be noted that there is no inverse) happens to be the author's matrix (48) in this case. The original 7 $x$'s could represent the currents in 7 parts of a net and the equations of condition could represent the application of Kirchhoff's law at 2 junction points: the $y$'s would then represent the currents in

*complete* circuits. This and many related topics are adequately expounded by Quade ("Klassifikation der Schwingungsvorgaenge in gekoppelten Stromkreisen," Leipzig, 1933) in terms of matrices. Redundant constraints, detectable by the rank of the Jacobian involved, are treated in the same way.

The fact that there are many ways of eliminating 2 of the $x$'s ordinarily would not be interpreted as bringing in as many admissible co-ordinate systems in the tensor sense particularly in the case where the $x$'s are the differentials of quasico-ordinates. Tensors come in only when the co-ordinates in one admissible co-ordinate system are related one-to-one to those in another, when the functional relation between them is of class $C^m$ (that is, having continuous partial derivatives up to and including the $m$th order, $m \geqslant 1$), and when the functional Jacobian is not equal to zero. If tensors really were being considered here, Quade's circuitization matrix would contain functions, that is, (48) would contain partial derivatives of one set of co-ordinates with respect to another admissible set instead of the 0's and 1's shown. The author's 2 paragraphs between equations 20 and 21 would appear to be therefore erroneous.

To sum up the discussion above as it bears on the question of tensors, the situation would seem to be that to date tensors have not been brought into the theory of electrical nets and machines. When this has been done, the question of their usefulness will be less difficult to settle.

Equations 41 and the discussion of figure 3 would appear to be new developments, but on close inspection the addition theorem given by (41) is found to be quite trivial because of the fact that both the circuitizing matrix $C$ and the impedance matrix of (*a*) and (*b*), figure 3, have to be of the same order. One does not know how to write down either of these matrices for (*b*) unless the order of the impedance matrix of the system that is to be connected at $g_2$ and $p_2$ is known in advance.

In the paper by L. V. Bewley the author implies that his method $C$ is dynamical but his use of the terms "ignoration," "constraint," and "canonical" seem to be at variance with the meanings of these expressions in classical dynamics. No co-ordinate is "ignorable" in dynamics when there is dissipation involved, a force polygon being closed implies no constraint and the canonical equations in dynamics are equations of motion in terms of the displacements and momenta as variables exclusively. The equation

$$e_k = z_{kl} i^l$$

or its equivalent, was called more appropriately the "generalized Ohm's Law" by Kennelly.

The author says that the "connection tensor" $C_\alpha^j$ expresses old currents "before interconnection" in terms of new currents "after interconnection." The false impression may be conveyed that there is a physical rearrangement of the net to correspond to the mathematics, or vice versa. Both the "old" currents and the "new" currents must refer to the same system arrangement: in the first case to where the variables are not independent and in the second case to where redundant variables have been eliminated by algebraic processes. The theory has been given matrix form by Quade and others and the above mentioned "connection tensor" appears to be nothing more than Quade's circuitizing matrix.

Given a system of circuit segments or meshes arranged in the form of a net, with or without inductive coupling, and specified by the kinetic energy, the potential energy, the Rayleighean dissipation and the external work functions, Quade ("Klassifikation der Schwingungsvorgaenge in gekoppelten Stromkreisen," Leipzig, 1933) has shown (*a*) how force equations free from Lagrangean multipliers can be obtained in a more fundamental manner than usual, (*b*) how the operational determinant or matrix of a system classifies it on the basis of the elementary divisors of the determinant, and (*c*) the significance of *representatives* of the classes in question, which are exhaustively studied. The author's first transformer circuit (windings in series), load-ratio control circuit, and forked auto-transformer circuit come under one or other of these classifications.

The author's procedure differs from Quade's in 2 minor respects: the use of equations of ampere-turn balance and the inclusion of the electromotive forces $e_0$, $e_1$, etc. Some of these electromotive forces are not truly external but are reactive (with one sign or another) which it is necessary to introduce together with the equations of ampere-turn balance when any of the mutual inductances are left out of the analysis. This procedure seems to be necessary when it is desired to take into account excitation losses (which the author does not do) but otherwise the method adopted by Quade would seem to be simpler. Quade's method of finding the external forces acting in the circuits, given those acting in the meshes, can hardly be improved upon for simplicity (cf. ibid. ¶18).

As the author's discussion is really one in terms of matrices it is not clear how tensors come in at all. The use of tensor notation is one thing, to have a tensor enter is another. Bôcher used vector notation for matrices but that does not make them vectors. On the other hand, we may have tensors without using tensor notation as is evidenced by the fact that the German mathematician Voigt, who originated the idea of a tensor, never omitted the summation sign, as is now done, and did not use dummy indices. There seems to be nothing against the use of tensor notation, except perhaps that it is too condensed, but if it is used it seems reasonable to demand that tensors really be involved in the discussion.

**V. Karapetoff** (Cornell University, Ithaca, N. Y.): Tensor analysis has been proved to be a powerful tool in the solution of quite advanced electrical problems; it is of interest to note, however, that some simpler problems involving stationary networks require only matrix algebra. This means that students of the subject may be able to solve a certain class of problems without going into the general theory of invariants. In particular, it has been felt that some of the earlier treatment in Kron's epoch-making articles in the *General Electric Review* (volume 38, page 231) could be developed in greater detail and shown to agree with Kirchhoff's law, without explicitly using power as an invariant.

Let figure 1 represent a stationary network with impedances and sources of voltage (indicated by small circles) in each branch. Only instantaneous values of the currents and the voltages will be considered, so that it is immaterial whether the inserted voltages are direct or alternating, and whether the régime is steady or transient. The individual conductors (or branches) are denoted by the letters $a, b, \ldots . n, p$. The positive directions of the currents in the individual branches are arbitrary and are indicated by arrowheads. An applied voltage in a branch is to be considered positive if it tends to produce a current in the positive direction in that particular branch.

Following Maxwell (*Electricity and Magnetism*, volume 1, page 406), fictitious mesh currents, $x, y, z, t, u, v$, are introduced, with the positive directions arbitrarily taken clockwise. These currents are supposed

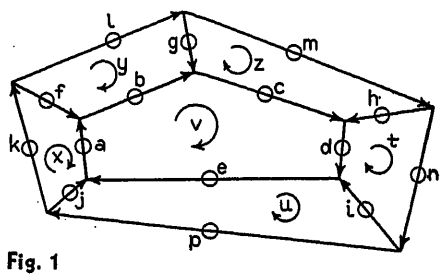



Fig. 1

to circulate in the individual loops of the network; an actual branch current is an algebraic sum of the corresponding mesh currents. For example, the current in $a$ is equal to $v - x$. It is well known that in this manner Kirchhoff's first law is satisfied automatically and need not be expressed by separate equations. We shall use the following notation and terminology:

The individual conductors (or branches), the currents flowing through the same, and the inserted (or applied) voltages will all be denoted by the same symbols, $a, b, c, \ldots n, p$. No confusion need arise as to whether a current or a voltage is meant, or the conductor itself. The potential differences between the terminals of the respective conductors will be denoted by the corresponding capital letters, $A, B, C, \ldots N, P$. The letters $x, y, z, t, u, v$, will mean interchangeably the respective loops or meshes, the fictitious currents circulating around these meshes, and the sums of the applied voltages in the same meshes. Those sources of voltage which give a positive energy output with the corresponding mesh currents are to be considered positive, when summing up around that particular loop. As a test, a source may be replaced by a storage battery; if the positive mesh current discharges that battery, the voltage of the source is positive; if the battery is charged, the source is negative.

Consider now the matrix shown in figure 2, with the "branch" letters written to the left, and the "mesh" letters on top. The first row is to be interpreted as $a = -x + v$, that is, the current in conductor $a$ is equal to that in mesh $v$ less the current in mesh $x$; this agrees with the sketch of the network.

The other horizontal rows have a similar meaning for the other branches of the network, as may be readily verified. The matrix thus represents the relationship between the branch currents and the mesh currents. The number of rows is equal to that of the branches, and the number of columns to that of independent loops or meshes. The idea behind this representation is to refer Kirchhoff's first law to the same meshes for which the second law is written, and thus to have all the relations among the currents and among the voltages represented by the same matrix.

Now read the last column of the dyadic from the top down, assuming the letters to

$C =$

| | x | y | z | t | u | v |
|---|---|---|---|---|---|---|
| a | -1 | | | | | 1 |
| b | | -1 | | | | 1 |
| c | | | -1 | | | 1 |
| d | | | | -1 | | 1 |
| e | | | | | -1 | 1 |
| f | 1 | -1 | | | | |
| g | | 1 | -1 | | | |
| h | | | 1 | -1 | | |
| i | | | | 1 | -1 | |
| j | -1 | | | | 1 | |
| k | 1 | | | | | |
| l | | 1 | | | | |
| m | | | 1 | | | |
| n | | | | 1 | | |
| p | | | | | 1 | |

Fig. 2.

refer to the voltages, and not to the currents. This column reads $v = a + b + c + d + e$, in other words, it states that the total applied voltage around the mesh $v$ is equal to the sum of the applied voltages in the branches $a$, $b$, $c$, $d$, $e$. The other columns contain the corresponding relationships for the other meshes; a comparison with the network itself will show the signs of the voltages to be also correct. Thus, for the total current the dyadic is written using the current vector combinations $ax$, $ay$, etc., whereas for the voltage it is written with $xa$, $xb$, etc. The second dyadic is called transpose or conjugate with respect to the first. The underlying reason for which the same dyadic is correct for both the currents and the voltages is now seen to be that currents are added in parallel, whereas voltages are added in series. Consequently, following the mesh letters ($x$, $y$, $z$, etc.) horizontally by rows, one encounters the meshes between which a given conductor is situated. Following the branch letters vertically by columns ($a$, $b$, $c$, etc.) one follows the branches which combined form a given loop. In this manner, the representation by dyadics becomes firmly established on the basis of the fundamental electrical principles.

Let the impedance of the individual branches of the network be denoted by $Z$'s with the corresponding double subscripts, the subscript $nn$ meaning that the resistance, the self-inductance, and the capacitance of the $n$-th conductor or branch are meant. In a steady state, $Z$ is a function of the frequency. In a transient state, the operator $p = d/dt$ is included in it. The mutual magnetic inductance between the $n$-th and the $m$-th branch is denoted by $X_{mn}$. It is identically equal to $X_{nm}$, and for this reason the impedance matrix of a stationary passive network is always symmetrical. In the dyadic notation $Z$ stands for both $Z_{nn}$ and $X_{nm}$, so that the general expression for the voltage drop in the individual branches is

$$E + e = Z \cdot i \qquad (1)$$

where $E$ is the voltage between the terminals of the conductor and $e$ is the sum of the external voltages inserted in the branch. The term $Z \cdot i$ includes a summation over all the branches which posses a mutual inductance with the branch under consideration. When summing up equation 1 over a closed mesh, the sum of the $E$'s becomes zero, and we have the usual expression for Kirchhoff's second law.

In accordance with Kron's notation, let the vector of the fictitious currents circulating over the meshes be denoted by $i'$, and the vector of the sums of the external applied voltages over the meshes by $e'$. In other words, let $i' = i_x x + i_y y +$ etc. Then, since all the relations are linear, we may write the dyadic expression in the form

$$e' = Z' \cdot i' \qquad (2)$$

where $Z'$ for the present simply stands for a dyadic of coefficients of proportionality between the new currents and the voltages. The relationship between $e$ and $e'$ on the one hand and between $i$ and $i'$ on the other hand is determined by the matrix in figure 2; consequently, there must be a definite dyadic relationship between the actual branch impedance $Z$ and the new impedance $Z'$. The components of the latter may be called mesh impedances or equivalent impedances, since they do not refer to the real branch currents, but to the fictitious mesh currents. Knowing $Z'$ and $e'$, these latter currents may be computed, and then the real branch currents calculated from the rows of the matrix in figure 2. Thus, our next problem is to find the relationship between $Z$ and $Z'$.

Let the matrix in figure 2 be denoted by $C$. It is called a transformation matrix, because by means of it the variables are changed from the branch currents to the mesh currents. The physical circuit itself is not modified. Thus

$$i = C \cdot i' \qquad (3)$$

For the voltages, the transpose matrix, $C_t$, must be used, as is explained above, and we have

$$e' = C_t \cdot e \qquad (4)$$

This equation may also be written as

$$e' = C_t \cdot (E + e) \qquad (5)$$

because a summation of the $E$'s over a mesh gives zero. From equations 1, 2, 3, and 5, the relationship between $Z$ and $Z'$ may be determined as follows: Multiplying both sides of equation 1 by $C_t$ and substituting for the left-hand side its value from equation 2 we get:

$$Z' \cdot i' = C_t \cdot Z \cdot i$$

Using the value of $i$ from equation 3 and cancelling $i'$, we finally obtain

$$Z' = C_t \cdot Z \cdot C \qquad (6)$$

This is Kron's equation 19, and from here on the procedure is the same as in his articles, namely: First find $Z'$ as on page 232, and then compute $Y' = 1/Z'$. Multiply vector $e'$ by $Y'$. This will give the mesh currents $i' = Y' \cdot e'$. Finally determine $i$ from $i'$ by using the transformation matrix $C$.

In the foregoing deduction of equation 6, it has not been necessary to introduce the power output, $P = i \cdot e = i' \cdot e'$, as an invariant. In fact, this mode of approach permits to deduce that the power is an invariant. Branch currents are changed to the mesh currents, but physically everything remains the same. Another advantage is that the inverse of the dyadic $C_t$ is not used in the deduction of equation 6. The dyadic being singular in its very nature, its determinant is equal to zero; therefore, it is preferable not to use $C_t^{-1}$ at all.

Because the transformation formulas are not derived from an invariant form, the foregoing deduction is not an example of tensor analysis; one is not permitted to use lower and upper indices in that sense. It is of interest to investigate the possibilities of generalizing this method, for example, by opening the network at a few points and connecting another circuit to it.

**Joseph Slepian** (Westinghouse Electric & Manufacturing Company, East Pittsburgh, Pa.): The first basis of good mathematics is probably the careful definition of terms. We have learned to follow and even improve upon the model set by Euclid, and to desire that each new term introduced into a mathematical work will be given a careful, and precise definition. We hope that the definition will have content. That is, that it should be free from self contradiction, and actually apply to some object. We hope that the definition will be sufficient. That is, that it will state all the qualities or properties necessary to distinguish the defined object from other objects. We hope the definition will be permanent. That is, that the meaning of the newly defined term will stay the same throughout the mathematical work. Lastly, we hope that so far as possible, the definition will conform to previous usage. The more widespread that previous usage, the less will we approve of any radical departure from previously used meanings.

The papers of Kron and Boyajian, appear to me to err in all these respects. Their definitions of the new terms or concepts which they introduce, seem mutually contradictory, insufficient, impermanent, and differ from previous and generally accepted usage.

From the titles of the papers, we would expect at least that adequate definitions of the "tensor" would be given. Also since the tensor is generally believed to be a generalization of the "vector," and opinion

apparently concurred with by Boyajian, but dissented from by Kron, we would expect an adequate definition of the "vector."

Kron, in his paper, page 1221, 1st column, refers to *General Electric Review*, volume 38 April 1935, page 181–91, and May 1935, page 230–43, "in which all the necessary definitions are stated." Turning to these references, we find in the first, page 181, first column, "the theory of tensors (known also under the name of hypercomplex numbers, polyadics, matrices, etc.)." Apparently then, the as yet undefined terms "tensors," "hypercomplex numbers," polyadics," "matrices," "etc., "all stand for the same thing. Perhaps a little dismayed by the plethora of names, including the "etc." for the same thing, we nevertheless proceed on in the reference.

The next suggestion of a definition we find on page 182, second column, "...replaced by hypercomplex numbers, that is, by sets of numbers arranged in a row (vector) or a square (matrix), etc." Here the terms "vector" and "matrix" seem to be no longer equivalent to the term "hypercomplex numbers," as before, but now the "vector" and "matrix" seem to be special cases of "hypercomplex numbers." "Vector" seems to refer to the capability of a set of numbers of being arranged in a row. Since, however, any set of numbers can obviously be arranged in a row, at least if it is a finite set, we seem to be told that any finite set of numbers is a "vector." Likewise "matrix" seems to refer to the capability of a set of numbers of being arranged in a square. But since any $n^2$ numbers, where $n$ is an integer, can be arranged in a square, we seem to be told that any set of $n^2$ numbers is a "matrix." These $n^2$ numbers, if we like can also be arranged in a row, so apparently a "matrix" is also a "vector."

Proceeding further in the reference, we find after $3^1/_2$ full pages of text, the first explicit definition, page 184, column 2, "An expression such as $(e_a a + e_b b + e_c c)$ ...is called a vector." Apparently, now, to be a "vector," the set of numbers must not only be placed in a row, but must be written with symbols, $a$, $b$, $c$, following each number, and with plus signs between successive numbers. But since obviously, any finite set of numbers can be set down in this way, if the writer chooses, again we seem to be told that any finite set of numbers is a "vector."

Boyajian is even more outspoken in enunciating this view, although there is some suggestion of uneasiness about a necessary relationship of the set of numbers to reference axes. Thus (ELECTRICAL ENGINEERING, August 1936, page 857, column 2), "Stated broadly, a vector is a quantity resolvable into a set of independent components." Again (ELECTRICAL ENGINEERING, August 1936, page 858, columns 1 and 2), "to constitute a generalized vector, the set of quantities $e_1 e_2 \ldots e_n$ need not represent a physically directed quantity in space, nor a harmonic quantity in time; in fact, it is not necessary to know what physical quantity they represent, in order to decide whether or not they constitute a generalized vector. They may be considered, at least tentatively, as constituting a generalized vector...if they ...constitute one group of related but independent quantities."

Since the members of any set of numbers are related, by being parts of one set, and independent, by being distinct from one another, Boyajian apparently also believes that any finite set of numbers is, "at least tentatively," a vector.

Thus according to these views, we have so bizarre a "vector" as today's closing quotations of the New York Stock Exchange. These are certainly a group of related quantities; in fact they are printed on the same newspaper page because of their common quality. That they vary independently, any speculator can testify. Although in the newspaper, they are usually arranged in columns, they could be arranged in a row. Actually on the ticker tape they are so arranged, and each number has set beside it a symbol, as *GM* $68^1/_2$...*GE* $59^1/_8$ ...*UP* 128, which, except for the absence of plus signs, is very reminiscent of Kron's $e_a a + e_b b + e_c c$. Apparently according to the definitions of Kron and Boyajian, the stock market quotations are "at least tentatively" a vector.

But these definitions are entirely different from the generally accepted meanings given to vectors. Let us limit outselves to vectors in ordinary Euclidean space. All the usual treatments of vectors in Euclidean space begin by assigning to vectors the notions of length or magnitude, and direction. These seem to be the primary defining properties of vectors which practically all text books agree upon. "Components" then come in only as the appropriate mathematical means for describing magnitude and direction.

In these days of relativity, we are all aware that length and direction have no absolute significance. We cannot describe the direction of a vector except with reference to other objects having direction, nor can we specify its length except with reference to some other object having length. Thus the "components" of a vector which mathematicians introduce to properly describe its length and direction are not absolute, but are relative to some system of reference object which themselves have length and direction. The "components" of a vector are relative to a reference system of vectors.

A vector, then, has not one set of components, but infinitely many sets, one for every vector reference system that may be chosen. Furthermore, all these various sets of components must be mutually related so that each in its own reference system indicates the same "directed magnitude." The so-called transformation equations which the sets of components must satisfy are merely the expression of the property of the vector of having length and direction.

A displacement in space which is the typical vector, has length and direction, and therefore has infinitely many mutually related sets of components referred to the various possible reference displacement systems, but the report of stock market quotations, which has only one set of components, has neither length nor direction and is not a vector according to usual notions.

Evidently the definitions of Kron and Boyajian which make an arbitrary set of numbers, such as a stock market report, a vector, "at least tentatively," must differ very radically from the generally accepted meaning given to "vector."

If we pursue further the reference given by Kron, we go through over 15 pages of text with the word tensor used scores of times. Although they are as yet undefined, "tensors," "dyadics," "polyadics," "matrices," "hypercomplex numbers," and "etc.," seem to be used indiscriminately synonomously. But, at last, page 234, we come to section VII, "Definition of a Tensor." We learn, "those polyadics whose formulas of transformation are the simple ones given in equations 37 are called 'tensors,'...the word tensor is limited to a definite class of polyadics..." Apparently the preceding use of the words "tensor" and "polyadic" as synonymous in Kron's work was a mistake.

Boyajian seems to be able to use the word "tensor" without requiring "polyadics." But his test for the tensor quality of his "transformation tensor" on page 862, seems to involve only such manipulation of indices as Kron performs upon all his "polyadics," which Kron states are not always "tensors." May I ask Boyajian whether his test may not merely demonstrate the "Kronian polyadic?" quality of his "transformation tensor" and perhaps not its tensor quality.

Going a little further in Kron's reference, page 234, column 2, "Whether a vector or a dyadic, etc., is a tensor or not, does not depend...." Apparently according to Kron a vector need not always be a tensor. However, every book, which I have consulted makes the vector a special case of a tensor, that is, a tensor of rank one. Boyajian also in his paper, says, page 857, column 2, "vectors come in as a special class of tensors" and page 860, column 1, "the common vector is merely a special case as a one-dimensional tensor, or a tensor of rank one." Can Kron justify his usage of the word vector which seems to differ from that of all others?

On page 235, column 2, of his reference, Kron becomes even more specific. He now says that a vector has "length," or magnitude, and "If the magnitude of a vector is the same irrespective of the co-ordinate system...it is called a tensor."

But Kron gives no definition of the "length" or "magnitude" of a vector. Would he find the "length" of the vector current such as he uses in his present paper by taking the scalar product of it with itself, meaning thereby the sum of the squares of its components? If so, then he would violate his rules for manipulating indices. But how otherwise? A similar question might be addressed to Boyajian who, on page 858, column 2, gives examples of a purportedly purely contravariant vector, and a purportedly purely covariant vector, each having length or magnitude. However, whatever the resolution of this dilemma may be, Boyajian, contrary to Kron, seems willing to let the lengths or magnitudes of his vectors vary with transformation of co-ordinates, without their losing their tensor character.

We might also ask Kron whether his criterion for the tensor character of a vector last quoted is consistent with the previously quoted "Definition of a Tensor" as those "polyadics" which satisfy the "equations" 37. If the components of a vector satisfy the "equations" 37 will its

"length" necessarily be unchanged by the transformation and vice versa?

One more question of definition. On page 239, column 1, of Kron's reference, we find "A tensor whose elements are complex numbers is called a spinor." Since "spinors" are used now quite widely in the literature of quantum-mechanics, and not at all in the sense of the quoted definition, will Kron give one reference to justify his definition?

I have already intimated that I believe Boyajian's treatment of covariance and contravariance to be unsound. If the space under consideration is metrical, as seems to be the case since Boyajian refers to the "magnitude" of his vectors, then any vector has both covariant and contravariant components as Sah brings out in his second paper in the section "Covariant and Contravariant Measure Numbers."

Refer to the equation in Kron's paper, page 1231, bottom of second column. This gives a relation between the components of the variables $\Delta X$ in the "old reference system" $\Delta X^m$ and the "new," $\Delta X^\alpha$. Is it not then the "transformation equation" and therefore does it not define the "transformation tensor?" But on page 1224, second column, we find "In this presentation all transformation tensors have only constant components..." In other words, is there not a contradiction with equations 38?

In Kron's paper page 1233, first column, the complex number

$$\Delta\hat{e}_1 = \Delta e_1 + j\Delta e_1'$$

is set down equal to a real number. Is this not a contradiction? The title of this section is called complex Taylor's series. But "Taylor's series" usually means the expansion of a function of a variable into a power series, such as equation 61 where the coefficient in each term is $1/n!$ times the value of the $n$th derivative of the function taken at some definite point. I fail to find any such expanison in this section. How does Kron justify the title, "Taylor's Series?"

In this section, where the applied voltage $\Delta e$ is supposed to be resolvable into $n$ components with different frequencies, it is said that there will in general be $n+2n^2$ components of current, (if, as I presume, higher powers than the second of the component $\Delta e$'s are neglected). Apparently the only distinguishing or defining feature of these components is their frequency. But, even in the most general case there will not by as many as $n + 2n^2$ different frequencies. For obviously in the square array of component currents shown in the second column of page 1233, the frequency $w_1 + w_2$ is equal to the frequency $w_2 + w_1$, etc. Hence in this square array there will in general be only $\frac{1}{2}n(n + 1)$ distinct frequencies. Does Kron intend the component $\Delta i^{w_2 + w_1}$ to be different from $\Delta i^{w_1 + w_2}$? If so, will he not need a different notation? Or is $w_1 + w_2$ not equal to $w_2 + w_1$? Will the total current $\Delta i$ always contain the two terms $\Delta i^{w_1 + w_2} + \Delta i^{w_2 + w_1}$ always summed together? If so, why not use only a single letter for this sum, since the component terms can never be determined by any test, and may therefore perhaps be said not to exist individually.

Similar remarks may be applied to the matrix for $\Delta i^{(\alpha)(-\beta)}$. The frequency $w_1 - w_2$ is the negative of the frequency $w_2 - w_1$. Does Kron permit the frequency to be negative? If so, how do these negative frequencies make their presence apparent? If not, then $\frac{1}{2}n(n-1)$ of the $n^2$ frequencies referred to in $\Delta i^{(\alpha)(-\beta)}$ disappear. Also in the matrix for $\Delta i^{(\alpha)(-\beta)}$ the frequencies for the diagonal terms are all alike and zero. Apparently even in the most general case there are for these $n + 2n^2$ components of current only $n^2 + n + 1$ distinct frequencies But if the $n + 2n^2$ components of current dealt with in this section are not defined by their individual frequencies, how are they defined?

In the next section, page 1234, entitled "Compound Series," Kron assumes that for any given total impressed voltage it is somehow possible to separate and distinguish components of "fundamental frequency" from components of "product frequency." But such a resolution is not at all unique. For example, suppose we have actually impressed upon a system a voltage having components of 10, 15, 25, and 35 cycles, and let us say each of these components has the value one. Then if we like, we may regard these all as "fundamental frequencies," and in Kron's equation 85 set $\Delta e_{(\sigma)}$, and $\Delta e_{(\gamma)}$ $\Delta e_{(\delta)}$, each as unity, and the $\Delta e_{(\gamma)}$ $(=\delta)$ each as zero. But we may, if we like, take only the 10 and 25 cycles as fundamental, and regard the 15 and 35 cycles as product frequencies. Then in Kron's equation 55, $\Delta e_{(\sigma)}$ stands for $\Delta e_{10}$ and $\Delta e_{25}$, each to be taken as one; $\Delta e_{(\gamma)}$, $\Delta e_{(\delta)}$ also stand for $\Delta e_{10}$ and $\Delta e_{25}$ and each to be taken as one. But $\Delta e_{(\gamma)}$ $(=\delta)$ now stand for $\Delta e_{25} = 10$, that is for $\Delta e_{15}$ and $\Delta e_{35}$ and are now to be taken as unity. Similarly we may take 10, 15, and 25 cycles as fundamental and regard only the 35 cycles as product frequency. Since each of these equally plausible ways of regarding the applied voltage, when applied to the equation 85 would seem to give different results, some doubt may be cast upon the correctness of the treatment.

At the end of this section, page 1234, column 1, it states that "all symbols,—such as $Z_{(\epsilon)(\sigma)}$ are not "polyadics" (as defined in reference 1*Da*)...." This contradicts the statement quoted earlier that "all the necessary definitions are stated" in reference 1*A*. It is most disconcerting, after receiving the impression in Kron's reference, from April 1935 to Jan. 1936, that "polyadics" and "hypercomplex numbers" are synonymous, to at last receive a definition in February 1936, which makes them different.

The section called "Inverse of the Complex Series," on page 1236, seems to deal with what were called "Compound Series" on page 1234.

Here, again, the lack of definition enabling one to distinguish between $\Delta i^{w_1+w_2}$ and $\Delta i^{w_2+w_1}$, and the ambiguity as to what are to be called "fundamental frequency" and what "product frequency" make the value of the work seem quite doubtful.

**A. P. T. Sah** (National Tsing Hua University, Peiping, China): The gateway to Kron's work hinges on his "connection tensor" $C$. It is unfortunate that Kron has not explained this fundamental quantity clearly in his writings, since 2 easily recognized inconsistencies in the exposition of the "connection tensor" $C$ have appeared in his papers. In the first place the "connection tensor," by its very nature, is necessarily singular and cannot have a reciprocal. And yet the reciprocal of $C$ or of its transpose has been not only written down in explicit equations (See equation 37, *General Electric Review*, volume 38, page 234, May 1935 and equation 38, ELECTRICAL ENGINEERING, page 1226, November 1936) but also used in making demonstrations. The second inconsistency has to do with Kron's "generalized network" (See figure 4, ELECTRICAL ENGINEERING, page 1228, November 1936). In figure 4*a*, the so-called "generalized network" is shown with all coils short-circuited through applied electromotive forces. From such a diagram one would necessarily conclude that the currents in the coils are uniquely determined when all the electromotive forces and the impedances are known. But these current values cannot satisfy the constraining conditions as shown in figure 4*b* for the same applied electromotive forces and the impedances of figure 4*a*. It is believed that Kron's generalized network is entirely uncalled for since it represents neither a mathematical fiction nor a physical reality. In fact, it is in plain contradiction with the physics of the problem

Leaving aside the question of the *engineering* utility of the "connection tensor" in setting up circuit equations in any case, which, as correctly pointed out by Bewley (ELECTRICAL ENGINEERING, page 1215 November 1936), is neither simpler nor shorter than the old-fashioned Kirchoff's laws, it is hoped that Kron will revise his statements and demonstrations so as to make his "connection tensor" a flawless tool.

**A. W. Tucker** (nonmember; Princeton University, Princeton, N. J.): Professor Struik has pointed out that my recent work on tensor algebra in topology has a bearing on the applications of tensors to electrical engineering. To illustrate let us consider a network consisting of (directed) lines numbered 1, 2, 3, etc. and terminals I, II, III, etc.; an example, with figure, is given below. The combinatorial structure of such a network is exhibited by the array of *incidence numbers*.

$$N_a^\alpha = \begin{cases} 1 & \text{if the line } a \text{ ends at the terminal } \alpha \\ -1 & \text{if the line } a \text{ begins at the terminal } \alpha \\ 0 & \text{otherwise.} \end{cases}$$

In each line $a$ let there be a current component $e^a$ and at each terminal $\alpha$ a component $h_\alpha$ of potential. Then, using the summation convention,

$$f^\alpha = N_a^\alpha e^a \tag{1}$$

$$i_a = h_\alpha N_a^\alpha \tag{2}$$

$$p = i_a e^a = h_\alpha N_a^\alpha e^a = h_\alpha f^\alpha \tag{3}$$

measure (1) the current flowing out of the network at the terminal $\alpha$ (say, into an external lead), (2) the voltage in the line $a$, and (3) the power in the network. If we now consider the same network in terms of

new elements 1′, 2′, 3′, etc. and I′, II′, III′, etc. formed from the old by a reversible process, we get new incidence numbers

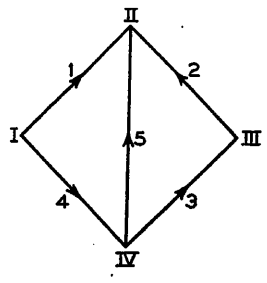
$$N_{a'}{}^{\alpha'} = C_{\alpha}{}^{\alpha'} N_a{}^{\alpha} C_{a'}{}^{a}$$

and new components of current, potential, voltage, etc.,

$$e^{a'} = C_a{}^{a'} e^a, \; h_{\alpha'} = h_\alpha C_{\alpha'}{}^{\alpha}, \; i_{a'} = h_{\alpha'} N_{a'}{}^{\alpha'} = h_\alpha N_a{}^{\alpha} C_{a'}{}^{a}, \text{ etc.},$$

where $C_{a'}{}^{a}$, $C_a{}^{a'}$ are inverse transformations (i.e. $C_{a'}{}^{a}\, C_b{}^{a'} = 1$ if $a = b$ and 0 otherwise) as are $C_{\alpha'}{}^{\alpha}$, $C_{\alpha}{}^{\alpha'}$.

*Example*




incidence table

| | 1 | 2 | 3 | 4 | 5 |
|---|---|---|---|---|---|
| I | −1 | 0 | 0 | −1 | 0 |
| II | 1 | 1 | 0 | 0 | 1 |
| III | 0 | −1 | 1 | 0 | 0 |
| IV | 0 | 0 | −1 | 1 | −1 |

$= N_a{}^{\alpha}$

change of line-basis:

$1' = 1, \; 2' = 2, \; 3' = 3, \; 4' = 4 + 5 - 1, \; 5' = 5 - 2 - 3$

| | 1′ | 2′ | 3′ | 4′ | 5′ |
|---|---|---|---|---|---|
| 1 | 1 | 0 | 0 | −1 | 0 |
| 2 | 0 | 1 | 0 | 0 | −1 |
| 3 | 0 | 0 | 1 | 0 | −1 |
| 4 | 0 | 0 | 0 | 1 | 0 |
| 5 | 0 | 0 | 0 | 1 | 1 |

$= C_{a'}{}^{a}$

| | 1 | 2 | 3 | 4 | 5 |
|---|---|---|---|---|---|
| 1′ | 1 | 0 | 0 | 1 | 0 |
| 2′ | 0 | 1 | 0 | −1 | 1 |
| 3′ | 0 | 0 | 1 | −1 | 1 |
| 4′ | 0 | 0 | 0 | 1 | 0 |
| 5′ | 0 | 0 | 0 | −1 | 1 |

$= C_a{}^{a'}$

change of terminal-basis:

$I' = II - I \qquad II' = II - III$
$III' = II - IV \qquad IV' = IV$

| | I′ | II′ | III′ | IV′ |
|---|---|---|---|---|
| I | −1 | 0 | 0 | 0 |
| II | 1 | 1 | 0 | 0 |
| III | 0 | −1 | 1 | 0 |
| IV | 0 | 0 | −1 | 1 |

$= C_{\alpha'}{}^{\alpha}$

| | I | II | III | IV |
|---|---|---|---|---|
| I′ | −1 | 0 | 0 | 0 |
| II′ | 1 | 1 | 0 | 0 |
| III′ | 1 | 1 | 1 | 0 |
| IV′ | 1 | 1 | 1 | 1 |

$= C_{\alpha}{}^{\alpha'}$

incidence table with respect to new bases

| | 1′ | 2′ | 3′ | 4′ | 5′ |
|---|---|---|---|---|---|
| I′ | 1 | 0 | 0 | 0 | 0 |
| II′ | 0 | 1 | 0 | 0 | 0 |
| III′ | 0 | 0 | 1 | 0 | 0 |
| IV′ | 0 | 0 | 0 | 0 | 0 |

$= N_{a'}{}^{\alpha'}$

In topological parlance a network of lines and terminals is a *graph* of *edges* and *vertices* or a *1-complex* (i.e. one-dimensional complex) of 1-cells and 0-cells. Numbers $e^a$ attached to the 1-cells give a *1-chain*. The numbers $f^\alpha = N_a{}^{\alpha} e^a$ attached to the 0-cells give a special 0-chain called the *boundary* of the preceding 1-chain. Notice that Kirchhoff's law asserts that the boundary of a current vanishes—except at terminals with external connections. Numbers $h_\alpha$ attached to the 0-cells give a "dual" 0-chain—here the terminology is not well established for the notion is new. The "dual" boundary of this is the dual 1-chain given by the numbers $i_a = h_\alpha N_a{}^{\alpha}$ attached to the 1-cells. Instead of basing our chains on cells we may base them on suitable combinations of cells (i.e. chains). Thus we are led to consider *changes of basis*. The particular changes chosen in the above example serve to reduce the table of incidence to an especially simple form. The components of a chain such as current change contravariantly and those of a dual chain such as voltage change covariantly; hence their scalar product, or *intersection index*, is invariant under change of basis.

I hope these remarks indicate how topology enters as an intermediary in the application of tensors to electrical engineering. There is nothing new in the separate items of the above discussion; the only novelty lies in putting them together. The topology involved seems quite essential although being one-dimensional it is rather trivial from the geometrical point of view. However it is far from ruled out that higher dimensions may not come into the development as it unfolds.

C. E. Rose (Federal Emergency Administration, Washington, D. C.): Vector and tensor symbols will be written in capital type and since a vector is in reality a tensor of rank zero no ambiguity will result, because in this convention a vector will be defined as such by being without a sub- or superscript, whereas a tensor will always be written with its definitive subscripts and / or superscripts. Given any 2 arbitrary vectors $A$ and $B$, existing within orthogonal or affine space, we write their product as $AB$. This is neither their scalar product $A \cdot B$, not their vector product $A \times B$, and it is therefore at this point undetermined.

Write:

$$A = a_1 i + a_2 j + a_3 k, \tag{1}$$

$$B = b_1 i + b_2 j + b_3 k \tag{2}$$

in which $i$, $j$, and $k$ are the unit vectors and $a_1$, $a_2$, $a_3$ and $b_1$, $b_2$, $b_3$ are the respective projections of $A$ and $B$ upon the axes measured by these respective unit vectors.

We know from elementary vector analysis that:

$$i \cdot i = j \cdot j = k \cdot k = 1 \tag{3}$$

$$i \cdot j = j \cdot k = k \cdot i = 0 \tag{4}$$

as the scalar products of these unit vectors.

We also know that:

$$i \times i = j \times j = k \times k = 0 \tag{5}$$

$$i \times j = -j \times i = k \tag{6}$$

$$j \times k = -k \times j = i \tag{7}$$

$$k \times i = -i \times k = j \tag{8}$$

as the vector products of these unit vectors.

We, therefore, now write the product of equations 1 and 2 as:

$$\begin{aligned} AB = {} & a_1 b_1 ii + a_1 b_2 ij + a_1 b_3 ik + \\ & a_2 b_1 ji + a_2 b_2 jj + a_2 b_3 jk + \\ & a_3 b_1 ki + a_3 b_2 kj + a_3 b_3 ik \end{aligned} \tag{9}$$

We may now, as usual, substitute $a_{11}, a_{12} \ldots\ldots a_{33}$ for the coefficients of $a_1 b_1, \; a_1 b_2 \ldots \ldots a_3 b_3$ above, and write the scalar product of $AB$ as, the matrix:

$$A \cdot B = \begin{Vmatrix} a_{11} a_1 b_1 & 0 & 0 \\ 0 & a_{22} a_2 b_2 & 0 \\ 0 & 0 & a_{33} a_3 b_3 \end{Vmatrix} \tag{10}$$

and the vector product of $AB$ as, the matrix:

$$A \times B = \begin{Vmatrix} 0 & a_{12} a_1 b_2 & -a_{13} a_1 b_3 \\ -a_{21} a_2 b_1 & 0 & a_{23} a_2 b_3 \\ a_{31} a_3 b_1 & -a_{32} a_3 b_2 & 0 \end{Vmatrix} \tag{11}$$

add equations 10 and 11, yields:

$$AB = (A \cdot B) + (A \times B) = \begin{Vmatrix} a_{11} a_1 b_1 & a_{12} a_1 b_2 & a_{13} a_1 b_3 \\ a_{21} a_2 b_1 & a_{22} a_2 b_2 & a_{23} a_2 b_3 \\ a_{31} a_3 b_1 & a_{32} a_3 b_2 & a_{33} a_3 b_3 \end{Vmatrix} \tag{12}$$

We may further condense equation 12 and write:

$$AB = \sum_{ik} a_{ik} a_i b k = \begin{Vmatrix} a_{11} a_1 b_1 + a_{12} a_1 b_2 + a_{13} a_1 b_3 + \\ a_{21} a_2 b_1 + a_{22} a_2 b_2 + a_{23} a_2 b_3 + \\ a_{31} a_3 b_1 + a_{32} a_3 b_2 + a_{33} a_3 b_3 \end{Vmatrix} \tag{13}$$

If the right hand member of equation 13 remains invariant in form when subjected to any rotation about its co-ordinates, then we may write in tensor notation:

$$T_{ik} = \sum_{ik} a_{ik} a_i b_k \tag{14}$$

and equation 14 defines a covariant tensor of rank 2.

To test whether equation 14 is invariant let us rewrite equation 9 as before and rotate it 90 degrees around the $i$-axis. To do so write:

$$AB = \begin{Vmatrix} a_1 b_1 ii + a_1 b_2 ij + a_1 b_3 ik + \\ a_2 b_1 ji + a_2 b_2 jj + a_2 b_3 jk + \\ a_3 b_1 ki + a_3 b_2 kj + a_3 b_3 kk \end{Vmatrix} \tag{9}$$

and to apply to it the versor:

$$\phi = ii \cos e (jj + kk) + \sin e \, (kj - jk) \tag{15}$$

Since the original unit vectors in equation 9 are $i$, $j$ and $k$, then by multiplication of equation 9 by equation 15 we have rotated equation 9 90 degrees around the $i$-axis and

$$\begin{aligned} i' &= i \\ j' &= j \cos e + k \sin e, \\ k' &= -j \sin e + k \cos e \end{aligned} \tag{16}$$

$e$, the angular rotation in this cases being 90 degrees, equation 16 reduces to

$$\begin{aligned} i' &= i \\ j' &= k \\ k' &= -j \end{aligned} \quad \text{or} \quad \begin{aligned} i &= i' \\ j &= -k' \\ k &= j' \end{aligned} \tag{17}$$

Substitution of the values of $i$, $j$ and $k$, in terms of $i'$, $j'$, and $k'$ from equation 17 into equation 9 yields:

$$AB = \left\| \begin{matrix} a_1b_1i'i' - a_1b_2i'k' + a_1b_3i'j' - \\ a_2b_1k'i' + a_2b_2k'k' - a_2b_3k_1j' + \\ a_3b_1j'i' - a_3b_2j'k' + a_3b_3j'j' \end{matrix} \right\| \quad (18)$$

which is identical in form to equation 9. We may designate the coefficients as usual of the components $a_1b_1 \ldots a_3$, by $a_{11} \ldots a_{33}$ without losing any generality and the result is again equation 13, which proves that equation 9 and its developments, equations 12, 13, and 14, define a tensor, because its form is identical after this rotation of 90 degrees.

A contravariant tensor represents the "Path"; a covariant tensor represents the force along the "Path"; the first is defined by superscripts, the second by subscripts and the mixed tensor by both, as $A^{ik}$, $A_{ik}$, and $A_i^k$ respectively.

# Induction Motors on Unbalanced Voltages

**Discussion and authors' closure of a paper by H. R. Reed and R. J. W. Koopman published in the November 1936 issue, pages 1206–13, and presented for oral discussion at the induction machinery session of the winter convention, New York, N. Y., January 27, 1937.**

**H. J. Reeves** (Paul and Reeves, Spokane, Wash.): The authors treatment of the 3-phase motor on single-phase voltage might be presented in a slightly different manner. Sketch *B* of their paper could be

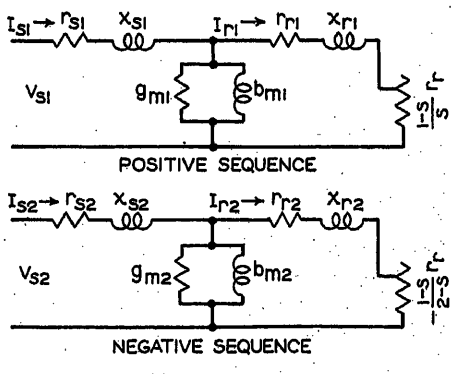



**Fig. 1**

changed to show the separate sequence circuits as in figure 1 of this discussion.

For the negative sequence circuit, the slip, $S_2$, is equal to 2 minus the positive sequence slip $S_1$. Thus,

$$\frac{1 - S_2}{S_2} = \frac{1 - 2 + S_1}{2 - S_1}$$

$$= -\frac{1 - S}{2 - S}$$

where $S_1$ is made equal to $S$ for the sake of brevity.

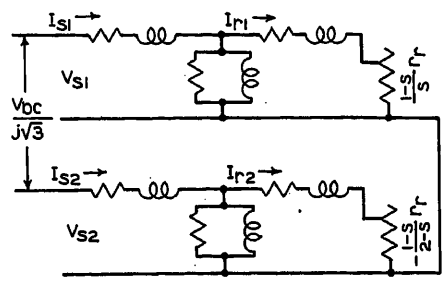



**Fig. 2**

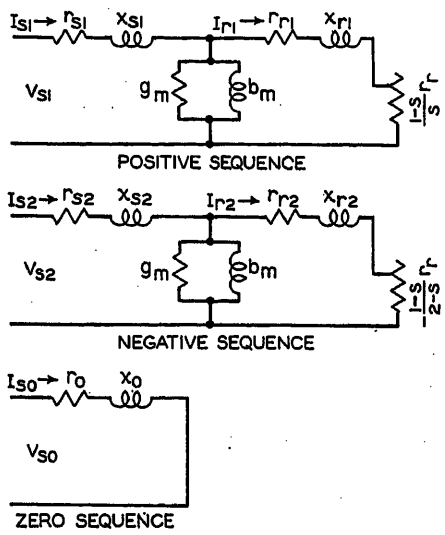



**Fig. 3**

For the 3-phase motor operating single phase we may assume $a$ phase open. The following relations will hold:

$$I_a = 0$$
$$I_b = I$$
$$I_c = I$$
$$I_{s1} = {}^1/_3 (0 + \alpha I - \alpha^2 I) = \frac{\alpha - \alpha^2}{3} I = \frac{j}{\sqrt{3}} I$$
$$I_{s2} = {}^1/_3 (0 + \alpha^2 I - \alpha I) = \frac{\alpha^2 - \alpha}{3} I = -I_{s1}$$

$$V_b = \alpha^2 V_{s1} + \alpha V_{s2}$$
$$V_c = \alpha V_{s1} + \alpha^2 V_{s2}$$
$$V_{bc} = V_c - V_b = (\alpha - \alpha^2) V_{s1} + (\alpha^2 - \alpha) V_{s2} = (\alpha - \alpha^2)(V_{s1} - V_{s2}) = j(\sqrt{3} V_{s1} - V_{s2})$$

$$I_{s1} = I_{s2} \quad (1)$$

$$\frac{V_{bc}}{j\sqrt{3}} = V_{s1} - V_{s2} \quad (2)$$

For analytical purposes, connect the sequence networks together as in figure 2 to satisfy the conditions of equations 1 and 2. This solution will permit the use of the familiar tabulation in columnar form for the calculation of motor performance curves. To the table for balanced 3-phase voltage operation will be added the negative-sequence calculations for the corresponding values of slip, and the changes in positive-sequence values resulting from the changes in positive-sequence voltage.

The practical limits of $\frac{1 - S}{S} r_r$ are zero and infinity, and of $-\frac{1 - S}{2 - S} r_r$ are zero and $-0.5 r_r$. It will be noted that in the working range, $-\frac{1 - S}{2 - S}$ may be assumed to be $-0.5$ without appreciable error. Since the values of negative-sequence voltage near synchronous speed are low we may assume

$$I_{r2} = I_{s1}$$

and the negative sequence torque will then be

$$T_2 = -0.176 \frac{P r_r}{f(2 - S)} I_{s1}^2$$

The loss in speed necessary for a balance between negative and positive sequence torques is slight and is usually less than one per cent.

Another interesting application can be made to the Y-connected motor operating on a 4-wire 3-phase circuit, with one of the phase wires open. A motor operating under this condition will have considerable starting torque, since a positive angular displacement between the 2-phase windings is maintained. The following solution for this condition might be used.

$$I_a = 0 = I_1 + I_2 + I_0 \quad (3)$$

$$I_b + I_c + I_N = 0$$

$$V_b = \alpha^2 V_1 + \alpha V_2 + V_0 \quad (4)$$
$$= \alpha^2 I_1 Z_1 + \alpha I_2 V_2 - (I_1 + I_2) Z_0$$
$$= I_1 (\alpha^2 Z_1 - Z_0) + I_2 (\alpha Z_2 - Z_0)$$

$$I_2 = \frac{V_b - I_1 (\alpha^2 Z_1 - Z_0)}{\alpha Z_2 - Z_0} \quad (6)$$

$$V_c = \alpha V_1 + \alpha^2 V_2 + V_0$$
$$= \alpha I_1 Z_1 + \alpha^2 I_2 Z_2 - (I_1 + I_2) Z_0$$
$$= I_1 (\alpha Z_1 - Z_0) + I_2 (\alpha^2 Z^2 - Z_0) \quad (5)$$

$$= I_1 (\alpha Z_1 - Z_0) + \frac{V_b - I_1(\alpha^2 Z_1 - Z_0)}{\alpha Z_2 - Z_0} \times (\alpha^2 Z_2 - Z_0)$$

$$I_1 = \frac{V_c(\alpha Z_2 - Z_0) - V_b(\alpha^2 Z_2 - Z_0)}{(\alpha Z_1 - Z_0)(\alpha Z_2 - Z_0) - (\alpha^2 Z_1 - Z_0)} \times (\alpha^2 Z_2 - Z_0) \quad (7)$$

The sequence networks are shown in figure 3. These should be connected together to satisfy the conditions of equations 3, 4, and 5, but as this condition does not lend itself readily for simple solution, $I_1$ may be calculated from equation 7 and $I_2$ from 6.

For this solution the values for 3-phase balanced operation may be utilized and the values for the negative-sequence circuit may be taken from the additions which have been noted above.

The starting torque and current values of table I and the speed-torque characteristics of figure 4 have been calculated from the following constants of a 5-horsepower, 220-volt, 3-phase, 60-cycle, 6-pole motor, all being expressed in unit values.

| | | | |
|---|---|---|---|
| $r_{s1} = r_{s2}$ | $= 0.044$ | $X_{r1} = X_{r2}$ | $= 0.140$ |
| $r_{r1} = r_{r2}$ | $= 0.067$ | $X_0$ | $= 0.140$ |
| $r_0$ | $= 0.044$ | $g_m$ | $= 0.023$ |
| $X_{s1} = X_{s2}$ | $= 0.140$ | $b_m$ | $= 0.380$ |

**Table I**

| | A | B | C |
|---|---|---|---|
| Starting current | 3.42 | 3.42 | 3.74/3.93 |
| Starting torque | 0.98 | 0 | 0.51 |
| Maximum power | 1.67 | 0.76 | 1.23 |
| Maximum torque | 2.00 | 0.80 | 1.38 |
| Unit current | 1.00 | 1.00 | 1.00 |
| Power | 1.00 | 0.35 | 0.52 |
| Speed | 0.94 | 0.97 | 0.97 |
| No load Current | 0.38 | 0.67 | 0.52 |
| No load Speed | 1.00 | 1.00− | 1.00− |

*A*—Motor operating on balanced 3-phase voltage
*B*—Motor operating single-phase line-to-line voltage
*C*—Motor operating on 2 phases of the 3 line-to-neutral voltages

**Selby Haar** (Board of Transportation, City of New York, N. Y.): Tests of a number of 3-phase squirrel cage rotor motors of 1 to 2½ horsepower, presumably with balanced windings, on a circuit with approximately 1 per cent unbalance of voltages showed unbalanced currents as high as 20 per cent. If the motors are provided with controllers of standard type with overloads in 2 lines only, an overload setting sufficient to carry the larger current may be too high to protect the other phase windings of the motor. Hence unbalanced voltages in a polyphase supply system may be a serious matter.

**G. F. Corcoran** (The State University of Iowa, Iowa City.): The authors have combined symmetrical-component circuit theory with classical polyphase-induction-motor theory to advantage. By strict adherence to accepted principles in these 2 fields they have simplified the general problem of predetermination of induction-motor characteristics under unbalanced voltage conditions.

An important feature of the method presented in this paper is the absence of empirical constants and other data that can be obtained only by elaborate tests. No parameters other than those which can easily be calculated from ordinary test data or from ordinary design data have been employed in the calculations. It is obvious that $g_e$, $b_e$, and $r_q$ are not exactly the same for the 2 equivalent circuits, namely, the positive-sequence circuit and the negative-sequence circuit. With the aid of empirical data and various assumptions several refinements in $g_e$, $b_e$, and $r_q$ might be affected. However, the amount of additional labor involved and the inaccuracies encountered in obtaining actual magnetizing reactances discourage any general attempt in this connection.

For a particular operating condition, certain refinements are entirely feasible. For example, at low values of slip $s_1$ the negative-sequence voltage is low and $g_e$ in the negative-sequence circuit could be adjusted accordingly with due regard for the saturation effects caused by the positive-sequence flux. It will be observed, however, that quite uniform results have been obtained neglecting "saturation effects" entirely. Also at low values of $s_1$ the approximate double-frequency rotor current in the negative-sequence circuit will make for higher rotor resistance and simultaneously there will be a high-frequency core loss. Both of these effects could, conceivably, be taken into account in the present method by increasing $r_q$ in the negative-sequence circuit by the appropriate amount for each different value of slip. Refinements of this nature are, of course, incidental to the general theory involved because accurate results necessarily involve the use of accurate circuit parameters.

The remarkable feature of the present method is that the experimentally determined results agree as well as they do with those calculated on the basis of constant $g_e$, $b_e$, and $r_q$. As shown in the paper, the calculated values agree with the experimentally determined values better for low values of $s_1$ than for higher values of $s_1$. Certain irregularities due to inherent space harmonic effects are to be expected for particular low values of $s_1$.

The theory underlying the introduction of a negative resistance

$$r_q \frac{(1 - s_2)}{s_2}$$

where $s_2 > 1$

is of some importance because the electromagnetic power developed by the negative-sequence field is:

$$-\left[I_q^2 r_q \frac{(1 - s_2)}{s_2}\right] \qquad (1)$$

In this connection it is interesting to note that power crossing the gap via the negative-sequence field is:

$$\left[I_q^2 \frac{r_q}{s_2}\right] \qquad (2)$$

Physically, of course, there are $I_q^2 r_q$ watts dissipated in heat in the $q$ branch of the negative-sequence circuit and this is supplied only partially by the power that crosses the gap via the negative-sequence field.

$$I_q^2 r_q = I_q^2 \frac{r_q}{s_2} - I_q^2 r_q \frac{(1 - s_2)}{s_2} \qquad (3)$$

The voltage relations involved in the negative-sequence circuit when $s_2 > 1$ are shown in the accompanying sketch. A comparison of these relations with the well-known positive-sequence circuit relations when $s_1 < 1$ will further disclose the reason for the introduction of negative resistance into the negative-sequence equivalent circuit.

Although the present method as applied

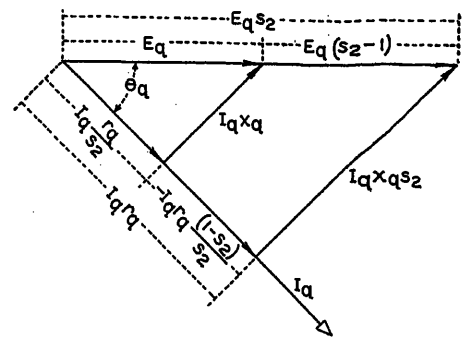



**Fig. 4. Voltage and current relations in the rotor of the negative-sequence circuit**

From a rotor point of view

$$I_q = \frac{E_q s_2}{r_q^2 - x_q^2 s_2^2}$$

From a stator point of view

$$I_q = \frac{E_q}{(r_q^2/s_2^2) - x_q^2}$$

to the single-phase case possesses certain features which are contained in the common 2-network single-phase equivalent circuit, it is definitely superior in several respects. The voltage to employ in connection with each circuit can be calculated in a straightforward manner. This particular feature is distinctly advantageous in the single-phase case and it is thought that the present method of attack will find its greatest field of usefulness in single-phase motor analysis.

**F. H. Pumphrey** (Rutgers University, New Brunswick, N. J.): I have been interested in the presentation of this paper primarily as a teacher of the subject of electrical machinery. The schools have faced tremendous pressure to reduce the amount of time spent in the study of electrical machinery. One of the ways that this has been accomplished is by obtaining a closer coordination of the theory of machines. With this in view, several years ago, I discarded the cross-field theory of single-phase induction motor operation, and adopted the symmetrical-component analysis as presented in this paper. It has had several advantages. First, it has given an excellent illustration of the use of symmetrical components, second, it has permitted me to use all of the polyphase motor theory that had been built up and thus save time, and third, it has given, I believe, a better physical understanding of the phenomena. I should welcome comments from designing engineers as to the relative merits of the symmetrical-component attack versus the cross-field theory where time permits the presentation of but one.

**P. H. Trickey** (Diehl Manufacturing Company, Elizabethport, N. J.): Is it possible to use this method when the turns and weights of wire in the two windings of a capacitor motor are not equal? (Note: (1) Kingsley of MIT replied to this question; (2) A professor from Rhode Island State asked what was being taught at

present, the revolving field or cross-field theory of single-phase motors; (3) Kingsley said that at MIT, they were teaching the revolving field theory exclusively; (4) Karapetoff, of Cornell, implied in a discussion that these methods of calculating capacitor motors were based on superposing 2 separately revolving fluxes, and that there was danger of inaccuracies due to saturation effects.)

1. The question as to whether the revolving field theory or cross-field theory should be used in single-phase motor analysis has been debated for many years. The engineers in our company are using both methods side by side in every day routine design problems, and I want to urge very seriously that neither method be allowed to drop out of the minds of men engaged in teaching.

For instance, the single-phase calculation method developed by C. G. Veinott and H. R. West, is based on the cross-field theory and is used by engineers of at least 4 large engineering companies. There are certain features that seem to be illustrated much more vividly than by the revolving field theory. On the other hand, such phenomena as the double-frequency rotor currents in a single-phase motor are not easily visualized by the cross-field method.

2. I think the authors of these papers on methods of calculating capacitor motors are to be commended, and I want to urge them as well as others, to keep working on this problem. There are now a number of different methods of attack, all of which can be used to calculate the performance. The principle difficulty now is the length of time involved. Those of us engaged in routine design need very badly a calculation method which is not appreciably longer than that which we use on single-phase motors. Our present method for polyphase motors involves 26 slide rule operations to calculate the performance for any given slip while the single-phase method takes 35 operations. The best I have been able to arrange any of the capacitor motor methods so far has been 107 operations. If we could cut this down to 40 or even 45, it would become very useful. This, of course, must be for capacitor motors where the two phases are not alike as we very seldom use equal windings.

3. I believe the inaccuracies due to saturation are not very serious due largely to the primary impedance dropping the induced voltage and the flux as the slip is increased. In any case, we need a method and it would be useful even with some error due to saturation.

**G. F. Tracy** (University of Wisconsin, Madison.): Reed and Koopman have used the expressions developed in their paper in order to predict the torque, currents, and voltages of a 3-phase motor operating as a capacitor motor at all slips from standstill to synchronous speed. From a practical standpoint the values of torque and line current at standstill are most significant, since these values determine the practicability of such a method for starting the motor. In a paper entitled "Split-Phase Starting of Three-Phase Motors," by Tracy and Wyss, in ELECTRICAL ENGINEERING, October 1935, page 1068, expressions for torque and current similar to those in Reed and Koopman's paper were developed for the case of split-phase starting using a noninductive resistance in series with one terminal of the motor, and an inductive reactance in series with the second terminal; the third terminal being connected directly to the other side of the line. The expression for torque was further analyzed by differentiation to find the "best" values of resistance and reactance in terms of the constants of the motor; i.e., that pair of values which will produce maximum starting torque (equation 22 in Tracy and Wyss' paper). A similar analysis of the companion case using a resistance and a capacitive reactance was subsequently carried out by J. W. Soule, graduate student at the University of Wisconsin. The best value of resistance was found to be zero in all cases (actually slightly negative); while the best value of reactance was shown to be given by the surprisingly simple and valuable expression $X_c = 1.5z$, where $X_c$ is the value of capacitive reactance in ohms and $z$ is the value in ohms of the equivalent impedance per phase of the motor at standstill, motor assumed Y-connected. The validity of the above expression was verified in a series of tests by Soule; and it is also interesting to observe that when applied to the $^3/_4$-horsepower motor in Reed and Koopman's paper this expression yields a value of capacitance of 245 microfarads, whereas figure 8 of the paper shows the maximum starting torque to occur at 240 microfarads. In the case of the 5 horsepower motor, Reed and Koopman do not show starting torque as a function of capacitance. The best value of capacitance according to the above expression is 690 microfarads; i.e., more than 4 times as large as that used in the curves of figures 5–7. Had the value of capacitance used in their tests been 690 microfarads instead of 160 microfarads the starting torque would have been 150 per cent of the 3-phase starting torque instead of approximately 13 per cent as in figure 5. The starting torque corresponding to the best value of $X_c$ is readily computed from $T = 28.8\, r/(z - x)$, where $T$ is in per cent of 3-phase starting torque, and $r$, $z$, and $x$ are respectively the numerical values of the resistance, impedance, and reactance, in ohms per phase of the motor at standstill, motor assumed Y-connected.

In general, the starting torque obtainable with an inductive reactance and a resistance connected as described above does not exceed 20 per cent of 3-phase starting torque even with the best values used for the resistance and reactance. It is a relatively inexpensive method, however, and is thus adaptable to large machines. On the other hand, the torque obtainable with a condenser only (as in sketch $C$ of Reed and Koopman's paper) is of the order of 100 per cent of 3-phase starting torque. This means that a 3-phase motor operating from a single-phase line and started as a capacitor motor has starting characteristics comparable with those of a repulsion-start single-phase motor or those of a 3-phase motor. The over-all cost, however, is greater than that of a repulsion-start motor at the present price of condensers.

The authors make the statement in the opening paragraph of their paper that their method is "quite different from those which have appeared in the recent literature." The writer would like to state that it appears to him that the procedure used by the authors in treating the 3-phase motor operating single phase and also the 3-phase motor on unbalanced 3-phase supply is essentially the same as that used by O. C. G. Dahl in his book "Electric Circuits, Theory and Applications," volume 1, and also by C. F. Wagner and R. D. Evans in their book "Symmetrical Components." Also the authors' procedure in handling the case of the 3-phase motor operating as a capacitor motor does not appear to differ fundamentally from that used in the paper by Tracy and Wyss quoted at the beginning of this discussion, together with the discussion of this reference by E. M. Sabbagh (in ELECTRICAL ENGINEERING, March 1936, page 285).

**H. R. Reed and R. J. W. Koopman:** Reeves' treatment of the induction motor operating on 4-wire 3-phase with one line open is interesting, especially since this point was raised in oral discussion by Karapetoff. This is not a common method of operating induction motors, and the problem of determining the impedance to zero-sequence current which would flow under these conditions should be of interest. Wagner and Evans in the December 1929 issue of the *Electric Journal* discuss this problem.

The statement by Selby Haar that unbalanced voltages in a polyphase supply system may be a serious matter has been considered by the writers from the point of view of decreased efficiency, in an article in a recent issue of *Electrical World*.

Tracy states that the "best" value of capacitance to have been used in the illustrative curves of figures 5–7 is that which produces maximum torque at starting. In the Tracy and Wyss paper referred to, however, the authors, using inductive reactance starting, state that "By 'best' values of $R$ and $X$ is meant that pair of values which will produce maximum starting torque—or, if such values should be accompanied by an excessive line current, the 'best' values would then be those which produce maximum torque at an arbitrarily fixed line current."

It would seem that the best value of capacitance to be used at starting should be that which would most nearly duplicate 3-phase conditions at the motor. It can be shown that for 3-phase motors with 3-phase

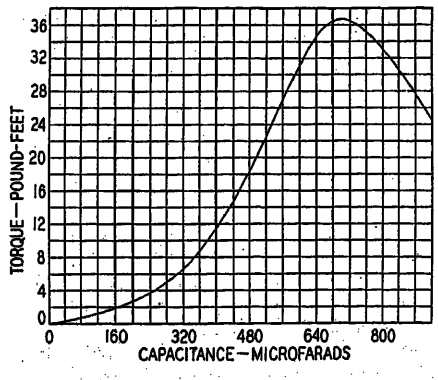
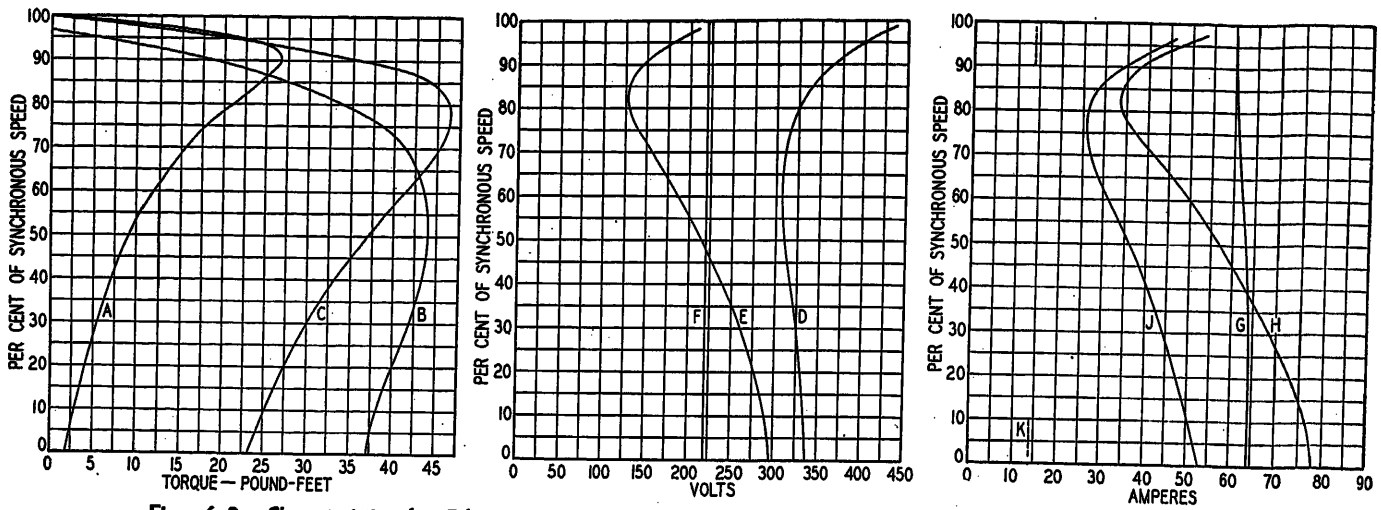



**Fig. 5. Starting torque-capacitance characteristic for 5-horsepower 3-phase motor starting on single-phase supply as capacitor motor**




**Figs. 6–8. Characteristics for 5-horsepower 3-phase motor operating on single-phase supply as capacitor motor**

*A*—Torque, single phase with 160-microfarad capacitor
*B*—Torque, single phase with 700-microfarad capacitor
*C*—Torque, 3 phase
*D*—Terminal voltage $V_{ab}$
*E*—Terminal voltage $B_{bc}$
*F*—Terminal voltage $V_{ca}$
*G*—Current $I_a$
*H*—Current $I_b$
*J*—Current $I_c$
*K*—Rated full-load 3-phase current

starting power factors less than 0.5, exact 3-phase conditions can be reproduced starting single-phase with a capacitor and a series resistor of proper size connected between the free terminal and one line. This resistor should have zero resistance if the 3-phase starting power factor is 0.5. Likewise it can be shown that for 3-phase starting power factors greater than 0.5, exact 3-phase conditions can be duplicated by placing an inductance of proper size between the terminal connected to the condenser (now without a series resistor) and the other line.

The relationship between starting torque and capacitance in microfarads for the 5-horsepower 3-phase 220-volt motor considered in appendix II of the paper is given in figure 5 of this discussion. The curve shows that the maximum starting torque is obtained with 700 microfarads capacitance; applying the expression $X_c = 1.5z$ gives 705 microfarads. The starting torque with 700 microfarads is 160 per cent of normal 3-phase starting torque; but the terminal voltages are 337, 296, and 220 volts, or 153, 135, and 100 per cent, respectively, of rated terminal voltage, and the coil currents are 78, 64, and 53 amperes, or 557, 457, and 379 per cent, respectively, of rated full load current.

Figure 6 is a comparison of the speed-torque curves when the motor operates 3 phase, single phase with the 160-microfarad capacitor, and single phase with the 700-microfarad capacitor. The relationships between the terminal voltages and the coil currents and per cent of synchronous speed are shown in figures 7 and 8 when the motor operates with the 700-microfarad capacitor. These curves show that when the motor operates with the 700-microfarad capacitor at 5 per cent slip it develops only 25.7 per cent of 3-phase torque at the corresponding slip, while the 160-microfarad capacitor it develops 108.5 per cent 3-phase torque. Figures 6 and 7 of the paper show that at this value of slip the currents and voltages are essentially normal whereas figure 7 of this discussion shows that the voltage $V_{ab}$ is 181 per cent of normal. The coil currents from figure 8 are seen to be 429, 339, and 307 per cent rated full load. It is also of interest to note from figure 6 that the no-load slip when operating with 700 microfarads is 3.5 per cent and that the above-named 3-phase torque is produced at a slip of 11 per cent.

In view of the foregoing discussion it would seem to be uneconomical to use a large capacitance, which would cause excessive coil currents to flow and which in itself would have to carry a large current as is shown in the preceding curves. In choosing the value of 160 microfarads to be used in the tests the writers were desirous of obtaining a value of capacitance which would give to the motor operating characteristics which were essentially normal. To obtain such characteristics it was obviously impossible to obtain a high starting torque. In practice, the motor would be started using that value of capacitance which would either give ample torque to start the load or most nearly duplicate 3-phase conditions and as the machine comes up to speed the capacitance would be reduced to a value which gives normal operation. The "best" value of capacitance to use in starting this motor would obviously not be that which produces the maximum starting torque as Professor Tracy indicates in his discussion, and that value would certainly not be used over the working range of the motor.

The expression $X_c = 1.5z$, which gives the value of capacitive reactance to produce maximum starting torque is noteworthy, as is likewise the expression which yields the per cent of 3-phase starting torque.

The writers are cognizant of the fact that the fundamentals are similar to those used by Dahl, Wagner, and Evans, and others. In considering the 3-phase motor operating single phase, Wagner, and Evans combine the sequence networks in an entirely different manner. The paper by Tracy and Wyss deals only with the inductive method of split-phase starting of 3-phase motors and considers neither the capacitor motor nor speed-torque curves, the accurate prediction of which the writers believe to be of paramount importance.

With reference to Trickey's question concerning operation with unequal windings we would refer to reference 3, "Analysis of Unsymmetrical Machines," by Lyon and Kingsley, AIEE TRANSACTIONS, volume 55, May 1936.

In the oral discussion the question of saturation was raised by Karapetoff. The writers believe that this question is adequately answered in the discussions of Corcoran and Trickey.

## Lightning Investigation on Transmission Lines—VI

**Discussion and authors' closure of a paper by W. W. Lewis and C. M. Foust published in the January 1937 issue, pages 101–6 and 189, and presented for oral discussion at the power transmission session of the winter convention, New York, N. Y., January 26, 1937.**

J. J. Smith (General Electric Company, Schenectady, N. Y.): During the last 10 years much work has been done on the problem of lightning interruption of electric-power service and now insulation and protection can be arranged in most cases to reduce tripouts to a very small number. While this progress is due to a number of circumstances it is nevertheless quite outstandingly evident from a survey of recent literature that an important factor has been the introduction of practical measuring instruments for direct connection to the transmission line. At the time the present investigation began there were available almost no direct measurement data which assisted toward an understanding of the problem.

Into this situation was introduced the Lichtenberg figure cameras such as the klydonograph, surge-voltage recorder, and lightning-stroke recorder. All these provided for the measurement of crest values of surge voltages and the determination of

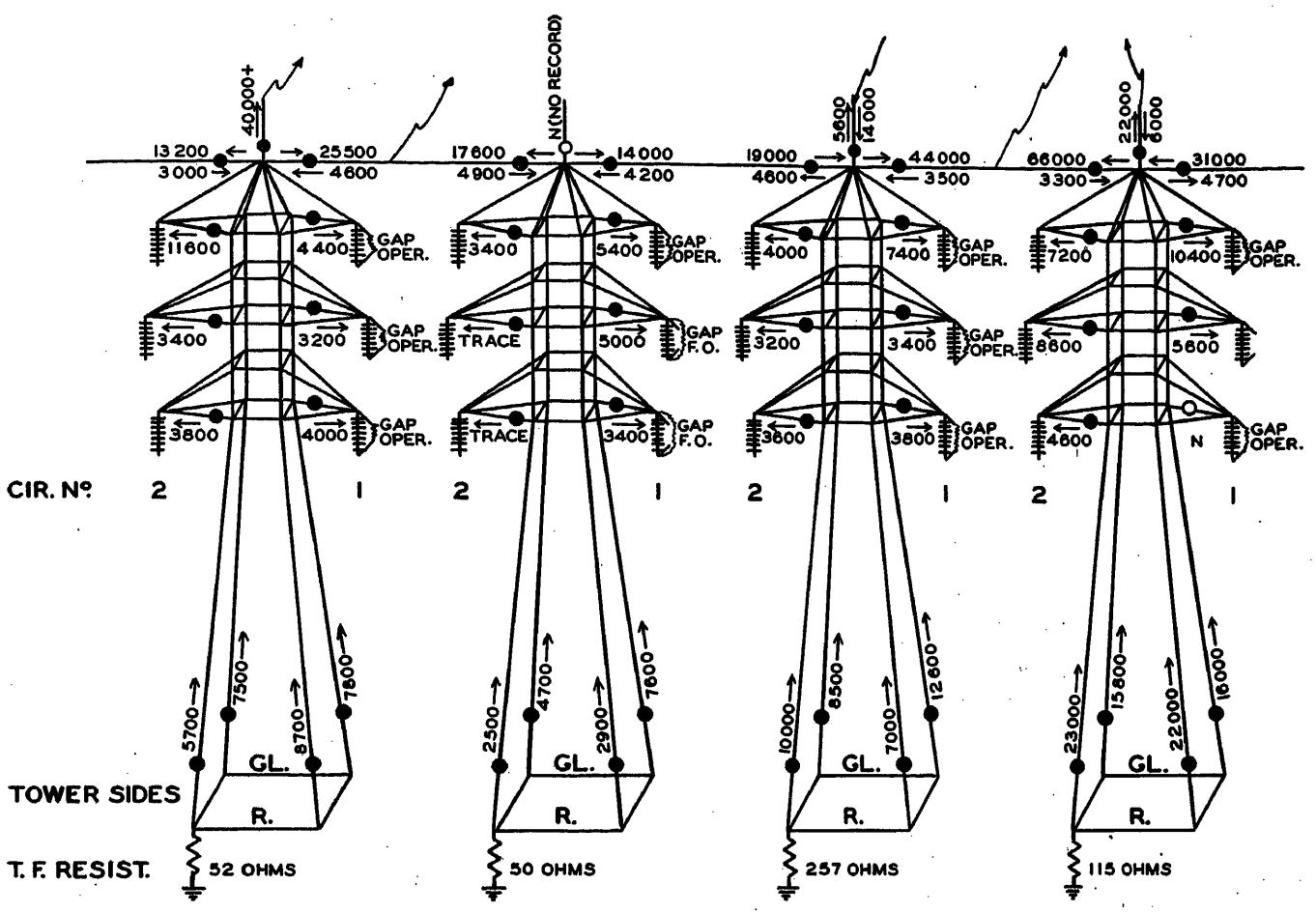



**Fig. 1. Lightning currents measured in towers of 132-kv Glenlyn-Roanoke line, May 4–15, 1936**

polarity. Conductor and structure potentials were then obtained by the hundreds. Lightning surges were followed along the conductor and attenuation directly measured. The Lichtenberg camera as a surge-voltage recorder therefore served to redirect the attack on the tripout problem, to take it away from the desk and laboratory and to concentrate effort on the task of requiring the lightning surge to locate and describe itself through the medium of such recorders.

The surge indicator or flashover indicator followed the surge recorder. This was a device which through the disruption of a small breakable powder link provided an indication of insulator assembly flashover until the patrolman observed it from the ground and reset it for the next flashover. Again many indicators, several thousand in fact, were used and hundreds of insulator flashovers and surges recorded.

The cathode-ray oscillograph was also applied to the measurement of lightning-surge wave shapes on line conductors. The elaborate equipment and somewhat complicated technique of operation required permitted the use of only a few oscillographs. Many valuable wave-shape records were obtained, however, among them one of conductor potential at a point within a few feet of a direct stroke.

All the instruments up to this time were used to obtain information concerning voltage conditions. The accumulating records, however, directed attention toward the necessity for lightning-current measurements and out of this need came the surge crest ammeter. Measurement stations again were established by the thousands. Entire lines were covered and many locations in the line structure such as tower legs, tower arms, overground wires, lightning rods, counterpoise and occasionally even the live conductor. Thousands of records were obtained and these when fitted in with the records from earlier instruments provided a greatly clarified picture of the lightning tripout problem. It is a thoroughly different picture from the previous desk-laboratory picture common at the beginning of the investigation, and this difference is mainly due to the devising of suitable recording and low cost, indicating and measuring devices through which the lightning surge has located and described itself automatically.

Table I of the paper gives an interesting comparison of the tripouts per 100 miles per year on different lines. Some of the differences are due to changed conditions on the same line over a period of years. However, for lines in different localities it is difficult to make a direct comparison since there must exist differences in the lightning conditions experienced. I wonder if the authors can suggest a way of taking these differences in lightning conditions into account.

On page 103 the authors show good correlation between the measurements when voltage exceeded flashover of the insulators and actual flashover. It is not quite clear, however, whether they have experienced flashover in cases where the measured voltage was well below that required. I should like to know their experience in this respect.

**Philip Sporn** (American Gas and Electric Company, New York, N. Y.): This paper is devoted in a large part to presentation and discussion of the field data obtained in the research and investigation that has been carried out over the past 4 or 5 years on the Glenlyn-Roanoke 132-kv line of the Appalachian Electric Power Company. However, the period covered by Lewis and Foust deals almost entirely with records obtained prior to 1936. Some of the most interesting data were not obtained until the year 1936, and in view of the fact that it was not found possible to present these data in summary form at this meeting of the Institute, owing to the shortness of time, it may be interesting to give some of the high lights of the 1936 investigation, and particularly those that bear directly on, and tie in with, the data presented by the authors of this paper.

In figure 2 is shown the magnitude and frequency of lightning stroke currents

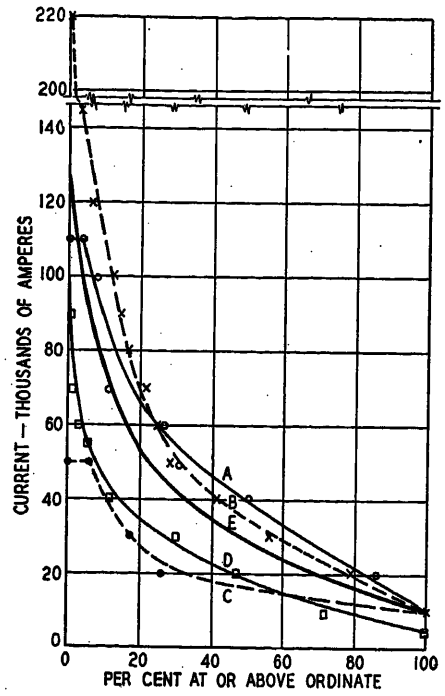



**Fig. 2. Magnitude and frequency of lightning stroke currents, 1933–36**

*A*—By ground-wire currents
*B*—Sum of adjacent tower currents
*C*—By tower-top lightning rods
*D*—Single tower currents
*E*—Average of A, B, and C

measured in the field by 3 different methods namely, currents in the ground wire, by addition of adjacent tower currents, and by direct measurement in tower-top lightning rods. While the current values recorded in this manner show some spread, the average of the 3 curves gives what is believed to be a fair representation of conditions which may be encountered in the field.

A considerable part of the investigation centered around the measurements of lightning currents in counterpoise wires. Figure 3 shows graphically the flow of current along the counterpoises, the counterpoise arrangement being shown in the upper right-hand corner.

The current in the long (150-foot) counterpoise is on the average 4 times the current in the short (40-foot) counterpoise, as measured at the point where connected to the tower. At the free, distant ends the currents are about equal in both. Uniform leakage of current from the long counterpoise is indicated by the averaged data. Clearly the long counterpoise is much more effective than the short one in draining current to ground. Other data, not presented here, indicates the short counterpoise behaving much like a plain ohmic resistance, while the long counterpoise displays an ability to carry current in excess of expectations on the basis of its d-c resistance alone.

An interesting relation between the current in the tower leg and connected counterpoise is shown in figure 4. It might be expected the current in any counterpoise would be less than the tower leg to which it is connected. However, it will be seen this was found to be true of the short counterpoise; but the reverse was true for the long counterpoise, where in some cases the long counterpose at the tower end carried some 30 per cent more than the tower leg. The reason for this has as yet not been fully explained.

Typical field records on which the correlation and interpretation of data were based are shown schematically in figure 1. One interesting feature of this record is the 66,000 amperes found in the ground wire associated with an apparent lightning stroke of 110,000 amperes to the line. Another feature is suggestive of a branched lightning stroke terminating at 2 adjacent towers and also midspan between them. These may, of course, be separate strokes during the same or different storms.

Still another feature of this one record is the high indicated tower potentials at the 4 adjacent towers, 2 of them being 9,800 kv and 8,830 kv, respectively, these being calculated on the basis of tower footing resistance and tower leg currents. Line flashover occurred at all 4 towers, as might be expected.

All this work is particularly interesting from the standpoint of showing what can be accomplished once measurements in terms of fundamental units, and particularly in terms of units of potential and current, are initiated. The great progress made in understanding the lightning phenomena is due in no small degree to the measurement of currents that have been made over the last 3 years under natural lightning conditions, and these in turn as this paper, and as I hope the brief discussion just given has brought out, have been directed more and more toward a detailed study of the various parts of the lightning circuit and an attempt to trace the lightning current from the time it discharges from the cloud until it definitely completes the circuit to ground, and all the current in the various parts of that circuit are accounted for.

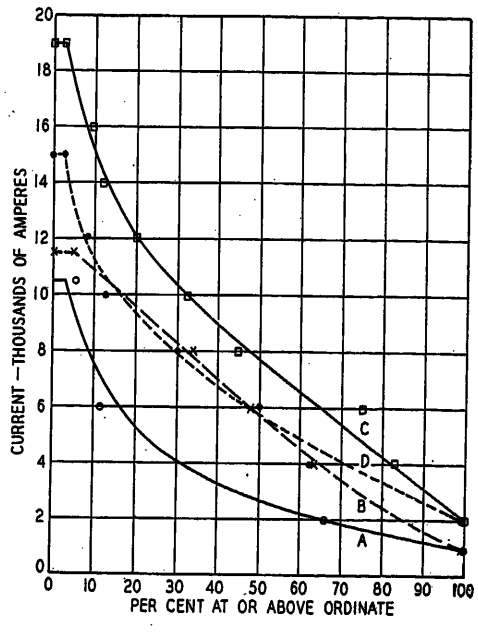



**Fig. 4. Relation between currents in tower leg and attached counterpoise on Glenlyn-Roanoke line, 1934–35–36**

*A*—Short counterpoise
*B*—Short-counterpoise tower leg
*C*—Long counterpoise
*D*—Long-counterpoise tower leg

A great deal more data along this line were obtained in last year's work on the Glenlyn-Roanoke line. A much more complete summary of some of this data, it is expected, will appear in an early issue of ELECTRICAL ENGINEERING.

L. V. Bewley (General Electric Company, Pittsfield, Mass.): In these papers there is the implication that the counterpoise "collects current" or "drains charge" throughout its length. Lewis and Foust, from measurements on 150-foot and 40-foot counterpoises arrive at a *uniform* collection per foot, but Bell shows records over several spans on continuous counterpoises of very irregular collection of current. The authors apparently do not regard the action as a simple traveling wave phenomenon, but rather as a *diffusion* of current up from the ground and along the counterpoise to the tower. That is, instead of a *negative* wave coming down the tower and moving out along the counterpoise, there is a veritable suction of *positive* charge up out of the earth which flows—but not as a wave—toward the tower and on up the lightning stroke to the cloud. Lewis and Foust speak of an essentially uniform potential along the counterpoise, and the natural inference is, then, that the counterpoise behaves merely as a concentrated resistance, presumably equal to its leakage resistance to earth. If

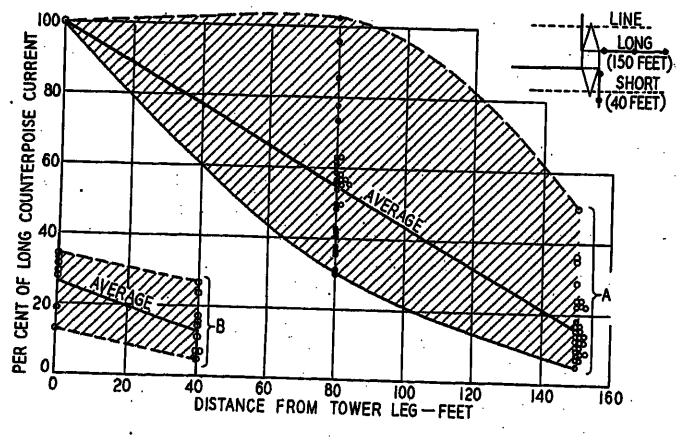



**Fig. 3. Attenuation of lightning currents in counterpoises on Glenlyn-Roanoke line, 1935–36**

*A*—Long counterpoise (30 records)
*B*—Short counterpoise (9 records)

this were so, it would make no difference whether a mile of wire were employed as one long counterpoise, or as many short ones in multiple. Moreover, a sufficiently low leakage resistance would be the only criterion for a counterpoise. For these reasons it seems to me somewhat dangerous to adopt such a point of view; at least until the traveling wave point of view has been found incapable of explaining the results. I therefore wish to demonstrate that the records obtained by the authors are in no wise contrary to ordinary theory and tests on the counterpoise.

It has been shown [1,2,3,4,5,6] both by theory and by field tests that the action of a counterpoise is essentially characterized by 3 effects:

1. The transient surge impedance starts at an initial value of 150 to 200 ohms and decays in a roughly exponential fashion to a final value equal to its leakage resistance.

2. The velocity of propagation is approximately 1/3 the velocity of light, and due to the heavy attenuation, a single reflection is sufficient to equalize a given length of counterpoise, so that a length $x$ is reduced from its initial surge impedance to its final leakage resistance in a time in microseconds equal to 6 times its length in thousands of feet.

3. The coupling with overhead conductors is of minor importance, amounting to less than 10 per cent for a parallel counterpoise.

Assume that a traveling wave $E$ comes down the lightning stroke of surge impedance $Z_0$ and strikes a tower having a counterpoise of transient impedance $Z(t)$. Then according to elementary theory, the voltage and current of the counterpoise are, respectively

$$e = \frac{2\,Z(t)}{Z(t) + Z_0} E$$

$$i = \frac{2}{Z(t) + Z_0} E$$

Obviously, the counterpoise voltage $e$, and therefore the tower top voltage, is a maximum in the neighborhood of the crest of $E$, but the counterpoise current $i$ does not reach its maximum until later. If $E$ were a moderately long wave, $i$ would not reach its maximum until $Z(t) = R$, where $R$ is the final, or leakage, resistance of the counterpoise. Now a surge crest ammeter merely measures the maximum current; and as is evident above, this maximum current *does not coincide with maximum voltage*, because the counterpoise impedance is changing. In other words, the leakage resistance of the counterpoise is not available at the instant of maximum voltage, and therefore the tower voltage will exceed the $RI$ of the counterpoise. The point is illustrated in figure 1, when a 10,000-kv lightning wave with a 1.5-microsecond front strikes a counterpoise. For simplicity the ground wires and tower footing resistance are neglected. The 500-foot counterpoise transient impedance falls from 200 ohms initially to 20 ohms finally in 6 x 500/1,000 = 3 microseconds. By the equations, the voltage is seen to reach a maximum of 2,600 kv at 1.0 microsecond while the current does not reach its maximum of 46,000 amperes until about 2.0 microseconds. If this maximum current were multiplied by the leakage resistance of the counterpoise the result of 920 kv would only be 1/3 the actual maximum voltage.

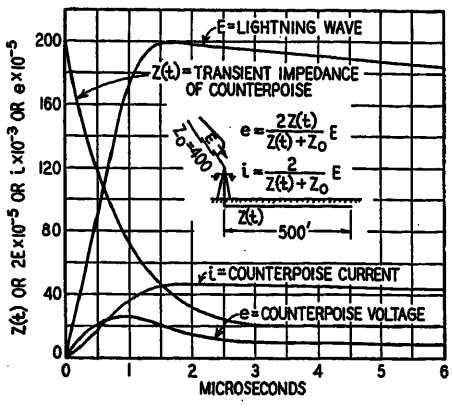



Fig. 5

This also explains why the $IR$ products are usually too small to account for the flashovers known to have occurred, especially in view of the fact that the voltage across the insulators is actually

$$V = (1 - \text{coupling factor})RI$$

and the coupling factor will be from 0.20 to 0.40.

Thus it appears that the observed results are in full accord with the ordinary traveling wave theory and tests of the counterpoise. Nor does the available surge crest ammeter data in itself offer any plausible reason for changing to a "diffusion" theory yielding a very much smaller voltage. It may be remarked, however, that the longer the wave front the more nearly do conditions approach the leakage resistance conditions of the counterpoise, but this is a natural result of wave theory and in no wise a substitution of mechanism.

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S. K. Waldorf (Pennsylvania Water and Power Company, Baltimore, Md.): Lewis and Foust present additional evidence that lightning difficulties can be practically eliminated by the use of overhead ground wires and counterpoise. The experience of the Pennsylvania Water and Power Company shows very markedly the efficacy of these lightning protective measures. The Safe Harbor - Westport - Takoma 230-kv. line passed through 1936 without a single outage, making the record of this line only one outage in 5 years. Also the Safe Harbor-Perryville 132-kv line has passed through its second year of operation without any outages occurring in its lifetime.

Of particular interest has been the experience with the Holtwood-York 69-kv line which is a double-circuit steel-tower line having 2 overhead ground wires and a double continuous counterpoise system. Formerly, this line had no overhead ground wires nor auxiliary grounding. Tower footing resistances ranged from 17 to 525 ohms, with an average of 133 ohms. Its operating record was particularly bad, having an average of 19.3 single- and double-circuit outages per year in the 6-year period, 1929–1934, inclusive. After the counterpoise was installed, the maximum tower-footing resistance became 20 ohms, with the average value at 9.2 ohms. In the 1 1/4 lightning seasons since the lightning protection has been added, there have been no outages. This record is worthy of special notice because it indicates that tower lines operating at as low as 69 kv in high-resistivity territory can be made to behave well with counterpoise and overhead ground wires.

P. L. Bellaschi (Westinghouse Electric & Manufacturing Company, Sharon, Pa.): These investigations clarify further the lightning behavior on transmission lines particularly the current distribution in the ground-wire network, the towers and the counterpoise. Perhaps there may be the impression that rather complete data are now available on the lightning protection problem. Practically speaking this viewpoint is correct in a good measure. That more need be known on the lightning

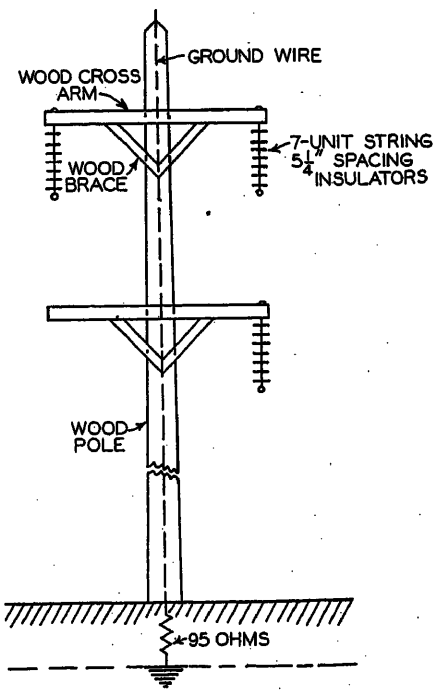



Fig. 6

phenomena even at this advanced stage need hardly be emphasized. I shall illustrate with an example which is rather typical of similar experiences encountered in the study of lightning.

Lightning struck the top end of a wood-pole ground wire (figure 1). Due to the high voltage resulting from the lightning current through the driven ground, flashover occurred from the ground wire to each of the 3 phase conductors. No indication of

flashover was observed at the adjacent poles.

Judging from the data on wood and insulators alone, the voltage time-lag curve for the combined insulation would be quite flat from the full wave (1.5x40 microsecond) down to a few microseconds and essentially the same for positive and negative polarities. Refinements are unnecessary for the purposes here. The estimated strength for the wood cross-arm and the insulator string (figure 1) is in the order of 1,400 kv. Though the resistance of the driven ground at the pole as measured by ordinary methods is 95 ohms, the effective surge resistance when a lightning current discharges through it would be some $^3/_4$ that amount (see for example discussion by Lewis and Foust, ELECTRICAL ENGINEERING, March 1936, page 279). The surge impedance of the 3 lines in parallel is approximately 200 ohms. The accuracy of all these figures are within practical tolerance—amply adequate for this example. The effective impedance from the wood pole-ground wire to zero-potential earth calculates in the order of 40 ohms. The coupling factor between the ground wire and the line conductors is rather small.

By token of the same methods as employed in the investigations here discussed and in other important work, the maximum current associated with the stroke in question is estimated to have been in the order of 50,000 amperes.

Consideration of all the available evidence reveal additional, pertinent information. The tip end of the wood pole ground wire which was struck by the lightning stroke was studied. This is a number 4 soft-drawn copper wire, i.e., 0.20-inch diameter. The tip end was fused and the molten metal flowed down the sides a length equal about the diameter. Evidence of overheating extended down a length of a few diameters. Tests were conducted in the laboratory on a similar conductor. Lightning currents from 50,000 to 100,000 amperes (approximately) and of a total duration of 100 microseconds were applied at an interval apart (2 minutes approximately) sufficient for the tip end of the conductor to cool down between applications. These tests indicate that $^1/_8$ inch of the tip down the side was raised near or to fusion temperature. Besides the oxydized surface extended downward some $^1/_2$ inch.

A close comparison of the field specimen and the samples tested in the laboratory lead to the following conclusions: (*a*) A repetitive stroke consisting of some 3 or 4 discharges apparently hit the conductor; (*b*) The maximum current in the discharges appears to have been in the order of 50,000 amperes.

The data pertaining to figure 4 in a paper by the writer (ELECTRICAL ENGINEERING, August 1935, page 839), similar information of the kind and the recent experiences abroad (Norinder in Sweden) further strengthen the conclusions above.

The case here described would appear to be similar to the 2 cases indicated as items 11 and 12 in table III of the paper by Lewis and Foust. Measurements with the crest ammeter would undoubtedly have contributed information on the crest value of the current but, as in the 2 cases in table III, no information on the "time factor"—an important element in lightning studies. It can be seen from this illustration and from similar cases that could be added that further methods of measurement and analysis than those employed in the investigations discussed are susceptible of giving additional, useful data on the lightning phenomena. This critique does not detract from the valuable contributions by Edgar Bell and Lewis and Foust.

**W. W. Lewis and C. M. Foust:** The authors wish to thank all those who have contributed discussions. J. J. Smith asks about the tie-in between lightning severity at particular locations and tripouts per 100 miles per year as given in table I of the paper. In course of this investigation, lightning-severity meters have been used at several locations over a period of a few years' time. The conclusion reached from their use was that severity does vary greatly at any particular location from year to year. It was not found possible to tie in the severity meter results closely with line performance, particularly because the latter depended so much on line construction. The most interesting scientific information on lightning frequency is obtained with the ceraunograph. These are electromagnetic instruments used by the weather bureau and through which the whole country is marked out in isoceraunographic lines of equal thunderstorm frequency. The transmission lines in table 1 extend over a territory from Albany, N. Y., to Washington, D. C., across New Jersey, eastern Pennsylvania, Maryland, and Virginia. The thunderstorm-frequency average ranged from no thunderstorm days in January to 150 to 200 thunderstorm days in July. The northern end of this territory has an average of about 45 storms per year and the southern end 55 from isoceraunograph records.

Smith also asks if flashovers have been experienced in cases where tower potential is well below that required. There are, according to the best analysis possible, several of such cases, but the preponderance of flashovers are co-ordinated with high tower potentials, and it is on this basis that the conclusions are drawn. It must be borne in mind at all times with regard to such data that correlation of flashover with a current record is never direct and positive unless by chance observation. Where automatic oscillographs are used to locate flashover, a strong evidence of tie-in is obtained, otherwise it is necessary to consider operator's reports, storm data, insulator inspections, tube performance, as well as current records in arriving at a correlation. It is to be expected that occasionally incomplete records do result in wrong correlation. However, these are infrequent, but may explain some of the few correlations of low tower potentials with flashovers.

In Philip Sporn's interesting discussion, attention is called to the case where the long counterpoise carried some 30 per cent more current than the tower leg to which it was attached. The explanation has been advanced that this is due to high currents in cross tower members, occasioned by the unsymmetrical counterpoise arrangement used.

Referring to L. V. Bewley's discussion, the term "diffusion" as a name for the lightning mechanism is inappropriate. We like to call it the Ohm's-law theory if a name is required. True, we do not regard the phenomena as a negative wave coming down the tower, nor do we regard it as a "veritable suction of positive charge up out of the earth." It is considered that, for the main stroke, current flows from the positive potential ground to the negative potential cloud. This conception is the common one of a current flowing from positive to negative. It is realistic to regard the counterpoise as practically at uniform potential in so far as flashover voltages are concerned. The counterpoise resistance to earth, however, is not a "concentrated resistance," but exactly the opposite, a distributed one and low because of it and that is just why it serves its purpose of holding down tower potential. Only by spreading out the conducting earth terminal by such wires at the tower footings is there deliberately achieved a decrease of tower-to-ground resistance. Comparing the extreme of a mile of single counterpoise to a number of short ones in multiple has no practical significance as the condition is not realistic. The sum total effect required is that of reducing the "across ground" voltage drop by reducing ground resistance which is highest immediately at the tower footings. Such a reduction in footing resistance shifts the ground potential up into the air arc.

Pertaining to Bewley's demonstration that records obtained are in no wise contrary to theory and tests on the counterpoise, it is regretted that the proof is not more convincing. Artificial lightning field tests are not particularly interesting in connection with such a proof. These are concerned with a quite different phenomenon from that of natural lightning. A 10,000-kv lightning wave with a 1.5-microsecond front striking a counterpoise is quite imaginary. The coupling factor of 0.2 or 0.4 may be correct or not, it should be measured and quite likely will in process of these investigations. The *IR* products of footing resistance and current are not usually too small to account for flashover, in fact the reverse is true, as we have pointed out, and these potentials are usually high enough to account for flashover.

Bewley's closing sentence is interesting and it is suggested that he consider carefully longer wave fronts, particularly those very slow in building up at the start, and then more rapidly as time increases.

Mr. Waldorf's discussion is valuable in that it calls attention to the usefulness of counterpoise and overhead ground wires as demonstrated by several cases of actual operational experience.

## Electrical Characteristics of Suspension-Insulator Units

**Discussion and authors' closure of a paper by C. L. Dawes and Reuben Reiter published in the January 1937 issue, pages 59–66, and presented for oral discussion at the power transmission session of the winter convention, New York, N. Y., January 26, 1937.**

**W. M. Goodhue** (Harvard University, Cambridge, Mass.): The curves obtained by the authors are remarkable in involving linear relationships, and particularly in

using *absolute* humidity instead of relative humidity as the variable. As is well known, the moisture content (including adsorption as in vegetable fibers, glass surfaces, etc.) of materials is not related to the absolute humidity, since materials tend to evaporate their moisture when the temperature is raised, just as water itself evaporates more at a higher temperature. Evidently some mechanism other than the moisture itself, but dependent on the moisture and *temperature*, is acting to counteract the effect of relative humidity.

The authors suggest that the island deposits are sputtering of the pin or cap metal in conjunction perhaps with chemical action. It would be important to know the effect of temperature on this action. A large increase of action with temperature increase would compensate the effect of temperature in reducing the relative humidity, when the absolute humidity is constant, and thus make absolute humidity the nearest significant variable, as it has been shown to be experimentally. A new avenue of experimentation would be to study corona sputtering itself, over a wide temperature range (say 20 degrees to 100 degrees centigrade), with temperature and absolute humidity as variables; something very practical may result from a *pure scientific investigation* of corona sputtering.

Time lag or hysteresis in corona measurements have doubtless been noticed in many types of apparatus. Some measurements that I made on *flat uniform dry air films* involved time lag. Evidently the authors have revealed new causes of hysteresis, so that in insulator work we have now a very large list: corona itself (electrical action), composition of the surrounding atmosphere (chemical change), *sputtering* (*islands*, surface action), heat (due to power loss), humidity (moisture acting merely as surface conductor), etc.

**M. G. Malti** (Cornell University, Ithaca, N. Y.): The results of this excellent paper recall to mind similar curves obtained on various insulating materials, as early as 1893, by Janet,[1] Potter,[2,3] Morris,[2,3] and others.[4-12] Many writers[13-18] have observed a hysteresis effect in the resistance of dielectrics with varying voltage gradient,[14,15] varying temperature,[13,18] varying mechanical pressure [15] and varying humidity.[17] The dielectric permittivity is also known to reveal a hysteresis effect with voltage gradient[19] and with temperature.[21,22] Finally the loss in dielectrics displays a hysteresis effect with temperature.[22,23] These are only a few of the many hysteresis effects that have been known to men interested in the study of dielectrics. The present paper adds the fact that porcelain and glass insulators display hysteresis effects in their loss, power factor, and capacitance when these are measured with varying voltage, varying mechanical pressure and varying degrees of humidity. These results are both interesting and significant. But I believe the authors could have laid more stress on the hysteresis and the hystero-viscosity phenomena in their interpretation.

It is impossible to interpret the hysteresis effects of figures 3 to 7 and 10 to 14 by the circuit figure 2 of the paper. This circuit owes its origin to Maxwell who used it as a model to interpret absorption and loss in

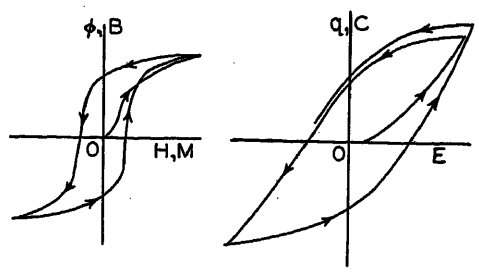



**Fig. 1a (left). Magnetic hysteresis**

**Fig. 1b (right). Dielectric hysteresis**

dielectrics. It served its purpose for a time. But very soon it became evident that dielecrics had properties which cannot be interpreted by such a simple model. This model has therefore been discarded and, to physicists, is now of historical interest only.

To interpret the results of this paper, as well as those of the researches mentioned in the bibliography, quantitatively would require an elaborate theory which we do not, at present, possess. A general qualitative interpretation, such as the authors have attempted, may be readily given on the assumption that dielectrics possess hysteresis just as magnetic materials do. In order to make this statement more real let us examine dielectric and magnetic hysteresis side by side to see the analogy.

In figure 1*a* is shown a magnetic hysteresis loop plotted with $B$ against $H$ which, by a change of scale, can be converted into $\phi = BA$ against $M = Hl$. Now, we engineers work directly with the $B$-$H$ curve. We never say that such a curve can be imitated by a model consisting of a series-parallel combination of pure inductances and pure resistances. The hysteresis loop is sufficient unto itself, is accepted as a physical fact and dealt with directly with no intermediate models to obscure the facts or becloud the issue.

Dielectrics display a similar behavior as shown by this paper and references 1–12. Indeed figure 1*b* is taken from reference 12 and represents the charge $Q$ plotted against the potential $E$. The hysteresis effect is unmistakable. Moreover, if we take the charge $Q$ figure 1*b*, as corresponding to the magnetic flux $\phi$ (figure 1*a*) and the voltage $E$ (figure 1*b*) as corresponding to the magnetomotive force $M$ (figure 1*a*), the analogy becomes irrefutible and complete.

Now the phenomena described by the authors in their figures 3 to 7 are purely dielectric hysteresis phenomena and show a part of the hysteresis loop figure 1*b*. Indeed the capacitance curves figure 3 and figure 6 of the paper can be easily shown to be simply hysteresis loops similar to figure 1*b* of this discussion by the following simple transformation:

We know that $q = ce$. Hence for any $e$, $q$ varies as $c$. Thus by merely changing the scale in figures 3 and 6 the curves $c$ versus $e$ may be changed to $q$ versus $e$, which are, respectively, the abscissa and ordinate of the curve figure 1*b*.

One more word about this research. The authors have an excellent experimental setup but they have introduced so many variables that their work has lost much of its fundamental importance. It is well known[24] that the following factors affect the capacitance, loss, and power factor of a dielectric: (*a*) voltage gradient; (*b*) shape of voltage wave; (*c*) time of application of voltage; (*d*) frequency; (*e*) temperature; (*f*) mechanical pressure; (*g*) humidity; (*h*) ionizing radiation; (*i*) shape of material; (*j*) shape of electrodes; (*k*) material of electrode; (*l*) electrode area; (*m*) thickness of dielectric; (*n*) physical condition of dielectric; (*o*) chemical composition of dielectric; (*p*) ionizing radiations.

Several of these factors entered simultaneously into the research under discussion and no attempt was made to eliminate all but one factor. For this reason the results cannot be generalized and must be restricted, in their application, only to the conditions under which they were taken.

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**Sidney Withington** (New York, New Haven, and Hartford Railroad, New Haven, Conn.): This paper has developed insulator characteristics of much interest, and the authors are to be complimented for their contribution to this very important subject. It is to be hoped they will continue their tests, and that their work will inspire others.

It is apparent, as the authors have stated, that in the case of the 2 insulators tested, each, it is understood, rated at 18,000 pounds a definite change of some kind occurs in the porcelain insulator at approximately 8,000 pounds and in the glass insulator at about 12,000 pounds. Any such change, while undoubtedly very small in extent and observable only in the laboratory, nevertheless may be of considerable interest and *may* indicate some slight damage to the porcelain or cement connection.

The loads at which this change occurs may be within the range of loads imposed under service conditions, especially in the case of the porcelain insulator, when this point occurs at less than half the designed M. and E. stress. Even if, as intimated by the authors, the change is due only to some readjustment of the pin, the cement and the compound used for sealing, nevertheless if this readjustment is recurrent each time the stress passes this point, there may ultimately be serious deterioration.

It would be of much interest I believe to continue these tests with other types of insulators to determine whether or not this is a general characteristic.

**J. J. Torok** (Corning Glass Works, Corning, N. Y.): This paper by Dawes and Reiter is quite interesting and timely. Some of the effects which they describe have previously been recognized and in some cases well understood. However, so sporadic was the work in this field that important secondary effects have been frequently overlooked.

The effects of the so-called island deposits can be often detected by radio interference measurements in the following manner:

The radio interference level of a clean insulator is first obtained. Then a voltage, slightly below flashover is applied for 5 minutes or more, after which the radio interference is again obtained. It will be found that the interference level after the application of voltage is somewhat higher than when the insulator was first tested. This rise in interference level is due to the deposit raising the surface conductivity around the pin and head of the insulator and reducing the gradient adjacent to the metal parts. The increase in surface conductivity seems to last for a considerable period of time.

Tests in which glass pin type insulators have been subjected to abnormally high voltages for periods of years show that the surface of the glass has not changed. This, of course, would be expected from the known chemical resistivity of glass. However, the tie wires and even the large conductor attached to the insulators were corroded. Apparently the acid depositing on the metal parts hastened the corrosion. This effect at first seemed quite rapid but after a period of several months when the protective coating was fully formed the rate of deterioration was considerably reduced. The lead head pins on which the insulators were mounted were likewise corroded. The conductors and pins on the no-static type of insulators that were included in these tests were practically free of corrosion, only the natural oxidation seemed to have taken place. The conducting layer in the pin hole and around the head eliminated the corona and prevented corroding acids from forming.

The study of electrical characteristics with varying loads, as the authors point out, shows only that relative movement between the hardware and porcelain or glass does take place.

One of the difficulties of measuring the loss in a sample dielectric is in obtaining an intimate bond between the electrodes and the dielectric. If the electrodes are not thoroughly bonded to the dielectric the resultant voids bring about losses and other inaccuracies of measurement. These factors in higher voltage measurements may even overshadow the losses in the dielectric. Therefore any slight movement of the cap or pin causing a change in the bond between the electrodes and the dielectric should be detected by power factor or capacitance measurements.

A study of the effects of mechanical loading on the electrical properties of glass has been made by Doctor Guyer and the results published in the *Journal* of the American Ceramic Society in 1933. In brief he found that mechanical stresses set up by shear, cantilever, or pure compression did not affect the electrical conductivity of glass. The variations in the properties of the insulator as shown in figure 13 are therefore undoubtedly caused by slight readjustment of the alloy both in the pin hole and in the cap.

**Philip Sporn** (American Gas and Electric Company, New York, N. Y.): The authors of this paper have done an excellent systematic and painstaking job in investigating the subject of insulator characteristics a hitherto altogether too neglected field. It is astonishing to find electrical characteristics of suspension insulators such as power factor, capacitance, watts loss, following a hitherto undiscovered trend detected here by the accurate measurements of small quantities under controlled laboratory conditions.

It is of course too soon to predict where this study of porcelain-insulator characteristics may lead us but the fact that the authors have developed and applied a technique for insulator testing ought, without doubt, to be of considerable benefit to the particular art and to the particular industry in general.

Specifically the application of this method of testing ought to be of great help in design testing of insulators, both present and new types, with a view of detecting those physical characteristics which are not obviously measurable but which do have an appreciable effect in determining insulator deterioration and insulator life. We, ourselves have carried out some work in this connection but the amount of further work to be done is astonishingly large and the handicap that we have been faced with heretofore owing to lack of proper instruments and technique ought to be at least partially removed by the application of some of the methods already disclosed by the authors and by a development and perfection of these methods. It is hoped that the authors themselves will continue their systematic research on insulator characteristics. I personally believe that the results so obtainable will be of considerable benefit to the electric power industry and to the electrical industry in general.

**C. L. Dawes and R. Reiter:** W. M. Goodhue states that it is remarkable that our power factor-absolute humidity characteristics are linear. We felt this same way when these characteristics were first obtained and in order to verify these relations we performed a considerable amount of experimental work over considerable periods of time and under wide ranges of atmospheric conditions. Moreover, data obtained by graduate students who conduct insulator tests as part of their laboratory work show this same linear relation, so that it seems to be an experimental fact. There has not, however, been opportunity to determine whether or not this relation is due to any fundamental law.

The material in this paper first appeared as part of a doctorate thesis, and specific humidity, rather than absolute humidity was used as the humidity parameter. The same linear relations of power-factor to humidity were obtained, however. The change to absolute humidity was made at the suggestion of the Institute Committee in order to conform to previous practice. Over the usual range of atmospheric conditions, the ratio of specific to absolute humidity is nearly constant, so that the character of the curves is not appreciably affected by the change. Goodhue states that evaporation from materials tends to increase with temperature just as water itself evaporates more at higher temperature, and the inference is that the insulator characteristics would seem to be functions of relative rather than absolute or specific humidity. This conclusion is logical and our initial reasoning was the same as his. Hence, as stated in the paper, every attempt was made to relate our chatacteristics to relative humidity, but we could find no definite relation. Fundamentally, with the insulator the phenomenon is one of adsorbed moisture. Surface adsorption of gases is often considered a physical effect and the gases adhere rather tenaciously to a surface. Possibly the relation of adsorbed moisture to temperature is quite different from that of water vapor intermingled with the atmosphere, which may be the explanation oft he fact that the characteristics are not directly related to relative humidity. There may be some temperature effect which is not yet known.

Goodhue feels that it would be important to know the effect of temperature on the sputtering action of corona on the metal wire and cap. This would, of course, be valuable as fundamental knowledge and might assist in the explanation of the humidity effects obtained. However, in our tests, although the temperature varied several degrees, the proportionate change in absolute humidity was very much greater than the proportionate change in temperature. Hence, the authors feel that the changes in humidity must have a much

greater effect on sputtering than does temperature.

The lag in corona measurements observed by Goodhue is undoubtedly due to the fact that corona formation is in part determined by the ionization conditions in the ambient air. It requires time for the number of free positive and negative ions in the ambient air to reach the steady-state value. The lag found by us is due primarily to the time required for the temperature of the surface to change and to the time required for the accumulation of surface deposit. In both cases lag is due to the fact that appreciable time is required for conditions to reach equilibrium. In his concluding comment, Goodhue summarizes quite completely the several factors contributing to the "hysteresis" effect.

In M. G. Malti's discussion, he has apparently confused the lag or hysteresis effect shown by us with the cyclic hysteresis occurring in magnetic and dielectric materials. Although both phenomena involve lag of the effect relative to the cause, the two are quite different phenomena. With magnetic and dielectric materials hysteresis involves molecular rearrangements and also storage of energy. The hysteresis observed by us is merely a lag of surface conditions with respect to the effects producing them, and no energy is stored at any part of the cycle. In fact, it is being dissipated continuously at each point on the hysteresis cycle. In the porcelain itself true dielectric hysteresis of course does occur, but this is a rapidly changing cyclic phenomenon, and except for the almost negligible energy loss, its effects do not appear in our steady-state measurements.

The circuit shown in figure 2*a* is not the usual Maxwell series-parallel combination of resistances and capacitances purporting to simulate the behavior of dielectrics when an electromotive force is impressed on them as stated by Malti. The circuit is an actual one consisting of true surface resistance in series combinations with the actual capacitances between the surfaces of the shell. Accordingly, the circuit is not a model and it can be replaced by the equivalent circuits of figures 2*b* and 2*c*, just as electrical networks can usually be replaced by more simple circuits.

The hysteresis effect shown in our capacitance characteristics as stated in the paper is due to the fact that changes in surface resistance vary the amount of effective shell capacitance in circuit between cap and pin. This does not involve the ratio of $q$ to $e$ in the same sense that it occurs during the cyclic changes in dielectrics.

In the last portion of his discussion, Malti enumerates the several factors which affect the results obtained by us and states that the work lacks fundamental importance. Most of the factors which he enumerates have been investigated in a fundamental manner and are represented by a large amount of published data, some of which are given in his bibliography. Yet so far as we know, up to now no one has been able to apply these data to a porcelain insulator to reach the conclusions given in the paper. It must be remembered that this is practically pioneer work in this particular field, and it is only due to these experiments with complete commercial insulators that we now know the several factors which affect the insulator characteristics. We have already been able to isolate some of the factors suggested by him and hope to publish these in a subsequent paper. We realize that these experiments have opened a wide field of research, as Malti's suggestions imply, and undoubtedly as time progresses, more will be known of the subject.

Sidney Withington refers to the effect of mechanical load on the electrical characteristics of the insulator. As he states, at certain loads there is a definite but small change in these characteristics. We agree with him that since these changes show some readjustment of pin and the cement they may be of some importance. In the time available we did not investigate this effect nearly as completely as we would have desired. He suggests that the effects of mechanical loading should be studied under recurring stress. We have done this to a limited extent, but the work should be carried much further to include several different designs of insulators and tests should be made under varying electrical stress and at different temperatures.

It is gratifying to learn from J. J. Torok that the results presented in the paper substantiate some of the effects noted in the past, such as radio interference. In fact, our discovery of the island deposits such as are shown in figure 8, and the statement that they cause radio interference, seem to be in accord with the measurements of radio interference, which he describes. His statement that the surface of glass does not change after being subjected to abnormally high voltages for periods of years we assume does not mean that the surface is immune from the surface deposits described in the paper. Although there was not opportunity to examine the surfaces of the glass insulator with the care devoted to the porcelain, the characteristic shown in figure 7 would indicate a pronounced surface deposit.

The information obtained by Doctor Guyer that the mechanical loading of glass does not affect its electrical characteristics shows that the changes in electrical characteristics shown in figure 13 must be due to readjustment of the alloy at the pin and cap.

It is also very gratifying to learn that Philip Sporn, who has had wide experience with insulators in service and under diverse operating conditions, feels that our work will be of considerable practical importance. We are continuing the work and hope that further developments in our technique will be of assistance in improving the design of insulators and in detecting faulty insulators.

## Lightning Protection for Transmission Lines

**Discussion of a paper by A. W. Gothberg and A. S. Brookes published in the January 1937 issue, pages 13–16, and presented for oral discussion at the power transmission session of the winter convention, New York, N. Y., January 26, 1937.**

L. V. Bewley (General Electric Company, Pittsfield, Mass.): The analysis given by the authors is based on a lightning stroke of constant magnitude (40,000 amperes) with a uniform rate of rise of 1,000 kv per microsecond. Figure 1 of this discussion shows the results of some calculations for the equivalent of 8 standard 10 x 5.75 suspension insulators based on assuming definite front lightning waves of 1-2-4 microseconds and the lightning expectancy curve given in "Flashovers on Transmission Lines," ELECTRICAL ENGINEERING, April 1936.

These curves take into account the tower-footing resistance, surge impedances of phase wires and lightning stroke (400 ohms), coupling factor, time lag of insulator flashover, and a "crest factor" depending upon the length of spans, lightning wave front, and successive reflections.

The left-hand curves give the percentage flashovers for a stroke to a protected pole, the middle column for strokes to an unprotected pole midway between protected poles, and the right-hand curves the consolidated results. The following conclusions may be drawn:

1. The longer the lightning wave front the fewer the flashovers, a 1-microsecond front causing

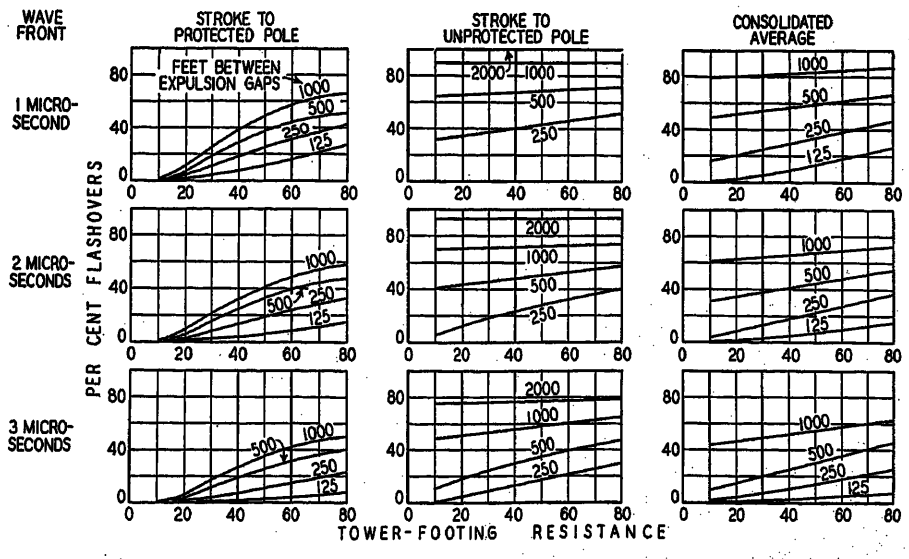



**Fig. 1. Per cent flashovers for stroke to protected and unprotected poles with expulsion gaps on top phase only and with ideal shielding, 125-foot spans and 10- by 5.75-inch insulator units**

perhaps twice as many flashovers as a 4-microsecond front.

2. The lower the tower-footing resistance the fewer the flashovers. But the curves are rather flat and the benefits of low footing resistance are by no means as good as in conventional ground wire practice. The reason is that resistance plays a minor rôle for a stroke at or near a pole not equipped with an expulsion gap, and as the number of unprotected poles between gaps increase, the bulk of flashovers become more independent of resistance. A stroke to an unprotected pole corresponds to a midspan stroke to a ground wire, with the essential difference that midspan flashover requires a very high voltage, whereas flashover of the insulation at the pole is comparatively small. The curves show that a reduction of resistance is about equally beneficial, regardless of wave front.

3. The percentage flashovers increase as the distances between gaps become greater, thus confirming the contention that the gaps should be installed at short intervals to realize their full advantages. Thus for a 2-microsecond wave front and footing resistances of 40 ohms the flashovers are:

| Distance Between Gaps | 125 | 250 | 500 | 1,000 |
|---|---|---|---|---|
| Per Cent Flashovers | 4 | 18 | 42 | 67 |

## Lightning Investigation on a 220-Kv System—II

**Discussion and author's closure of a paper by Edgar Bell published in the December 1936 issue, pages 1306–13, and presented for oral discussion at the power transmission session of the winter convention, New York, N. Y., January 26, 1937.**

**L. V. Bewley:** See discussion, page 626.

**P. L. Bellaschi:** See discussion, page 627.

**S. K. Waldorf** (Pennsylvania Water and Power Company, Baltimore, Md.): The surge current measurements on counterpoise conductors reported by Bell are of great value and more of them are needed, because they give an indication of the answer to one of the open questions in the design of lightning protection for transmission lines. This question is the proper length for counterpoise conductors. Bell has shown that currents flow along the counterpoise toward the point of stroke contact from as far away as $1^1/_2$ miles. This is a remarkable condition with tower footing resistances being as reported between 1 and 2 ohms. It would seem that such low footing resistances would permit neutralization of charge in the vicinity of a tower without charge flowing along the counterpoise for long distances. If such were the case, counterpoise conductors would not need to be so long.

The records presented in figure 2 of the paper must have been caused by a stroke having a relatively slow rate of voltage rise. Several microseconds must have been required for charge to travel more than a mile to the struck tower. The current law of Kirchhoff was followed at junctions of counterpoise and towers, a point not at first clear, as surges travel with different velocities on unburied and buried conductors. Maxima of surges on overhead ground wires and buried counterpoise under these conditions would not occur simultaneously at junctions, and the crest surge currents recorded would not obey Kirchhoff's current law. Apparently this effect did not enter into the measurements reported, indicating slow rates of current change.

The matter would be clarified to some extent if Bell would give details of the measurement of tower footing resistances on the line, such as amount of counterpoise and overhead ground wire included in the protective system during measurement and the reference used for the measurement. On this depends the conclusion which can be drawn whether the behavior noted is common to all types of counterpoise installation or only to counterpoises installed in soil of high resistivity.

**Edgar Bell:** Surge-crest ammeter records are not precision measurements and only tell the maximum or crest value of current without any indication of the time at which this maximum occurred, nor any direct indication of the current wave shape. Present technique allows any measurement to have an uncertain error; and the degree of accuracy of any single measurement is unknown. In general, however, surge-crest ammeter measurements appear to be consistent and reliable, but they have their limitations. Consequently, although the fact that the crest magnitudes of currents at various junction points in the overhead ground wire-tower structure-ground network apparently obey Kirchhoff's law, the accuracy of measurement does not permit us to say that reflections did not occur, but merely that such reflections were not particularly large.

Measurements of tower footing resistance were made during 1929 on the 14-tower section of line now equipped with continuous counterpoise. These were made under 4 conditions, namely:

1. Before installation of counterpoise, and with overhead ground wires disconnected from the tower under test.

2. Same as (1) but with overhead ground wires in place.

3. After installation of counterpoise and with overhead ground wires disconnected from the tower under test.

4. Same as (3) but with overhead ground wires in place.

Summarized results were as follows:

| Method | Maximum Ohms | Minimum Ohms | Average Ohms |
|---|---|---|---|
| 1 | 150 | 50 | 93 |
| 2 | 3.0 | 2.1 | 2.5 |
| 3 | 1.6 | 1.0 | 1.4 |
| 4 | 0.8 | 0.8 | 0.8 |

These resistance measurements were made with a megger ground tester. Measurements made in 1926 using a Kolrausch bridge and before overhead ground wires were installed gave approximately the same results as method 1.

The 1935 and 1936 counterpoise-current measurements show that currents flow for long distances, (except for extremely small lightning discharges) and indicate that lightning surges have relatively slow rates of voltage rise. The numerous records obtained some years ago from lightning stroke recorders also suggest that lightning strokes themselves do not have as rapid wave fronts as formerly assumed. Consequently the megger resistance measurements, except for the fact that they were made at low voltage and small current, more nearly approximate the resistances existing under lightning conditions than if lightning surges were of steep wave front.

## First Report of Power System Stability

**Discussion and closure of a report of the AIEE subcommittee on interconnection and stability factors published in the February 1937 issue, and presented for oral discussion at the power transmission session of the winter convention, New York, N. Y., January 26, 1937.**

**A. C. Monteith** (Westinghouse Electric & Manufacturing Company, East Pittsburgh, Pa.): The committee should be congratulated on the completeness of this first report on a very broad and involved system problem.

The vital facts are presented for a large number of systems already in operation. The introduction of the a-c calculating table has given a tool that simplifies the solution of involved systems being planned. Its use has allowed a very accurate treatment of the interconnection and stability problem




**Fig. 1**

(a)—Zero ohms tower-footing resistance
(b)—3 ohms tower-footing resistance

with considerable saving in time and also the elimination of the human factor from a large part of the solution. The attached figure not only illustrates the results obtained from the a-c calculating board on a particular 6-machine problem but further shows the effect of considering 3 ohms tower-footing resistance in the zero-sequence circuit for a fault just outside station 1. This is a very nominal amount of resistance and its consideration in this case saved going to higher speed breakers or the use of higher speed relaying.

In another study the system was stable when 5-cycle breakers and carrier-current relaying was used assuming no tower-footing resistance. The system was in a high-resistance area and no ground wires were contemplated. The consideration of 10 ohms tower-footing resistance allowed the use of standard 8-cycle breakers and impedance-type relays resulting in a large saving in the equipment. The value of resistance selected and when it can be used

will depend on the particular system under consideration.

The effect of tower-footing resistance is emphasized in this discussion to point out that the proper consideration of ground resistance sometimes permits the use of less expensive equipment. It is possible also that data of this character might have been collected from the operating companies and included in table III.

**E. F. Scattergood** (Bureau of Power and Light, City of Los Angeles, Calif.): This report has been of particular interest to me because the field covered and the results presented so closely parallel the similar work done with respect to the design of the Boulder Dam transmission system of the City of Los Angeles.

In connection with the study of system stability, a point that should receive special consideration in the future is the effect of the characteristics of system load. A considerable part of the load on a metropolitan system is not pure resistance or pure impedance but consists of induction motors. Under the lower voltages existing during the recovery period after the fault, such motors tend to draw increased currents, a condition unfavorable to system stability.

To account for this effect on our system in an approximate way that was reasonably easy to apply, the system load was assumed to be 40 per cent motor load; and the load conductance representing this portion of the total load was assumed to vary inversely as the square of the voltage at the load during the recovery period.

Power limits found by this method are about 15 per cent lower than if the usual assumption of fixed impedance load is made.

Also in connection with table III of the paper, I should like to made certain corrections with respect to item I, the Boulder Dam-Los Angeles line: Line *A*-4 should read 265,000 kw.

This corresponds to the minimum head rating of the 4 turbines. The value of 240,000 kv which you used is the operating capacity representing load delivered at the receiving end. This is taken as 0.8 of the theoretical stability limit determined as outlined in greater detail in my paper given in your bibliographical reference 158.

In line *C*-2, the short circuit ratio should have been given as 2.74 at 60 cycles.

In line *F*-5, in designating use of lightning arresters, it should have read: at terminal stations, yes; at switching stations, no.

**C. W. Franklin** (Consolidated Edison Company of New York, N. Y., Inc.): In discussing methods of increasing the stability of metropolitan power systems, the "Report of Power System Stability," includes the system arrangement known as "synchronized at the load." Since this arrangement was placed in operation in the New York area in 1929, it is felt that a review of operating experiences in this area and the modifications resulting from those experiences should be helpful to those contemplating such an arrangement.

In the original concept of a system of this type, each generator was connected to a group of feeders and thence to the load. The only paralleling connections between generators were to be at the load, which in the ultimate, would be the low-voltage network mains, and during the transition period would also be through the low-voltage busses at substations. Service continuity was assured by the segregation of sources and the connections to a given network were deversified between as many bus sections as were available in a generating station and where economically feasible, also by feeder connections to 2 stations. Circuit breaker duty was greatly reduced due to the high impedance of the connections between generators. Economical loading of generators was accomplished partly by rearrangement of station switching and in part by unbalancing feeder loads. Stability both steady state and transient was assured by calculation, test, and subsequent experience.

In attempting to operate generators and stations at their economic loadings, some unbalancing and thereby overloading of network transformers resulted, and difficulty was experienced due to premature operation of network protectors at light loads. Late in 1930, while transferring load from Hudson Avenue to Hell Gate, the substation connections opened and the accompanying unbalance on network transformers and mains in one of the districts resulted in some equipment damage.

As a result of these experiences, it was decided that there should be no load transfer through the high-impedance connections. Stations and sections within the stations were to be operated substantially in phase and economy transfer was obtained by switching within the stations and between stations, by direct tie feeders with load control devices.

The maximum size of network which could be re-energized after shutdown had long been a matter of concern and study and the system was therefore divided into a number of separate low voltage networks, several of which were supplied from 2 stations. The difficulty of co-ordination between different stations during system trouble led to the conclusion that quicker restoration would be effected after an interruption if each network is under the control of one operator and thereby supplied from one station.

As a result of these experiences we have adopted the following as our fundamental plan of system development. Generating stations will be interconnected by a system of direct tie feeders and the distribution load will be segregated into blocks which are small by comparison with the capacity of the interconnected stations.

1. The a-c network will continue to be divided into network areas, each area being completely segregated from all other network areas. The load in each area should be small enough, so that the area can be re-energized by the station which serves as its base supply. Stations will be properly subdivided to meet the following requirements.

2. Network feeders should carry load in only one network area and should not be bifurcated with feeders to other areas.

3. The supply to each network area should be distributed between 2 or more major bus sections and further distributed among 4 or more subsections, and network capacity provided so that each network area fed from the station may be carried in emergency with one major section out of service. If the station has 3 or more major sections, it should be possible to re-energize a dead network area with one major section out of service. Each major bus section or subsection should have complete automatic protection.

4. Each network area should be supplied from a single station except during periods of initial development when the station has insufficient facilities to meet the above requirements. When it is necessary to feed an area from 2 or more stations, the supply should be such that one of the stations can pick up and carry the area in emergency without the other stations. This requires that the base station should have connected to it at least ½ of the feeder and distribution transformer capacity to the area.

5. Ties between stations should be adequate to pick up and carry the load of certain predetermined network areas fed from a station temporarily out of service due to mechanical trouble. These ties will generally be of capacity required for normal operating purposes such as economy of operation and pooling of reserve capacity.

A network system of this type has the following merits:

1. It is simpler to operate under normal conditions than any other type of system.

2. It requires a minimum of voltage and phase-angle control devices.

3. It minimizes the amount of operating co-ordination required for the restoration of service in the event of interruption and correspondingly simplifies the operating rules covering the re-energizing procedure.

4. In the event of the loss of communication or failure of the interconnections between stations, it enables each station to operate as an independent unit which in most cases will be able to supply all the load to the network areas which it serves.

5. It offers great flexibility in planning the expansion of the system.

To satisfy the above principles a station must be electrically segregated so as to substantially provide the equivalent of three or more stations at one location. This requires segregation of the switch and bus galleries by fire walls, so that fire will be confined to a small section of the station. In addition to automatic bus protection, any connections between major sections should be indirect physically and should have sufficient sets of automatic protection in the link to preclude the spread of electrical trouble. It is also desirable, if practical to sectionalize or make provision for quick sectionalization in case of failure on a steam or water main.

The work necessary at Hudson Avenue to satisfy these principles is practically complete and the new Waterside 60-cycle installation is being made in accordance with the fundamental plan. Plans for the revamping of Hell Gate are complete whereas plans for the rebuilding of the Sherman Creek galleries are being formulated. Further sectionalization of the network proceeds whenever the load in an area exceeds the permissible limit.

**R. D. Evans:** Franklin's discussion of the system arrangement known as "synchronised at the load" is of considerable interest. While the report referred to this method principally for the purpose of illustrating a principle applying to system arrangements, it is pertinent to include an authoritative statement covering the recent developments in connection with this scheme.

Monteith's discussion has emphasized the importance of the a-c calculating board in the solution of system stability problems. He has also called attention to the part which fault and tower-footing resistances plays in the stability studies. It may be pointed out that while fault resistance is usually a beneficial factor, it is possible for the fault path to be of very high resistance

and to accentuate the problem. It is suggested that in the preparation of future subcommittee reports consideration be given to the inclusion of data on faults and tower-footing resistance as part of the tabulations along the line suggested.

The method of representing the load at the receiving end of a transmission system has a considerable effect on the stability limits as pointed out by Scattergood. The particular method of approximation which he described is of considerable interest.

Scattergood's discussion has called attention to certain corrections to be made in table III of the report. In the same table on pages 278–9 Sels has called attention to the fact that the tabulation should show high tension bussing arrangements at both the sending and receiving ends of all eight lines listed under the Philadelphia Electric Company, Pennsylvania Power and Light Company, and Public Service Electric and Gas Company. If any other errors exist in the table it is quite desirable that attention should be called to them by subsequent written discussions.

# Capacitor Motors With Windings Not in Quadrature

**Discussion and authors' closure of a paper by A. F. Puchstein and T. C. Lloyd published in the November 1935 issue, pages 1235–9, and presented for oral discussion at the induction machinery session of the winter convention, New York, N. Y., January 27, 1936.**

**C. G. Veinott** (Westinghouse Electric & Manufacturing Company, Springfield, Mass.): This paper is an interesting extension of Morrill's paper on the revolving field theory of the capacitor motor. In Morrill's paper, the 2 stator windings are assumed to be displaced by 90 electrical degrees in space; therefore, the voltage induced in one stator winding, by a revolving field set up by the other stator winding, is displaced 90 degrees in time from the voltage induced by its own rotating field. (This displacement may be either forward or backward, as the case may be.) This phase displacement of 90 degrees is taken care of in Morrill's paper by the use of the familiar $j$ operator; it is $+j$ or $-j$; depending upon whether the displacement is forward or backward. The operator $j$ always revolves a vector 90 degrees.

Puchstein and Lloyd use a more generalized operator, namely, a vector operator expressed in exponential form,

$$\epsilon^{j\alpha} \text{ or } \epsilon^{-j\alpha}$$

where $\alpha$ = any angle, expressed in radians.

This vector operator rotates a vector, either forward or backward by the angle $\alpha$. The authors study the case of the capacitor motor where the windings are displaced by an angle, say $\alpha$, and the more generalized operator just given is used to take care of the angular time phase displacement of $\alpha$, occurring between the voltage induced in a winding by its own field and the voltage induced by the field of the other winding. The 2 generalized vector operators above, of course, have to be reduced to the slightly more familiar forms

$$\epsilon^{j\alpha} = \cos\alpha + j\sin\alpha$$

$$\epsilon^{-j\alpha} = \cos\alpha - j\sin\alpha$$

before they become usable in practical equations.

The new idea of this paper is the introduction of this general vector operator into Morrill's equations, which are then reworked, just as Morrill originally worked them; but with the different operator. This idea is the principal contribution of the paper. The authors are to be highly commended, however, for their working out quantitatively of a practical example showing the effect of using winding displaced by angle other than 90 degrees by comparing the performance with a conventional 90 degrees motor. Would that more AIEE authors followed this example!

The use of vector operators other than $j$ is not new.

Fortescue uses a 120 degree operator or

$$\pm a = -\frac{1}{2} \pm j\frac{\sqrt{3}}{2}$$

in his classic paper on symmetrical co-ordinates.

Capacitor motors with windings not 90 degrees apart are of little commercial importance. The analysis of this paper is applicable to shaded-pole induction motors with distributed windings, a type which is of some commercial importance. The methods of this paper might also be used to analyze the performance of a 3-phase delta-connected induction motor with one open primary phase. This latter case could likewise be studied by Fortescue's methods.

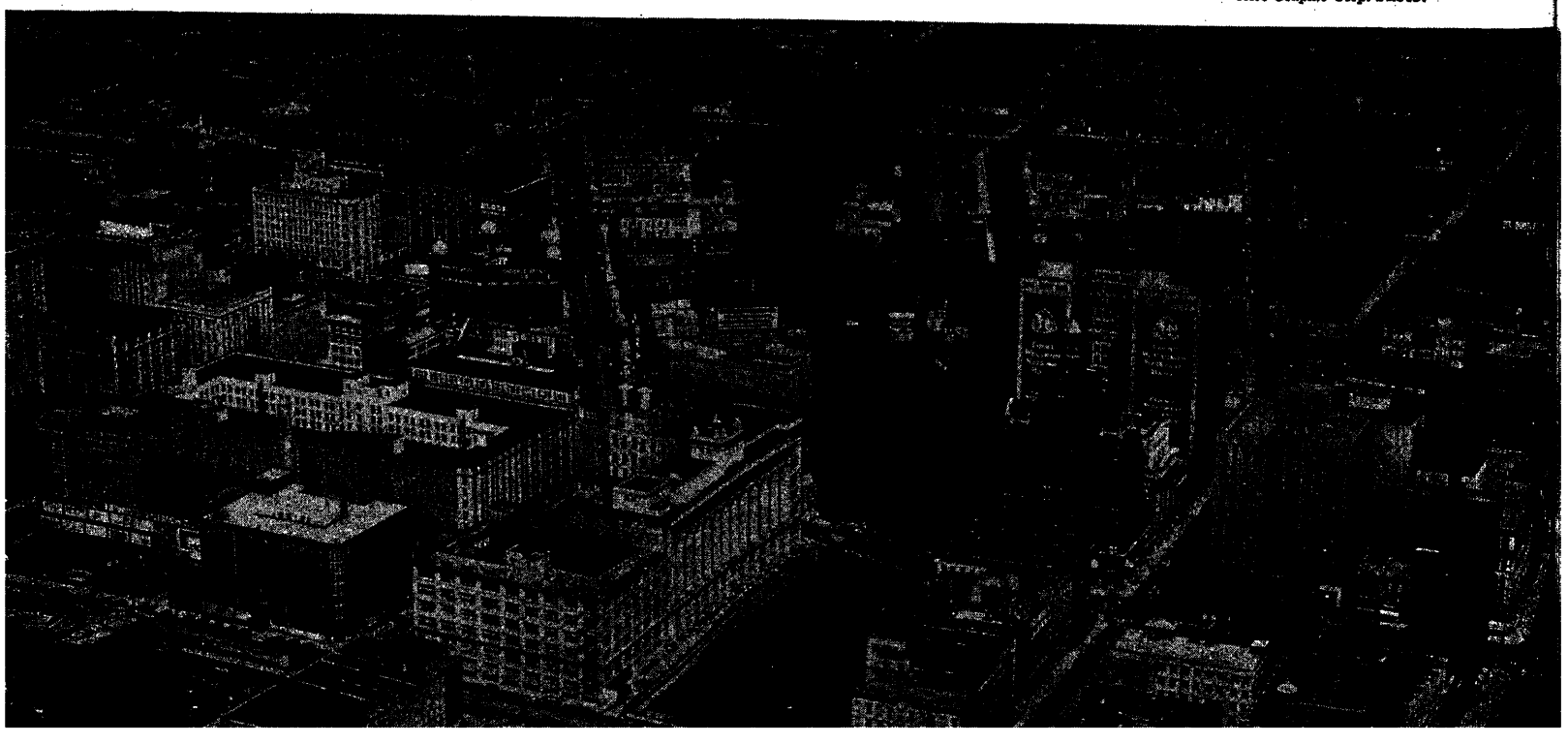
**A. F. Puchstein and T. C. Lloyd:** We agree in general with the points expressed by Veinott.

He states, however, that $\epsilon^{\pm j\alpha}$ must be put into the form $\cos\alpha \pm j\sin\alpha$ before it becomes usable in practical equations. This of course (although a minor point) depends upon whether the calculation is carried on in rectangular or polar co-ordinates, since $\epsilon^{\pm j\alpha}$ is always equivalent to $1\angle \pm\alpha$.

Material for this paper aside from the reasons given therein, arose from the attempt to obtain torque equations which would be applicable to motors of various types in which the number of slots would not divide properly for 90 degrees displacement of windings. Replacement of the $j$ operator by its more generalized form was not so obviously simple as it appears when dealing with such torque equations. The final value was obtained as the result of an integration covering 24 letter-size pages, although Lyon and Kingsley, by the aid of symmetrical co-ordinates, have given what appears to be a shorter process.

**A portion of the business district of Milwaukee, Wis., scene of the Institute's forthcoming summer convention**

Aero-Graphic Corp. Photo.



# News
## Of Institute and Related Activities

# Institute's 1937 Summer Convention Offers Unusual Vacation Opportunities

THE Institute's annual summer convention, which will be held in Milwaukee, Wis., June 21–25, 1937, with headquarters in the Schroeder Hotel, offers many unique features. Milwaukee, situated on the shore of Lake Michigan, and the State of Wisconsin, with its numerous inland lakes, possess an unusual appeal for all lovers of sports and nature to combine business with vacation. The schedule of events includes the annual business meeting, 10 technical sessions, and 1 general session which is designed to interest a great many members and which is not concurrent with any of the other sessions. The afternoons will be devoted principally to committee meetings, conference sessions, sports, and inspection trips to plants of internationally known manufacturers. Evenings will be devoted to social functions and entertainment.

### Vacation Opportunities

Members of the Institute are urged to consider the opportunities afforded for combining their vacations with the summer convention. Regardless of the kind of of vacation desired—whether it be the social gayety of a smart hotel, the peaceful comfort of a small resort, the rugged sport of a fishing lodge, the restful seclusion of a private cottage, or the good fellowship of tourist camps—all are available near Milwaukee. To the fisherman, Wisconsin offers 7,000 inland lakes and 10,000 miles of trout streams all well-stocked. To lovers of nature there is an abundance of wild life. The northern forests in many places are untouched by man; deer frequently are seen right from the highways. Wisconsin has 160,000 acres in 19 scenic state parks and forests at various points in the state, each possessing its own peculiar and impressive characteristics. To lovers of sports there is almost everything that could be sought, including bathing and swimming in inland lakes or Lake Michigan and Lake Superior, motor boating, sailing, canoeing, golfing and tennis. Members desiring additional information regarding Wisconsin as a vacation land may write to the chairman of publicity, summer convention committee: W. E. Gundlach, 231 West Michigan Street, Milwaukee, or to the Wisconsin Conservation Commission, State Capitol, Madison.

### Friendliness and Hospitality Will Pervade the Inspection Trips

According to the committee, a feature of the inspection trips is that they will be not only interesting and valuable from a technical standpoint, but also outstanding in their personal or social aspects. A spirit of friendliness and hospitality will be exhibited along with production processes, new equipment, and new products: (See special message from summer convention committee elsewhere in this issue.) At least 3

## Schedule of Events

**Monday, June 21**

9:00 a.m.—Registration

10:00 a.m.—Opening Session—Crystal Ball Room

Annual Business Meeting

Annual report of board of directors, in abstract, by H. H. Henline, national secretary

Report of committee of tellers on election of officers

Introduction of and response from president-elect

Presentation of prizes for papers

Presentation of Lamme Medal to Doctor Frank Conrad

President's address by A. M. MacCutcheon

12:45 p.m.—Inspection trip with luncheon at Harnischfeger Corporation, after which the group will divide for a lecture on prefabricated houses or inspection of the National Avenue plant

1:45 p.m.—Inspection trip to Cutler-Hammer, Inc.

2:00 p.m.—Conference of Officers, Delegates, and Members (*a*) Section delegates (*b*) Student Branch counselors

2:30 p.m.—Inspection trip to A. O. Smith Corporation

Evening —Stag Smoker

**Tuesday, June 22**

10:00 a.m.—Power Transmission

General Power Applications

Instruments and Measurements

Education

1:30 p.m.—Inspection trip to Schlitz Brewery—refreshments

2:00 p.m.—Conference of Officers, Delegates, and Members (continued)

Evening —Lecture by Doctor Vannevar Bush

**Wednesday, June 23**

10:00 a.m.—General Session

12:30 p.m.—Inspection trip to Allis-Chalmers Manufacturing Company—luncheon

2:30 p.m.—Conference on Electrical Apparatus for 3-Phase Arc Furnace

Evening —Boat trip on Lake Michigan—dancing, cards, and buffet service on steamer

**Thursday, June 24**

10:00 a.m.—Lightning Protective Equipment and Insulation Co-ordination

Power Generation and Electrical Machinery

Illumination

12:30 p.m.—Directors' luncheon meeting

Afternoon—Inspection trips to:

1. Port Washington Power Plant
2. A. O. Smith Corporation
3. Cutler-Hammer, Inc.

2:30 p.m.—Conference on Field Problems

Evening —President's Reception—dinner and dancing

**Friday, June 25**

10:00 a.m.—Lightning Protective Equipment and Insulation Co-ordination

Vibration and Balance

Communication and Research

Afternoon—Inspection trips to:

1. Globe-Union Manufacturing Company.
2. Allen-Bradley Company
3. A. O. Smith Corporation (if shut down on previous days)

Evening —Farewell gathering at Blue Mound Country Club



Looking north along Lake Michigan and Lincoln Memorial Drive in Milwaukee

of the principal industries already have indicated a desire to provide luncheon for their visitors.

Trips already have been arranged to plants of the following companies: Allis-Chalmers Manufacturing Company, leading manufacturers of all types of heavy electrical equipment, including generators, motors, rectifiers, transformers, and switchgear, and also steam and hydraulic turbines, and tractors; A. O. Smith Corporation, makers of automobile frames, steel pipe, and pressure vessels; Cutler-Hammer, Inc., producers of electrical control and switching equipment; Harnischfeger Corporation, manufacturers of electric cranes and hoisting equipment, electric welders, and more recently a prefabricated steel home of new design; the Port Washington Power Plant of The Milwaukee Electric Railway and Light Company; and the Schlitz Brewing Company.

### Milwaukee's Lake Shore and Harbor Facilities Add Interest

Attendants at the convention will have an opportunity to enjoy the natural scenery and recreational facilities along the beautiful shores of Lake Michigan. Lincoln Memorial Drive leads from downtown Milwaukee north along the lake shore for a distance of 5 miles to Lake Park. It affords a view of the harbor entrance, the Coast Guard station, Milwaukee Yacht Club, fine swimming beaches, Milwaukee Gun Club, and the beautiful treed ravines of Lake Park.

At the north end of the Drive is Milwaukee's new $5,000,000 water purification plant which is rapidly nearing completion. The plant is on 24 acres of made land on the shore of Lake Michigan. It will have a rated capacity of 200,000,000 gallons daily and uses what is known as the rapid sand or mechanical type of filtration. All pumping is by electric drive using a total of 4,000 installed horsepower.

Milwaukee has long been known as one of the important harbor cities of the Great Lakes, receiving and shipping a wide variety of commodities in both foreign and domestic commerce. It is a principal grain shipping port and the foremost coal receiving port on Lake Michigan. More than 4,000 vessels arrive at and clear this port annually. The tonnage in and out over a period of years averages in excess of 7,500,000 net tons annually.

### Future AIEE Meetings

**Summer Convention**
Milwaukee, Wis., June 21–25, 1937

**Pacific Coast Convention**
Spokane, Wash., Aug. 30–Sept. 3, 1937

**Middle Eastern District Meeting**
Akron, Ohio, Oct. 13–15, 1937

**Winter Convention**
New York, N. Y., January 24–28, 1938

**North Eastern District Meeting**
Pittsfield, Mass., Spring 1938

### Post-Convention Trip to the Dells

Many people attending the convention will not want to miss the opportunity of seeing the dells of the Wisconsin River. For this reason special arrangements are being made for a chartered-motor-bus trip to this and other scenic and historical spots on Saturday, June 26, the day following the close of the convention. The trip will include a visit to the dells in the morning, a chicken dinner at Kilbourn, a visit to Devil's Lake and the University of Wisconsin campus in the afternoon and evening dinner at the Hotel Lorraine at Madison, returning to Milwaukee after dinner. The expense of the trip will be very reasonable.

### Technical Sessions

Ten technical sessions have been tentatively scheduled to provide a program of broad scope and current interest. Two sessions will be held on the subject of lightning protective equipment and insulation co-ordination. These sessions are sponsored jointly by the committees on protective devices, power transmission and distribution, and electrical machinery. The subject of insulation co-ordination was first introduced about 1928 and since has been discussed frequently by both operating companies and representatives of electrical manufacturers. Two of the papers report the latest information on the subject as developed by joint committees of the Edison Electric Institute and the National Electrical Manufacturers Association. Two others consist of reports by the lightning arrester subcommittee of the committee on protective devices and the transformer subcommittee of the committee on electrical machinery. The remaining papers are by operating-company engineers.

The subjects for other sessions are as follows: power transmission, general power applications (control), education, power generation and electrical machinery, illumination, vibration and balance, communication and research and instruments and measurements. Those interested in the technique of measurement should find the sessions on insulation co-ordination and vibration and balance also to be of interest. Several papers in the various sessions treat subjects of general interest, such as police radio, industrial economics and business methods, and industrial lighting.

### General Session

Wednesday morning, June 23, has been set aside exclusively for a general session to be held in 2 parts. The first part will consist of an address by Ralph E. Flanders "The Engineer in a Changing World." The second part will consist of discussions by various members of the Institute on the topic: "How Can the Institute Programs Be Made of Greatest Value to the Membership?" (See special announcement elsewhere in this issue.)



A sample of the scenery in the "The Dells" of the Wisconsin River near Kilbourn. A special post-convention trip to this attraction is being arranged

### Rules on Presenting and Discussing Papers

At some of the technical sessions, a few papers may be presented only by title. This will permit the devotion of more time to discussion. At other sessions, papers

# Tentative Technical Program

## Tuesday, June 22

### 10:00 a.m.—Power Transmission

POWER SYSTEM FAULTS TO GROUND—PART I: CHARACTERISTICS, C. L. Gilkeson, Edison Electric Institute, and P. A. Jeanne and J. C. Davenport, Bell Telephone Laboratories, Inc.
April issue, pages 421–8

POWER SYSTEM FAULTS TO GROUND—PART II: FAULT RESISTANCE, C. L. Gilkeson, Edison Electric Institute, and P. A. Jeanne and E. F. Vaage, Bell Telephone Laboratories, Inc.
April issue, pages 428–40

SYSTEM RECOVERY VOLTAGE DETERMINATION BY ANALYTICAL AND A-C. CALCULATING BOARD METHODS, R. D. Evans and A. C. Monteith, Westinghouse Electric & Manufacturing Company.
Scheduled for June issue

NEW OIL-FILLED CABLE LINES IN CHICAGO, Herman Halperin, Commonwealth Edison Company, and G. B. Shanklin, General Electric Company. Scheduled for June issue

### 10:00 a.m.—General Power Applications

A-C MOTOR PROTECTION, C. W. Kuhn, Cutler-Hammer, Inc. May issue, pages 589–93

IMPULSE OPERATION OF MAGNETIC CONTACTORS, Carroll Stansbury, Cutler-Hammer, Inc.
May issue, pages 583–8

COINCIDENTAL ELECTRIC DRIVES, L. E. Miller, Reliance Electric & Engineering Company.
May issue, pages 578–82

### 10:00 a.m.—Instruments and Measurements

A NEW MAGNETIC FLUX METER, G. S. Smith, University of Washington. April issue, pages 441–5

SIXTY-CYCLE CALIBRATION OF THE 50-CENTIMETER UNGROUNDED SPHERE GAP, C. S. Sprague and G. Gold, Purdue University. May issue, pages 594–6

A NEW PHOTOELECTRIC HYSTERESIOGRAPH, R. F. Edgar, General Electric Company.
Scheduled for June issue

A NEW HIGH-SPEED CATHODE-RAY OSCILLOGRAPH, H. P. Kuehni and Simon Ramo, General Electric Company. Scheduled for June issue

### 10:00 a.m.—Education

A SUGGESTED COURSE ON INDUSTRIAL ECONOMICS AND BUSINESS METHODS, R. E. Hellmund, Westinghouse Electric & Manufacturing Company.
April issue, pages 446–54

CURRENT LOCI IN THE GENERAL LINEAR A-C NETWORK, L. A. Hazeltine, Stevens Institute of Technology. March issue, pages 325–30

PER UNIT QUANTITIES, Irven A. Travis, University of Pennsylvania.

FUNDAMENTAL CONCEPTS OF SYNCHRONOUS MACHINE REACTANCES, B. R. Prentice, General Electric Company.

## Wednesday, June 23

### 10:00 a.m.—General Session

1. Address: THE ENGINEER IN A CHANGING WORLD, Ralph E. Flanders, chairman, engineering economics committee, American Engineering Council; President, Jones and Lamson Machine Company, and past-president, ASME.

Intermission

2. Discussion by members of the Institute on HOW CAN THE INSTITUTE PROGRAMS BE MADE OF GREATEST VALUE TO THE MEMBERSHIP?

**In this program, reference to the issue and, in so far as possible, to the page in ELECTRICAL ENGINEERING, is given for all papers.**

### 2:30 p.m.—Conference on Electrical Apparatus for 3-Phase Arc Furnaces

## Thursday, June 24

### 10:00 a.m.—Lightning Protective Equipment

FLASHOVER CHARACTERISTICS OF ROD GAPS AND INSULATORS, subcommittee on correlation of laboratory data of Joint NEMA-EEI Committee on Insulation Co-ordination.
Scheduled for June issue

EXPULSION PROTECTIVE GAPS, W. J. Rudge and E. J. Wade, General Electric Company.
May issue, pages 551–7

DISTRIBUTION LIGHTNING ARRESTER PERFORMANCE DATA, lightning arrester subcommittee of the committee on protective devices.
May issue, pages 576–7

SURGE PROTECTION OF DISTRIBUTION SYSTEMS, J. K. Hodnette and L. R. Ludwig, Westinghouse Electric & Manufacturing Company.

### 10:00 a.m.—Power Generation and Electrical Machinery

SWITCHBOARDS FOR BOULDER POWER PLANT, L. N. McClellan, U. S. Bureau of Reclamation, A. J. A. Peterson, Westinghouse Electric & Manufacturing Company, and C. P. Garman, Bureau of Power and Light, City of Los Angeles.
February issue, pages 224–36

END-CONNECTION REACTANCE OF ELECTRICAL MACHINERY, J. F. H. Douglas, Marquette University. February issue, pages 257–9

END-WINDING LEAKAGE INDUCTANCE OF A SYNCHRONOUS MACHINE, B. H. Caldwell, Jr., General Electric Company. April issue, pages 455–61

CHARACTERISTIC CONSTANTS OF SINGLE-PHASE INDUCTION MOTORS—PART I: AIR-GAP REACTANCES, W. J. Morrill, General Electric Company.
March issue, pages 333–8

## Notice of Annual Meeting

The annual meeting of the American Institute of Electrical Engineers will be held at the Hotel Schroeder, Milwaukee, Wis., at 10 a.m. on Monday, June 21, 1937. This will constitute one session of the annual summer convention which is to be held this year in Milwaukee, Wis.

At this meeting, the annual report of the board of directors, and the reports of the committee of tellers on the ballots cast for the election of officers will be presented.

Such other business, if any, as properly may come before the annual business meeting may be considered.

(Signed) H. H. HENLINE
*National Secretary*

### 10:00 a.m.—Illumination

A NEW APPROACH TO THE INDUSTRIAL LIGHTING PROBLEM; SPECIFIC LIGHTING FOR DIFFERENT SERVICES, H. B. Dates, Case School of Applied Science. May issue, pages 545–50

Address: WHAT A UNIVERSITY HAS DONE TOWARD PROTECTING THE EYESIGHT OF ITS STUDENTS, F. A. Kartak, Marquette University.

FURTHER CHARACTERISTICS OF THE CARBON ARC, W. C. Kalb, National Carbon Company, Inc.
March issue, pages 319–24

Demonstration Address: NEW LIGHT SOURCES, THEIR CHARACTERISTICS AND APPLICATIONS, D. W. Atwater, Westinghouse Lamp Company.

### 2:30 p.m.—Conference on Field Problems

## Friday, June 25

### 10:00 a.m.—Insulation Co-ordination

BASIC IMPULSE INSULATION LEVELS, EEI-NEMA Joint Committee on System Insulation Co-ordination. Scheduled for June issue

INSULATION STRENGTH OF TRANSFORMERS, transformer subcommittee of the committee on electrical machinery. Scheduled for June issue

APPLICATION OF ARRESTERS AND THE SELECTION OF INSULATION LEVELS, J. H. Foote and J. R. North, The Commonwealth & Southern Corporation.
Scheduled for June issue

INSULATION CO-ORDINATION, Philip Sporn and I. W. Gross, American Gas & Electric Company.
Scheduled for June issue

APPLICATION OF SPILL GAPS AND SELECTION OF INSULATION LEVELS, H. L. Melvin and R. E. Pierce, Ebasco Services Incorporated.
Scheduled for June issue

### 10:00 a.m.—Vibration and Balance

DYNAMIC BALANCING OF SMALL GYROSCOPE ROTORS, O. E. Esval and C. A. Frische, Sperry Gyroscope Company, Inc.
Scheduled for June issue

VIBRATION MEASURING INSTRUMENTS: FUNDAMENTAL CONSIDERATIONS IN THEIR DESIGN, C. D. Greentree, General Electric Company.
Scheduled for June issue

THE VIBRATION ISOLATION OF MACHINERY, L. H. Hansel, The Felters Company, Inc.
Scheduled for June issue

PRELIMINARY REPORT ON A PROPOSED TEST CODE FOR APPARATUS NOISE MEASUREMENT, subcommittee on sound of standards committee.

### 10:00 a.m.—Communication and Research

POLICE RADIO COMMUNICATION, E. L. White, Federal Communications Commission, and E. C. Denstaedt, Police Department, Detroit.
May issue, pages 532–44

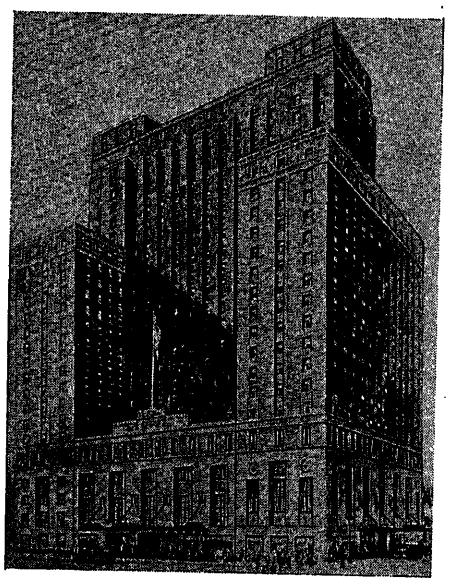
OXIDATION IN INSULATING OIL, J. B. Whitehead, The Johns Hopkins University, and F. E. Mauritz.
April issue, pages 465–74

PROPERTIES OF SATURANTS FOR PAPER-INSULATED CABLES, G. M. L. Sommerman, American Steel & Wire Company. May issue, pages 566–76

THE DIELECTRIC STRENGTH OF NONINFLAMMABLE SYNTHETIC INSULATING LIQUIDS, P. M. Clark, General Electric Company.
Scheduled for June issue

will be presented in abstract, 10 minutes being allowed for each paper unless otherwise arranged, or the presiding officer meets with the authors preceding the session to arrange the order of presentation and allotment of time for papers and discussion. Authors will be notified officially in each case about one month in advance.

Any member is free to discuss any paper when the meeting is thrown open for general discussion. Usually 5 minutes is allowed to each discusser for the discussion of a single paper or of several papers on the same general subject. When a member signifies his desire to discuss several papers not dealing with the same general subject, he may be permitted a somewhat longer time.



**Hotel Schroeder, Milwaukee, headquarters for the summer convention**

It is preferable that a member who wishes to discuss a paper give his name in advance to the presiding officer of the session at which the paper is to be presented. Each discusser is to step to the front of the room and announce, so that all may hear, his name and professional affiliations. Three typewritten copies of discussion prepared in advance should be left with the presiding officer.

Other discussion to be considered for publication must be submitted, typed double spaced, in triplicate to C. S. Rich, secretary, technical program committee, AIEE headquarters, 33 West 39th St., New York, N. Y., on or before July 9, 1937. Discussion received after this date will not be accepted.

**Principal Hotels in Milwaukee, and Rates**

| Hotel | Single Room | Double Room |
|---|---|---|
| Schroeder | $3.00–4.00 | $6.00–20.00 |
| Wisconsin | 3.00–5.00 | 5.00–10.00 |
| Plankinton | 2.50–4.50 | 4.00–15.00 |
| New Pfister | 2.50–3.00 | 4.00–15.00 |
| Astor | 3.50–5.00 | 4.00– 6.00 |
| Ambassador | 3.00–4.00 | 5.00– 6.00 |
| New Randolph | 2.50–3.50 | 3.50– 6.00 |
| Knickerbocker | 3.00 | 5.00– 6.00 |
| Martin | 2.25–5.00 | |
| Juneau | 2.00–3.00 | 3.00– 5.00 |
| Medford | 1.75–3.00 | 2.75– 5.00 |
| Republican | 1.50–2.50 | 2.50– 4.00 |
| Miller | 1.50–3.00 | 3.00– 5.00 |

## To Summer Conventioners

GEMUTLICHKEIT is the only word to express adequately the spirit which will pervade the coming summer convention in Milwaukee. The entertainments, the hospitality extended to inspection-trip guests, and the sportsmanship displayed on links and courts, will all bear the stamp of *gemutlichkeit.*

One dictionary translation of this word is "quality of good nature," but experts in philology say that no English word, or combination of words, conveys its precise meaning. It is representative of a state of mind which must be lived and felt to be understood; that is, whatever it stands for must be "experienced" to be fully comprehended.

In Milwaukee a committee consisting of more than 60 able and alert men and women is so planning the convention that no one will leave without knowing the meaning of the word "gemutlichkeit." Never again will they have to look in the dictionary or inquire about this word whose meaning is so finely shaded and elusive that it can hardly be expressed with any degree of exactitude in any other language.

However, there are some ways in which you, our guests, can materially assist the committee to accomplish the task to which it has set itself, and I am sure we shall have your hearty cooperation.

(1) The committee will greatly appreciate it if you will make a serious effort to be present at the opening session of the convention. The tenor of a convention is often determined by the spirit which prevails at the first session. If this meeting is well attended and enthusiastically supported, the convention is sure to be a success. Furthermore, this session is the occasion of several impressive ceremonies, such as presentation of prizes and medals.

Above all, the members should keep in mind that the president delivers his annual message to the Institute at the opening session. Always of interest and importance to Institute members, the president's address has special significance when stirring times issue a challenge to professional organizations to take an active part in shaping the destinies of our civilization. No one attending the convention should miss the president's address.

(2) Some of the industries to which inspection trips will be made are planning to serve luncheons to their guests, and it will help them greatly to know as early as possible how many to prepare for. Therefore, register as early as you can for the inspection trips you intend to take.

(3) Elsewhere in this issue is published a list of the principal hotels in Milwaukee. All these hotels are within a 12- to 15-minute ride from convention headquarters (Schroeder). Because of these excellent facilities to please visitors with regard to housing, Milwaukee is a very popular convention city; and in order to avoid last minute congestion, choose your hotel and send in your reservation early. In case you have any difficulty, get in touch with the housing committee and efforts will be made to get you placed to your satisfaction. But do it early.

K. L. Hansen

General Chairman
Summer Convention Committee

### Women's Entertainment

In addition to the regular entertainment the women's entertainment committee is arranging an attractive program for the visiting ladies, which will be announced later.

### Sports

The annual tournaments for both the Mershon golf and tennis trophies will be held as usual, as well as the competition for the Lee golf trophy. The details of the sports program will be announced in a subsequent issue as soon as they have been made available by the sports committee.

### Advance Registration

Members who will attend the convention are urged to register in advance by promptly returning the addressed advance-registration card which they will receive by mail. This will be helpful to the committees and permit badges to be made ready in advance, thus avoiding congestion at the registration desk.

A minimum registration fee of $2 will be charged all nonmembers, except Enrolled Students and the immediate families of members.

### Hotel Reservations

All members planning to attend the convention should make their own hotel reservations, and the committee urges that this be done well in advance. A list of the principal hotels in Milwaukee and their rates for

single and double rooms are given in an accompanying tabulation. All are within a 12- to 15-minute ride from convention headquarters (Schroeder). Any one having difficulty in obtaining rooms should contact the housing committee.

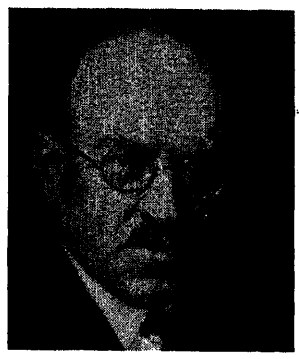
COMMITTEE

The personnel of the 1937 summer convention committee is as follows: Otto H. Falk, *honorary chairman;* K. L. Hansen, *chairman;* L. H. Hill, *vice-chairman;* C. H. Krueger, *secretary;* W. E. Crawford, *treasurer;* R. R. Benedict, A. G. Dewars, C. F. Harding, H. S. Osborne, G. G. Post, J. A. Potts, D. L. Smith, and W. H. Timbie. Subcommittee chairmen: J. F. H. Douglas, technical program; E. W. Seeger, finance; L. W. Copeland, entertainment; C. D. Brown, transportation; W. O. Helwig, registration and housing; W. E. Gundlach, publicity; G. F. Crowell, sports; S. H. Mortensen, inspection trips; and Mrs. A. C. Flory, women's entertainment.

## Session on Economics and Institute Activities

A special "general" session on the economic aspects of engineering and Institute activities has been scheduled for Wednesday morning, June 23, during the Institute's 1937 summer convention. The session, which will not be paralleled by any other, has been arranged by the newly appointed special committee on Institute activities, of which H. S. Osborne is chairman. The session will be divided into 2 parts, consisting of: (1) an address "The Engineer in a Changing World," by Doctor Ralph E. Flanders, president of the Jones and Lamson Machine Company, Springfield, Vt.; and (2) a discussion of the topic "How Can Institute Programs Be Made of Greatest Value to the Membership?" by various members of the Institute.

Doctor Flanders has devoted a large amount of time to engineering society activities, having served as president of the American Society of Mechanical Engineers and as member or chairman of many ASME committees. He is a vice-president of American Engineering Council and chairman of its committee on the relation of



Ralph E. Flanders

consumption, production, and distribution; since 1932 he has been active in the public works program of Council. During 1936 he was chairman of Council's committee on engineering economics, and has been a director of the Social Science Research Council. He has written numerous technical papers and 2 books.

Doctor Flanders was born September 28, 1880, at Barnet, Vt., and started his technical career as an apprentice machinist in 1897. In 1903 he became a designer for the International Paper Box Machinery Company, Nashua, N. H., which position he held until 1905, when he became associate editor of *Machinery*, with offices at New York, N. Y. He held that position for 5 years before joining the engineering staff of the Fellows Gear Shaper Company. Springfield, Vt., in 1910. In 1912 Doctor Flanders became director and manager of the Jones and Lamson Machine Company, and has been president of that company since 1933. He has received several honorary degrees.

At the conclusion of Doctor Flanders' address, the meeting will be opened for any questions that those present may wish to ask concerning the subject. Then, after a brief intermission, the second part of the session will begin with brief discussions of various phases of Institute activities by several prominent Institute members, leading up to a general discussion from the floor.

## Membership—

Mr. Institute Member:

The Institute has done much to improve the status of electrical engineering as a profession but much remains to be done. Increased membership will materially aid achievement of one of the aims of the Institute—public recognition of our profession.

Too many of us regard our membership in the Institute as a matter of paying dues. We should attend meetings frequently and take an active part in the affairs of our local Section. We cannot arouse interest in nonmember electrical engineers unless we display interest ourselves.

Let's all take a nonmember guest to our next Section meeting and show him the advantages of membership in the Institute.

E. T. Gunther

Vice-Chairman, District No. 7
National Membership Committee

## AIEE Executive Committee Meets

A meeting of the executive committee of the American Institute of Electrical Engineers was held at Institute headquarters, New York, N. Y., on March 25, 1937, in place of the regular meeting of the board of directors.

Present: President A. M. MacCutcheon (chairman), F. M. Farmer, W. H. Harrison, Everett S. Lee, and W. I. Slichter, members of the committee; Vice-President A. C. Stevens, and National Secretary H. H. Henline. By standing vote, resolutions were adopted in memory of Junior Past-President E. B. Meyer, who died on January 30, and Past-President and Honorary Member Elihu Thomson, deceased, March 13. (The resolutions were published in the April issue of ELECTRICAL ENGINEERING.)

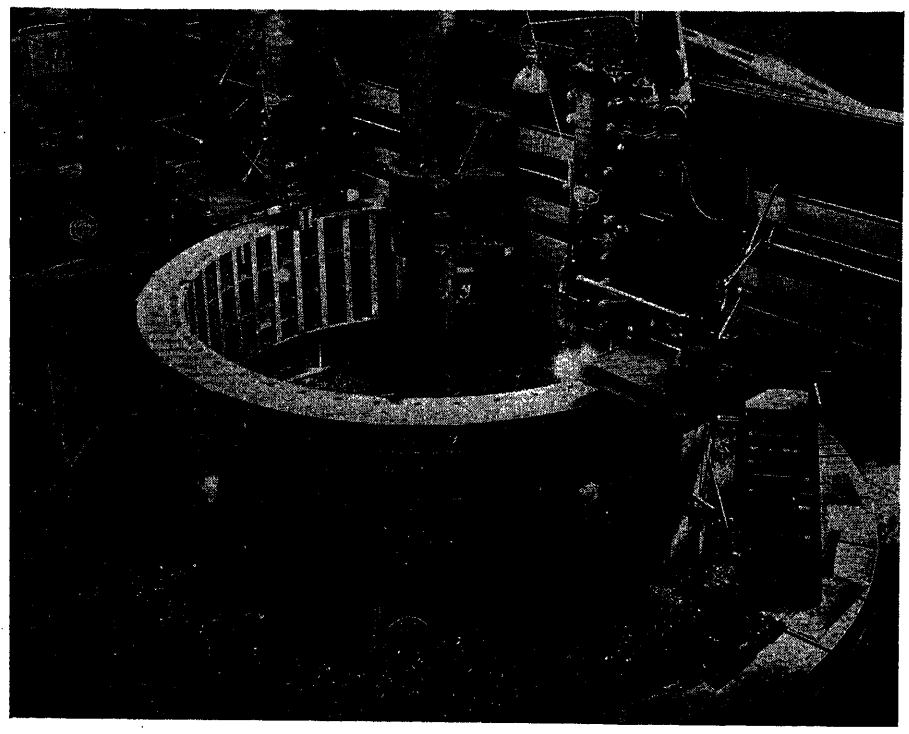
Reports were presented and approved of meetings of the board of examiners held February 17 and March 17, 1937. Upon the recommendation of the board of examiners, the following actions were taken: 1 applicant was elected to the grade of Fellow; 14 applicants were elected and 19 were transferred to the grade of Member; 96 applicants were elected to the grade of Associate; 106 Students were enrolled.

Monthly expenditures were reported by the finance committee and approved, as follows: February, $27,819.71; March, $17,691.20.

The selection by the District meeting committee of the dates, October 13–15, for the previously authorized 1937 meeting of the Middle Eastern District, at Akron, Ohio, was reported.

Doctor William McClellan was appointed a representative of the Institute upon the Hoover Medal board of award for the six-year term beginning in May 1937, succeeding Doctor F. B. Jewett, whose term expires at that time.

Professor R. W. Warner was appointed a third alternate of the Institute upon the delegatory committee for region V of the committee on engineering schools of the Engineers' Council for Professional De-



**Machining a fabricated-steel stator yoke on a 40-foot boring mill in the plant of the Allis-Chalmers Manufacturing Company, Milwaukee, Wis. An inspection trip to this plant during the forthcoming AIEE summer convention has been scheduled**

velopment, in connection with the accrediting of engineering schools by ECPD.

The executive committee confirmed the appointment, upon nomination by the standards committee, of Doctor Clayton H. Sharp to represent the Institute upon the subcommittee of the United States National Committee of the International Commission on Illumination to consider a proposal of the National Bureau of Standards for the international standardization of photometric units.

Other matters were discussed, reference to which may be found in this or future issues of ELECTRICAL ENGINEERING.

## President MacCutcheon Visits New England Sections

During the week of March 8, 1937, President A. M. MacCutcheon, accompanied by National Secretary H. H. Henline, Vice-President A. C. Stevens, and R. G. Lorraine, secretary of the North Eastern District, visited 5 Sections and one Student Branch of the Institute. This brief report of the tour has been prepared from information supplied by District Secretary Lorraine.

The following meetings were attended by the group:

**New Haven, Conn.** Dinner followed by meeting of Connecticut Section.

**Lynn, Mass.** Meeting of national members of Lynn Section and dinner as guests of the General Electric Company, followed by general Section meeting.

**Boston, Mass.** Dinner followed by Section meeting.

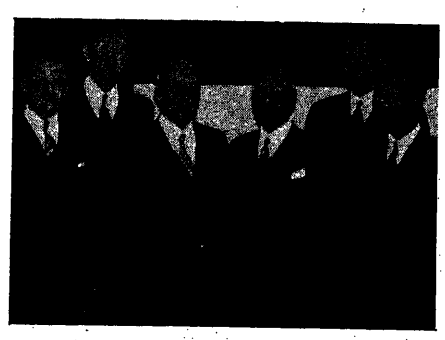
**Providence, R. I.** Luncheon with Providence Section and Brown University Branch followed by joint meeting of Brown University and Rhode Island State College Branches.

**Worcester, Mass.** Dinner followed by joint meeting of Worcester Section and Worcester Polytechnic Institute Branch.

**Springfield, Mass.** Dinner followed by Section meeting.

President MacCutcheon spoke on "The Selection and Training of Electrical Engineers" at the New Haven, Boston, Providence, and Springfield meetings; and on "The Section's Part in Institute Activities" at the Worcester meeting. The dinners preceding the meetings were featured by intimate and informal discussions of Institute policies and procedures. At some of the meetings, in addition to the talks by the president, Vice-President Stevens made short talks on District activities; National Secretary Henline discussed the Sections' records as the national organization sees them, and District Secretary Lorraine discussed the forthcoming District meeting.

In addition to the meetings, the group visited the Cambridge (Mass.) plant of the Simplex Wire and Cable Company, where they were conducted on the inspection trip by officials and other members of the organization; this was followed by a luncheon in the private dining room of the company. At Springfield, Mass., an inspection was made of the Westinghouse plant under the direction of Section Chairman C. G. Veinott and others, and of the United American Bosch plant by officials of that company.



**At the Worcester Section meeting, left to right: District Secretary Lorraine, Professor T. H. Morgan (A'23, M'31) of Worcester Polytechnic Institute, President MacCutcheon, Admiral Ralph Earle, National Secretary Henline, and Vice-President Stevens**

## Baltimore Section Is Host to Student Branch Convention

In 1925, the Philadelphia Section initiated the idea of AIEE Student Branch conventions. Since that time, other Sections in the eastern portion of the Middle Eastern District have joined with the Philadelphia Section in promoting and supporting this successful phase of Institute activities. During the ensuing 12 years, the idea has been widely and effectively adopted by other Sections and Districts.

Monday, April 19, 1937, was Student Branch convention day at The Johns Hopkins University school of engineering, Baltimore, where the thirteenth such meeting of the eastern section of District No. 2 was held, with about 190 students, faculty members, and others interested in attendance. The day's program was full, with a technical session in the morning, a noon luncheon, an afternoon inspection trip, and an evening dinner meeting.

At the technical session, 4 student technical papers were presented:

A LABORATORY POLYPHASE POWER RECTIFIER, T. Chase, Drexel Institute, Philadelphia, Pa.

ELECTRICAL TIME STANDARDS, T. R. Brown, Lehigh University, Bethlehem, Pa.

AN ALGEBRAIC EQUATION SOLVER, D. L. Herr and R. H. Graham, University of Pennsylvania, Philadelphia, Pa.

APPLICATIONS OF A SONIC OSCILLATOR, L. Broomell, Swarthmore College, Swarthmore, Pa.

By decision of a committee of judges, Mr. Brown was awarded a first prize of $10 and Mr. Chase a second prize of $5. Presiding throughout the session was Chairman H. B. Peck of the Johns Hopkins student Branch. Preliminary introductory remarks were made by AIEE Past-President J. B. Whitehead, dean of the school of engineering of Johns Hopkins University, by AIEE President A. M. MacCutcheon, who discussed Institute activities, services, and affairs, by R. L. Thomas, chairman, Baltimore Section, and by National Secretary H. H. Henline.

Those attending the sessions were the guests of the Johns Hopkins Student Branch at luncheon where Dr. Isiah Bowman, president of The Johns Hopkins University, addressed the group on "Flood Control." An afternoon inspection trip to the plant of the Locke Insulator Corporation gave to those attending an opportunity to witness a demonstration of high-voltage insulator testing, and also to observe the



**A group of those that attended the recent Southern District Student Branch conference at Alabama Polytechnic Institute**

manufacture of porcelain insulators by the wet process.

The evening dinner meeting was held jointly by the Johns Hopkins Student Branch and the Baltimore Section in honor of President MacCutcheon, who spoke on "The Selection and Training of Electrical Engineering." Past-President Whitehead and President-Designate Harrison, and others spoke briefly.

With the co-operation of the Baltimore Section, the meeting was jointly participated in by the 8 Student Branches of the eastern section of the Middle Eastern District:

Drexel Institute, Philadelphia, Pa.
The Johns Hopkins University, Baltimore, Md.
Lafayette College, Easton, Pa.
Lehigh University, Bethlehem, Pa.
University of Pennsylvania, Philadelphia, Pa.
Princeton University, Princeton, N. J.
Swarthmore College, Swarthmore, Pa.
Villanova College, Villanova, Pa.

Although having no Student Branches, the University of Delaware and Haverford College both contributed support. Visiting Branches also participating in the meeting were:

Catholic University of America, Washington, D. C.
George Washington University, Washington, D. C.
University of Maryland, College Park, Md.

A generous delegation of students and faculty was present representing each of the Branches.

Plans already decided upon provide for similar meetings at Lehigh University in 1938, and at Drexel Institute in 1939.

## 1937 AIEE Year Book Is Now Available

In accordance with the provisions of the Institute's 1936–37 budget as approved by the finance committee and the board of directors, the 1937 edition of the AIEE Year Book has been issued, in limited edition, and is available to members of the Institute who have use for it. The book contains essentially the same material as was included in the 1936 edition; business and mailing addresses have been corrected as of February 27, 1937.

In keeping with established custom, copies of the Year Book have been distributed to all national, District, and Section officers, to Student Branch counselors, and to all members of all national committees. Other members wishing to secure a copy may do so by writing to the AIEE order department, 33 West 39th Street, New York, N. Y., giving correct mailing addresses.

The Year Book is not available to nonmembers of the Institute, nor is its use permitted for commercial, promotional, or other circularization purposes.

## Student Conference Held at Alabama Polytechnic

Some 140 of the South's top-ranking students in electrical engineering, and Student Branch counselors from 15 colleges and universities registered at the annual student conference of the AIEE Southern District, held April 1–3 at Alabama Polytechnic Institute, Auburn. All principal features of the program were confined to Friday, April 2, with Thursday afternoon given over to registration followed by an informal smoker in the evening, and Saturday devoted to inspection trips to Tuskegee Institute and to hydroelectric plants of the Alabama Power Company on the Coosa River.

For the first time since the initiation of the Student Branch conferences in the Southern District, every Branch in the District was represented:

Alabama Polytechnic Institute, Auburn, Ala.
University of Alabama, University, Ala.
Clemson Agricultural College, Clemson, S. C.
Duke University, Durham, N. C.
University of Florida, Gainesville, Fla.
Georgia School of Technology, Atlanta, Ga.
University of Kentucky, Lexington, Ky.
Louisiana State University, Baton Rouge, La.
University of Louisville, Louisville, Ky.
Mississippi State College, State College, Miss.
North Carolina State College, Raleigh, N. C.
University of North Carolina, Chapel Hill, N. C.
University of South Carolina, Columbia, S. C.
University of Tennessee, Knoxville, Tenn.
Tulane University, New Orleans, La.
Virginia Military Institute, Lexington, Va.
Virginia Polytechnic Institute, Blacksburg, Va.
University of Virginia, University, Va.

Six technical papers were presented at the Friday morning technical session:

ELIMINATION OF MAN-MADE STATIC, Gordon Rogers, Clemson College, Clemson College, S. C.

A TREATISE ON RURAL ELECTRIFICATION, J. E. Lowery, Alabama Polytechnic Institute, Auburn, Ala.

TESTING VACUUM TUBES, T. M. Ferril, Jr., Mississippi State College, State College, Miss.

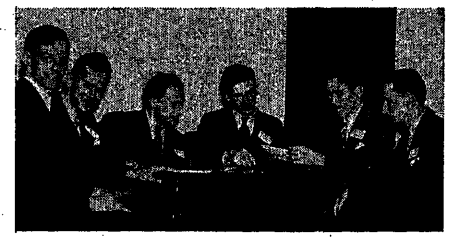
HIGH FREQUENCY RADIO TRANSMITTERS, Wayne Mason, University of Florida, Gainesville, Fla.

AN ELECTRICAL NURSE, J. A. Potter, Georgia School of Technology, Atlanta, Ga.

NOTES ON A SERIES SCHEME OF MODULATION, C. W. Harrison, Jr., University of Virginia, University Va. (Presented by Mr. Porter of University of Virginia.)

At the elaborate banquet held Friday evening, a first prize for the best technical paper was presented to Mr. Mason, with second and third honors conferred, respectively, upon Mr. Potter and Mr. Rogers. The presentation of prizes was made by Professor W. W. Hill, counselor of the Student Branch at Alabama Polytechnic Institute and chairman of the District committee on student activities. Professor Hill carried the principal responsibilities of the conference, ably assisted by L. C. Balch, chairman of the API Student Branch.

Principal speaker at the banquet was National Secretary H. H. Henline. The gist of his address was to the effect that engineering, instead of having in the near future a decadent place in modern civilization, will have an increasingly important place and opportunity to function in the world's development. He stressed the need for engineers of the future to have a greater knowledge of economics and a better understanding of social problems. Mark Eldredge, AIEE vice-president for the Southern District, also spoke briefly as did some others including API President L. N.



**The student authors of papers presented at the Southern District Student Branch conference**

(Left to right) James A. Potter (2d prize) Georgia Tech; T. M. Ferrill, Jr., Mississippi State; G. J. Porter, Virginia; Gordon Rogers (3d prize) Clemson; John E. Lowery, Alabama Poly.; Wayne Mason (1st prize) Florida

Duncan. The toastmaster was Professor John C. McKinnon of the API mechanical engineering faculty. Following the banquet an engineers' ball was held for visitors and API engineering students at the college's newly constructed WPA Hall.

At a short official business session Friday afternoon, Virginia Military Institute was selected as the location for the next annual District Student Branch conference. Colonel S. W. Anderson, professor of electrical engineering at VMI and counselor of its Student Branch, accordingly was elected chairman of the District committee on student activities and designated so to represent the Fourth District at the forthcoming summer convention. An extended discussion among counselors and students led to a decision to restrict to 20 minutes the time allowed for the presentation of technical papers, but to allow unlimited time for discussion of them. The papers committee decided to give preference to papers based upon original investigations.

## Chicago Section Sponsors Joint Meeting on Economics

At a joint meeting on March 22, 1937, the Chicago Section of the AIEE and the Western Society of Engineers heard 2 papers on "A Broader Field of Action for the Engineers." In the first, P. B. Juhnke (M'20, F'36) discussed the position of the engineers in the general economic structure of the nation and urged that they become better acquainted with questions involving the production and consumption of goods and the effect of changes in the monetary system. The second paper, presented by F. R. Innes (A'25, M'26) western editor of *Electrical World*, discussed the part that the engineer can take in directing the activities of the government in the electric-power field.

Some 200 members and guests of the participating bodies attended the meeting. According to Earle Wild (A'27, M'36) chairman of the publicity committee of the Chicago Section, those present expressed themselves as being highly in favor of meetings of this type. Further, it was the reported consensus of opinion that engineering societies in general should take more effective action concerning public affairs and broad economic problems within their respective fields.

**ASTM Standards Index.** An index to the standards and tentative standards of the American Society for Testing Materials which gives information as of January 1, 1937, has been made available. Copies are furnished without charge on request to ASTM headquarters, 260 South Broad St., Philadelphia, Pa.

**Willard Gibbs Medal Awarded.** Doctor Herbert Newby McCoy, internationally known for his achievements in radioactivity and in many other fields of chemical science, has been awarded the 1937 Willard Gibbs Medal of the Chicago (Ill.) section of the American Chemical Society. Doctor McCoy, for 16 years a member of the faculty of the University of Chicago and now vice-president and director of research of the Lindsay Light and Chemical Company, Chicago, was cited as "pioneer in a greater number of fundamental discoveries than any but 3 or 4 living American chemists." The medal was founded in 1911, and is awarded by a national jury of scientists.

## High-Voltage Conference to Be Held in Paris

The ninth session of the International Conference on High Voltage Electric Systems (CIGRE) is scheduled to be held in Paris, France, from June 24 to July 2, 1937. This permanent organization of CIGRE was created in 1921 under the auspices of the International Electrotechnical Commission, and its biennial sessions bring together delegations from 40 different countries for the discussion of all problems relating to the design, construction, and operation of high-voltage electric systems. The last session in 1935 was attended by more than 1,200 delegates including government officials, power-utility engineers and executives, electrical manufacturers, and university professors interested in high-voltage developments.

At the June session in Paris, 112 technical papers from 20 different countries are already scheduled to be presented, including the following 6 American papers:

1. HIGH-SPEED CLEARING AND ULTRA-HIGH-SPEED RECLOSING OF FAULTED HIGH-VOLTAGE TRANSMISSION LINES, by Philip Sporn (A'20, F'30) American Gas and Electric Company, New York, N. Y., and D. C. Prince (A'16, F'26) General Electric Company, Philadelphia, Pa.

2. LIGHTNING CURRENTS ON TRANSMISSION LINES, by W. W. Lewis (A'09, M'13) General Electric Company, Schenectady, N. Y.

3. LIGHTNING-STROKE TESTS ON HIGH-VOLTAGE APPARATUS IN THE LABORATORY, by P. L. Bellaschi (A'29, M'34) Westinghouse Electric and Manufacturing Company, Sharon, Pa.

4. LIGHTNING-PROOF TRANSMISSION LINES, by A. F. Bang (A'11) and Edwin Hansson (A'19, M'35) both of the Pennsylvania Water and Power Company, Baltimore, Md.

5. INVESTIGATION BY PRECISE MEASUREMENTS OF SUSPENSION-INSULATOR DESIGN CHARACTERISTICS FROM THE STANDPOINT OF SERVICE REQUIREMENTS, by L. A. Meisse and J. J. Taylor, both of the Ohio Brass Company, Barberton.

6. INSULATING OILS, by K. S. Wyatt (A'32) The Detroit (Mich.) Edison Company.

The proceedings are conducted in English, French, and German, and advance copies of all papers are available to all registered delegates. All delegates and their families are accorded reductions of 50 per cent in railway fares, and 40 per cent in hotel rates in France, and visits have been arranged for the delegates to the Paris International Exposition and to interesting electrical installations as well as to points of historical and scenic interest.

A permanent United States national committee has been formed, composed of Frederic Attwood (M'27), F. A. Allner (A'12 M'14), P. L. Bellaschi (A'29, M'34), W. W. Lewis (A'09, M'13), E. L. Moreland (A'11, F'21), Philip Sporn (A'20, F'30), and a large American delegation is expected to attend the June session in Paris. Further information may be obtained from CIGRE Headquarters, 54 Avenue Marceau, Paris, or from the president of the United States national committee, Frederic Attwood, 30 Church Street, New York, N. Y.

**Perkin Medal for 1937 Presented.** Thomas Midgley, Jr., vice-president of the Ethyl Gasoline Corporation, was presented with the Perkin Medal for 1937 of the Society of Chemical Industry at a joint meeting of the society and the American Chemical Society held on January 8, 1937. The medal is awarded annually for the most valuable work in applied chemistry and was presented to Mr. Midgley in recognition of his work in the development of antiknock motor fuels and safe refrigerants. Mr. Midgley is a fellow of the American Association for the Advancement of Science, and a member of the American Chemical Society, American Institute of Chemical Engineers, Society of Automotive Engineers, and other organizations.

## Joint Summer Session on Economics Planned

The seventh annual economics conference for engineers will be held at Stevens Institute of Technology camp, Johnsonburg, N. J., June 18–26, 1937, concurrently with a summer session sponsored by the Society for the Promotion of Engineering Education on the study of economics in engineering colleges. Members of the conference will be welcome at any of the lectures arranged for the SPEE session. A series of evening lectures by leading authorities on economic and industrial topics has been arranged for both groups. The 4 courses planned are:

1. INDUSTRIAL MANAGEMENT, conducted by Professor George W. Barnwell of Stevens Institute of Technology.

2. COURSE CONTENT AND TEACHING METHODS organized by Professor W. D. Ennis of Stevens Institute of Technology and conducted by several lecturers.

3. INDUSTRIAL ECONOMICS, conducted by Doctor Dexter S. Kimball, formerly dean of engineering, Cornell University, and Professor W. D. Ennis of Stevens Institute of Technology.

4. INDUSTRIAL PSYCHOLOGY, conducted by Doctor R. W. Uhrbrock, head of research department, industrial relations division, The Procter & Gamble Company.

Correspondence on enrollment should be addressed to President Harvey N. Davis, Stevens Institute of Technology, Hoboken, N. J.

**Semiannual Meeting of ASME.** The American Society of Mechanical Engineers will hold its semiannual meeting at Detroit, Mich., May 17–21, 1937. The meeting will stress the contribution of the automotive industry to industry in general, al-

though power plant engineering and other subjects will be included. The use of the Diesel engine will be discussed in several railroad sessions. Inspection trips to points of interest in the vicinity of Detroit have been arranged and include the River Rouge plant of the Ford Motor Company, Connors Creek station of The Detroit Edison Company, and the continuous strip mill of the Great Lakes Steel Corporation.

## Triennial Montefiore Prize Award Now Open

Constituting interest on 150,000 Belgian francs, distributed triennially in international competition for the best original work presented on scientific advancement and progress in technical application of electricity in every field, the George Montefiore Foundation prize award now is open again to candidates. The amount available for 1938 is 18,000 francs (about $600); the closing date for entries is April 30, 1938.

The competition is limited to works presented during the 3 years that immediately precede the meeting of the jury of award. Papers either signed or anonymous are acceptable in typewritten manuscript or printed form, and must be written in either French or English and submitted in duplicate. By a $^4/_5$ vote of the jury of award, composed of 5 Belgian and 5 other electrical engineers, $^1/_3$ of the available amount may be awarded to a person who has not taken part in the competition, or to a work which without completely fitting the program, discloses a new idea that may have important developments in the electrical field.

The secretary-registrar of the foundation may be addressed at the headquarters of the Association des Ingénieurs Électriciens, 31 Rue Saint-Gilles, Liege, Belgium.

**TVA Report.** The annual report of the Tennessee Valley Authority for the fiscal year ended June 30, 1936, has been printed as a 377-page paper-bound volume, and may be obtained from the Superintendent of Documents, Washington, D. C., at 55 cents per copy.

## Niagara Hudson Companies Consolidate

The Buffalo General Electric Company, the Niagara Electric Service Corporation, and the Tonawanda Power Company have filed a certificate of consolidation with the department of state at Albany, N. Y., following receipt of an order of the public service commission approving the consolidation of these companies as the Buffalo Niagara Electric Corporation. The announcement by Colonel William Kelly, (F'25) president of the Buffalo Niagara & Eastern Power Corporation, parent company for the 3 operating units involved in the consolidation, points out that the move is a further step in the simplification of the corporate structure of the Niagara Hudson power system, and reduces the number of system companies to 33 from a total of 59 in existence on December 31, 1929, the year the Niagara Hudson Power Corporation was formed.

The Buffalo General Electric Company was incorporated in 1892 from a consolidation of 2 smaller companies, and in 1915 absorbed a third company. Under another name, Niagara Electric Service Corporation also was formed in 1892, and adopted its present name in 1915; in 1928 2 smaller companies were acquired. The Tonawanda Power Company was incorporated in 1899 as a consolidation of 2 companies. Together these companies serve over 700,000 people.

## Pennsylvania Railroad Continues Electrification

The Pennsylvania Railroad has awarded contracts to 5 companies for continuation of electrification work. The chief lines now to be electrified are the main line from Paoli, near Philadelphia, to Harrisburg, Pa.; the freight line from Morrisville, Pa., near Trenton, N. J., to Harrisburg; the freight line from Columbia, Pa., to Perryville, Md.; and the freight line from Monmouth Juction to South Amboy, N. J. This will mark the completion of the original electrification program on the eastern lines as announced by the railroad in 1928. The work will be financed by a $52,670,700 bond issue, and is expected to be completed in 18 months.

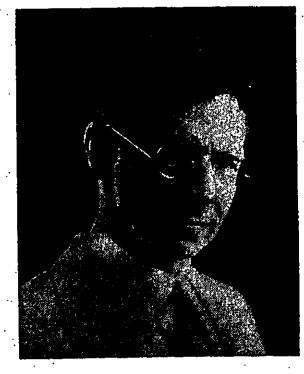
The new work will involve electrification of 315 miles of line and 773 miles of track. Upon completion of the work, the Pennsylvania Railroad system will have 2,677 miles of electrified trackage. The new construction work will be of the same type as that now employed elsewhere in the railroad's eastern electrified territory. It is known as the cross-catenary construction, based on a system of overhead conductors held in place by an arrangement of flexible wires supported between structural steel poles set in concrete beds beyond the outer edges of the track.

The 4-track main line of the Pennsylvania is now electrified between New York, Trenton, Philadelphia, Wilmington, Baltimore, and Washington, as are also the commutation lines around Philadelphia and New York.

**Annual Convention of American Transit Association.** The 56th annual convention of the American Transit Association and its affiliates will be held September 19–23, 1937, at White Sulphur Springs, W. Va. The convention is expected to bring together executives, operators, and mechanical men representing more than 90 per cent of the transit operations in the United States, Canada, and Mexico. Representatives of manufacturing companies also will attend.

# Personal Items

W. D. Coolidge (A'10, M'34, Edison Medalist '27) director of the research laboratories of the General Electric Company, Schenectady, N. Y., recently was awarded a John Scott Medal "for the application of a new principle in X-ray tubes," as announced in the April 1937 issue of Electrical Engineering, pages 495-6. Doctor Coolidge was born October 23, 1873, at Hudson, Mass., and received the degrees of bachelor of science in electrical engineering (1896) and doctor of philosophy (1899) at Massachusetts Institute of Technology and the University of Leipzig (Germany), respectively. Following his graduation in 1899 he was appointed to the faculty of Massachusetts Institute of Technology in 1901, as an instructor in physical chemistry. In 1904 he was promoted to assistant professor of physicochemical research, but served in that capacity for only one year before joining the staff of the General Electric research laboratories at Schenectady. From 1908 until 1927 Doctor Coolidge served as assistant director of the research laboratories, and in 1928 was made associate director. He has been director of the laboratories since 1932. He has been active in many branches of electrical research, but is most widely known for his development of a process for manufacturing ductile tungsten for use in incandescent lamps, for the Coolidge X-ray tube, for improvements in submarine detecting devices, and



W. D. COOLIDGE

for researches on cathode-ray tubes. Doctor Coolidge received the Edison Medal in 1927 "for his contributions to the incandescent electric lighting and the X-ray arts." He has been honored by several

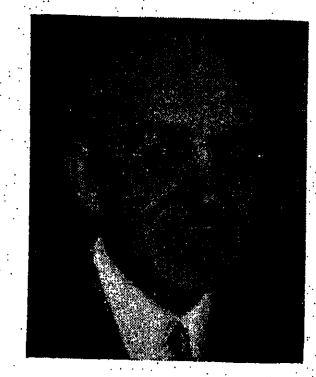
other scientific organizations, having received the Rumford Medal in 1914 "for invention and applications of ductile tungsten," the Howard N. Potts Medal "for development of a new and improved X-ray tube," the Louis Edward Levy Medal of the Franklin Institute, the gold medal of the American College of Radiology, a medal of award at the Panama-Pacific International Exposition in 1915, the Hughes Medal of the Royal Society in 1927, and the Washington Award in 1932. Doctor Coolidge served the Institute as a member of the committee on electrophysics from 1927 to 1929. He has contributed the results of his original researches to many scientific publications, and has presented several papers before the Institute. Doctor Coolidge is a member and past-vice-president of the Washington Academy of Sciences, and honorary member of the American Roentgen Ray Society, a fellow of the American Academy of Arts and Sciences, and a member of the American Chemical Society, American Electrochemical Society, American Physical Society, National Academy of Sciences, American Association for the Advancement of Science, Radiological Society of North America, American College of Radiology, and several foreign scientific societies. He was a member of the Corporation of Massachusetts Institute of Technology from 1930 to 1935.

R. H. TAPSCOTT (A'18, F'29, past vice-president) who has been vice-president in charge of electrical operations, Consolidated Edison Company of New York (N. Y.), Inc., recently was elected president and a trustee of that company. Mr. Tapscott was born in Brooklyn, N. Y., August 31, 1885 and was graduated from Union College with the degree of bachelor of science in electrical engineering in 1909, following which he joined the testing department of the General Electric Company, Schenectady, N. Y. Shortly afterward he was transferred to the lighting engineering department, where his work largely involved co-operation with a group of New York utility companies. In 1917 Mr. Tapscott left the General Electric Company to become assistant chief electrical engineer of the New York Edison Company. In 1925 he was promoted to the position of electrical engineer, and in 1932 became vice-president of that company and of the United Electric Light and Power Company. In 1936 he was elected vice-president of the Consolidated Edison Company of New York when the New York Edison Company, Inc., was merged with the Consolidated Edison Company. For the last 5 years Mr. Tapscott has been co-ordinating the engineering, construction, and operation of the electric companies affiliated with the Consolidated Edison Company. He served the Institute as a director (1930-34) and as a vice-president (1934-36); in addition, he has been a member of the committees on standards, 1924-29; electrical machinery, 1926-27; power transmission and distribution, 1926-28; headquarters, 1928-36 (chairman, 1929-33); Edison Medal, 1930-34; finance, 1931-36 (chairman, 1934-36); and co-ordination of Institute activities, 1934-36. Mr. Tapscott was active in the former National Electric Light Association. He was chairman of the electrical apparatus committee, and later a member of the engineering national committee of that organization.

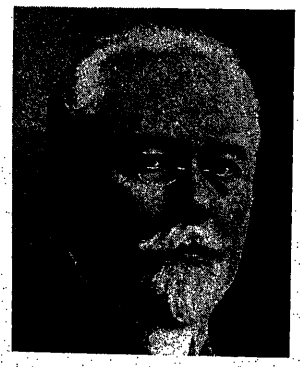
ANDRÉ BLONDEL (A'05, HM'12) professor of applied electricity at l'Ecole Nationale des Ponts et Chaussees, Paris, France, has been awarded the Faraday Medal of the British Institution of Electrical Engineers. The medal is awarded once each year for notable scientific or industrial advancement in electrical engineering, or for conspicuous service rendered to the advancement of electrical science. Professor Blondel was born at Chaumont, France, in 1863, and was graduated from the universities of Paris and Dijon in 1889. He was then appointed engineer in the Department des Ponts et Chaussees (civil engineering), and from 1890 to 1927 was engaged in the lighthouse service of that department, with the titles of engineer-in-chief and inspector-general. He has held his present position as professor of applied electricity since 1904. During his long service, Professor Blondel has been instrumental in introducing many important changes in signaling on the coasts of France, principally by means of radio. In 1897 he conducted an exhaustive series of experiments on the electric arc, which led him to study the measurement of electrical quantities and to develop the art of photometry, a field in which he has long been a leading authority. His investigations have been extended to include the advancement of electrical theory and practice in relation to many types of equipment. He is perhaps most famous for his 2-reaction theory of synchronous machines and his work on the oscillograph, although he has to his credit many inventions in widely diversified electrical applications. His published contributions to electrical-engineering literature have been extensive. He has presided over committees and commissions, national and international, and has received many honors in his own land and abroad.

R. A. MILLIKAN (M'22, HM'33, Edison Medalist '22) director of the Norman Bridge Laboratory of Physics and chairman of the executive council of California Institute of Technology, Pasadena, has been awarded a 1937 Franklin Medal of the Franklin Institute "for his isolation and measurement of the fundamental unit of electricity, the electron." Doctor Millikan was born at Morrison, Ill., March 22, 1868, and received the degree of bachelor of arts at Oberlin College in 1891; in 1895 he received the degree of doctor of philosophy at Columbia University, and during the following year attended the universities of Berlin and Göttingen. He has received honorary degrees from universities in the United States and other countries. From 1891 to 1893 Doctor Millikan tutored in physics at Oberlin College, and in 1896 became an assistant in physics at the University of Chicago, becoming assistant professor in 1902. In 1906 he became associate professor and continued to serve in that capacity until he was appointed professor in 1910. Since 1921 he has been director of the Norman Bridge Laboratory of Physics and chairman of the executive council of California Institute of Technology. Doctor Millikan has conducted many fundamental experiments in physics that have become important contributions to scientific knowledge. Recently he has been active in researches pertaining to the so-called cosmic ray and to the physics of the electron, although many of his earlier investigations were more directly applicable to electrical engineering. Doctor Millikan is a member of many technical and scientific societies in the United States and in foreign countries, and has served as president of several of them.

H. A. WINNE (A'16) manager of sales in the mining and steel mill section of the industrial department, General Electric Company, Schenectady, N. Y., has joined the engineering department of that company as general assistant to the vice-president in charge of engineering. Mr. Winne, a native (1888) of Cherry Valley, N. Y., attended Syracuse University, graduating in 1910 with the degree of electrical engineer. In the same year he entered the employ of the General Electric Company as a student engineer in the testing department. In 1911 he became head of the large motor, generator, and synchronous converter test, and in the following year was made assistant general night foreman of the testing department. In 1916 Mr. Winne was promoted to the power and mining engineering department, where he remained until 1922, when he was transferred to the steel



R. H. TAPSCOTT



ANDRÉ BLONDELL



R. A. MILLIKAN

mill section of the industrial engineering department. He became head of the steel mill section in 1930, and in 1936 was appointed manager of sales of the combined mining and steel mill sections. Mr. Winne is a member of the Institute's committees on electric welding and applications to iron and steel production.

E. V. CATON (M'23) chief engineer and manager of power production, Winnipeg (Man., Canada) Electric Company, has been elected president of the Association of Professional Engineers of Manitoba. Mr. Caton, a native (1884) of Hore, England, attended Brighton Technical College and Sheffield University, and received an honors certificate from the City of Guilds Institute in Electrical Engineers. He received his early technical training in various English firms before going to Canada in 1912 to accept a position as chief engineer of the Hydro Electric System of the City of Winnipeg, with full charge of extensions and construction. In 1922 he became electrical engineer for the Winnipeg Electric Company and has been manager of that company since 1925.

C. H. SHARP (A'02, F'12, member for life) consulting engineer, White Plains, N. Y., has been appointed to represent the Institute upon the subcommittee of the United States National Committee of the International Commission on Illumination to consider a proposal of the National Bureau of Standards for the international standardization of photometric units. Doctor Sharp is a member of the Institute's committee on standards and of the Thomas Alva Edison Foundation.

W. S. GORDON, Jr. (A'27, M'35) has resigned as superintendent of electrical construction at the Philadelphia, (Pa.) Navy Yard to accept a position as supervising engineer with Vare Brothers, Philadelphia, in connection with that firm's portion of the Harrisburg electrification of the Pennsylvania Railroad. Mr. Gordon is co-author of a paper "A Review of European Railway Electrification," published in the April 1932 issue of ELECTRICAL ENGINEERING, pages 244-52.

WILLIAM MCCLELLAN (A'04, F'12, past-president) president of the Potomac Electric Power Company and the Washington (D. C.) Railway and Electric Company, has been appointed a representative of the Institute upon the Hoover Medal board of award for the 6-year term beginning in May 1937. Doctor McClellan is also the Institute's representative on the council of the American Engineering Council.

A. A. THOMPSON (A'08) Downers Grove, Ill., an employee of the General Electric Company, has received a 1936 Charles A. Coffin Foundation award "in recognition of his unusual keenness in seeing trouble and his persistence in correcting it." Mr. Thompson has been associated with the General Electric Company since 1905.

R. W. WARNER (M'28) professor of electrical engineering, University of Kansas, Lawrence, has been appointed a third alternate upon the delegatory committee for region 5 of the committee on engineering schools of the Engineers' Council for Professional Development, relative to the accrediting of engineering schools by the Council.

T. O. SWEATT (A'33) recently resigned from the electrical department of Gibbs & Cox, Inc., marine architects and engineers, New York, N. Y., to accept a position with the consulting engineering firm of Gibbs & Hill, Inc., New York.

E. C. BROWN (A'26) assistant manager, Connecticut Valley Power Exchange, Hartford, Conn., recently was elected chairman of the New England System Operators' Club.

H. A. WAGNER (A'98, M'03) president of the Consolidated Gas, Electric Light, and Power Company of Baltimore, Md., has been elected a member of the executive committee of the Baltimore Association of Commerce.

H. C. HAMILTON (A'23, M'26) superintendent of the standardizing and testing department of the Edison Electric Illuminating Company of Boston, Mass., has been elected chairman of the New England Electrical Equipment Committee.

# Obituary

EDGAR KNOWLTON (A'11) electrical engineer, General Electric Company, Schenectady, N. Y., died January 19, 1937. Mr. Knowlton was born July 7, 1871, at Portland, Me., and received his formal engineering education through correspondence schools and independent study. He entered the employ of the General Electric Company in 1893 as a draftsman on a-c motor and generator design, and was continuously associated with that company for almost 44 years. In 1899 Mr. Knowlton was transferred to the a-c engineering department on preliminary mechanical and electrical design of a-c machinery, and in 1903 was transferred to the design of turboalternators. Later he was placed in charge of turbogenerator design, and for many years was engaged in a-c engineering problems.

JAMES DHU ANDREW (A'06) manager of The American Boiler Manufacturers Association, New York, N. Y., died March 22, 1937. Mr. Andrew was born October 29, 1874, at Brooklyn, N. Y., attended the school of mines of Columbia University and in 1899 became a mechanical engineer for the Metropolitan Street Railway Company of New York, N. Y. From 1903 to 1906 Mr. Andrew was chief engineer for the New York Edison Company. For 6 years thereafter he was superintendent of power for the Boston (Mass.) Elevated Railway Company, following which he was superintendent of engineering for the Edison Electric Illuminating Company of Boston. Later he was manager of ship construction of the Hog Island Shipyard, president of the American Balsa and Balsa Refrigerator Company, New York, and president of the Standard Tank Car Company, Sharon, Pa. He served also as vice-president of Stevens and Wood, Inc., of New York, in charge of design, construction, and operation of some power plants in Ohio. From 1926 to 1929 Mr. Andrew was a general consulting engineer for Armour & Company, Chicago, Ill. Later he was chief engineer of the Niagara Hudson Power Corporation. He was a member of The American Society of Mechanical Engineers and the Society of Naval Architects and Marine Engineers.

FREDERICK STEWART CUTTING (M'31) deputy public service engineer of the City of Providence, R. I., died March 13, 1937. Mr. Cutting was born January 18, 1882, at Cranston, R. I. In 1904 he became assistant to the president of the Massie Wireless Telegraph Company, Providence, and was placed in charge of design, construction, testing, and maintenance. He remained in the employ of that company until 1912, when he was engaged as an electrician for the New London (Conn.) Ship and Engine Company. In the following year he became chief clerk of the power and line department of The Rhode Island Company, which later became the United Electric Railways Company. During the World War, and until 1923, Mr. Cutting served in the United States Navy, first as an instructor in electrical engineering at the United States Naval Radio School at Harvard University, and later as an engineering officer and inspector of machinery. From 1923 to 1926 he was employed in electrical construction work for the Dwight P. Robinson Company and the Carleton-Mace Company, of Boston, Mass., and for a brief period was employed as appraisal engineer for Jackson and Moreland, consulting engineers. In 1927 Mr. Cutting was appointed deputy smoke inspector for the City of Providence; in 1929, deputy public service engineer. He was a member of The American Society of Mechanical Engineers.

FRANK GEORGE MCRAE (A'07) New York Power and Light Corporation, Albany, N. Y., died January 24, 1937. Mr. McRae was born February 5, 1879, at Schuylerville, N. Y., and was graduated from Cornell University with a degree in electrical engineering in 1902. In 1903 he entered the employ of the Hudson River Electric Power Corporation, Albany, where he served in various capacities in the operating department of that company until 1914. At that time he became superintendent of distribution of the Adirondack Electric Power Corporation at Glen Falls, N. Y. In 1922 Mr. McRae was transferred to the Amsterdam (N. Y.) offices of that company and in the following year to the Schenectady offices. He remained in the Schenectady offices of the Adirondack Electric Power Corporation until 1928, when he became associated with the New York Power and Light Corporation at Albany.

# Membership

## Recommended for Transfer

The board of examiners, at its meeting on April 14, 1937, recommended the following members for transfer to the grade of membership indicated. Any objection to these transfers should be filed at once with the national secretary.

**To Grade of Fellow**

Childerhose, E. A., senior engineer, Federal Power Commission, New York, N. Y.
Donnell, P. S., dean of division of engineering, Oklahoma Agricultural and Mechanical College, Stillwater, Okla.
Eshbach, O. W., special assistant, personnel department, American Telephone and Telegraph Company, New York, N. Y.
Newton, J. M., president, The Roland T. Oakes Company, Holyoke, Mass.
4 to Grade of Fellow

**To Grade of Member**

Baines, H. A., technical assistant to executive staff, The Narragansett Electric Company, Providence, R. I.
Barron, D. W., vice-president and assistant engineer, Albert F. Ganz, Inc., New York, N. Y.
Clary, H. L., erecting engineer, Allis-Chalmers Manufacturing Company, Boulder City, Nev.
Connell, D. J., electrical engineer, The Scranton Electric Company, Scranton, Pa.
Crumley, H. L., electrical engineer, E. M. Gilbert Engineering Corporation, Reading, Pa.
Defandorf, F. M., physicist, National Bureau of Standards, Washington, D. C.
Linney, R. W., transmission and protection engineer, Southwestern Bell Telephone Company, Oklahoma City, Okla.
Long, Marvin, engineering assistant to toll fundamental plan engineer, Bell Telephone Company of Pennsylvania, Philadelphia.
Peterson, J. B., aeronautical engineer, National Bureau of Standards, Washington, D. C.
Schuetz, R. F., audio facilities engineer, National Broadcasting Company, Inc.; New York, N. Y.
Wichum, Victor, chief engineer, C. J. Tagliabue Manufacturing Company, Brooklyn, N. Y.
Wilfley, V. B., electrical engineer, Westinghouse Electric & Manufacturing Company, Portland, Ore.
12 to Grade of Member

## Applications for Election

Applications have been received at headquarters from the following candidates for election to membership in the Institute. If the applicant has applied for direct admission to a grade higher than Associate, the grade folllows immediately after the name. Any member objecting to the election of any of these candidates should so inform the national secretary before May 31, 1937 or July 31, 1937, if the applicant resides outside of the United States or Canada.

Allen, S. R., Washington Water Power Company, Spokane, Wash.
Anderson, J. R., New York Worlds Fair, Inc., New York, N. Y.
Atkinson, J. M., California Institute of Technology, Los Angeles, Calif.
Banks, G. F., Commonwealth Edison Company, Chicago, Ill.
Bauerle, J. L., Cleveland Electric Illuminating Company, Cleveland, Ohio.
Baur, H. W., Eastman Kodak Co., Rochester, N. Y.
Bender, D. S., 1835 Arch Street, Philadelphia, Pa.
Bingham, H. C., Cleveland Electric Illuminating Company, Cleveland, Ohio.
Bittrick, W. E., Consolidated Gas, Electric Light, and Power Company, Baltimore, Md.
Brand, S. (Member) Bell Telephone Laboratories, Inc., New York, N. Y.
Brewster, L. C., Ohio Bell Telephone Company, Cleveland, Ohio.
Butler, C. H., Portland General Electric Company, West Linn, Ore.
Carey, A. J., New York Telephone Company, Brooklyn, N. Y.
Carr, B. P., The Commonwealth & Southern Corporation, Jackson, Mich.
Chase, C. N., New York Rapid Transit Corp., Brooklyn, N. Y.
Chase, G. E., Public Utilities Commission, Bowmanville, Ont., Canada
Colby, P. S., Kansas Gas and Electric Company, Wichita, Kans.
Crevi, I. P. (Member) Westinghouse Electric & Manufacturing Company, New York, N. Y.
Cupitt, I. M. (Member) American Telephone and Telegraph Company, New York, N. Y.
Dailey, J. A., General Electric Company, Kansas City, Mo.
Devereaux, A. J., Central Nebraska Public Power and Irrigation District Hastings, Nebr.
Dietsch, R. C., Texaco Development Corporation, Los Angeles, Calif.
Edwards, J. H. (Member) General Cable Corporation, New York, N. Y.
Enquist, E. A. Jr., Consolidated Edison Company of New York, Inc., New York, N. Y.
Fletcher, G. R. (Member), Virginia Public Service Co., Alexandria, Va.
Galle, Paul F., Tennessee Valley Authority, Knoxville, Tenn.
Garrett, P. A. (Member) Commonwealth Edison Company, Chicago, Ill.
Gaskill, H. R., 4415 Pine Street, Philadelphia, Pa.
Gatchell, O. W. (Member) Cooper Wire Engineering Association, Washington, D. C.
Gibson, G. P., Westinghouse Electric & Manufacturing Company, East Pittsburgh, Pa.
Hartzell, H. W., Locke Insulator Corporation, Baltimore, Md.
Henderson, O., Ohio Bell Telephone Company, Cleveland, Ohio.
Henderson, W. D., 3721 Locust Street, Philadelphia, Pa.
Hendricks, J. B., The Milwaukee Electric Railway and Light Company, Milwaukee, Wis.
Herter, C. C., New York and Queens Electric Light and Power Company, Flushing, N. Y.
Holme, S. A. (Member) General Electric Company, Schenectady, N. Y.
Hughes, P. E., Star Route, Newburgh, N. Y.
Jirka, F. J., Public Service Company of Northern Illinois, Chicago, Ill.
Jones, J. O., Pacific Gas and Electric Company, Oakland, Calif.
Jordan, T., American Smelting and Refining Company, Garfield, Utah.
Julian, L. P., Duke Power Company, Charlotte, N. C.
Kelley, R. R., Westinghouse Electric and Manufacturing Company, Sharon, Pa.
Kethley, B. L., South East Joslyn Company, Atlanta, Ga.
Kocsis, P., R. K. O., Franklin Theatre, New York, N. Y.
Koester, H. F. (Member) New York and Queens Electric Light and Power Company, Flushing, N. Y.
Kostriza, J. A., 90 St. Mark's Place, St. George, Staten Island, N. Y.
Lack, F. R. (Member) Bell Telephone Laboratories, Inc., New York, N. Y.
Latta, E., Airway Electric Appliance Corp., Toledo, Ohio.
Lukacs, J. J., Bell Telephone Laboratories, Inc., New York, N. Y.
MacDonald, L. L., Public Service Electric and Gas Company, Newark, N. J.
Mancini, P. S., 65 Chatham Street, Providence, R. I.
Markuson, O. S., Bell Telephone Laboratories, Inc., Baltimore, Md.
Marshall, A. E. (Member) Monsanto Chemical Company, St. Louis, Mo.
Marshall, M. B. Jr., Jackson and Moreland, Boston, Mass.
Matthysse, I. F., Burndy Engineering Company, New York, N. Y.
Maull, J. R., Massachusetts Institute of Technology, Cambridge, Mass.
Mayberry, W. R., H. J. Heinz Company, Pittsburgh, Pa.
McCarthy, E. J., Bell Telephone Laboratories, Inc., New York, N. Y.
McElroy, C. H., Department of Water and Power, Los Angeles, Calif.
McIntosh, F. H. (Member) Pacific Coast Radio Engineer, for Graybar Company, San Francisco, Calif.
McNeice, L. G. (Member), Orillia Water, Light, and Power Commission, Orillia, Ont., Canada.
McWilliams, H. G., Southern California Telephone Company, Los Angeles, Calif.
Mead, S. P. (Mrs.) Bell Telephone Laboratories, Inc., New York, N. Y.
Mintz, L. L., Parker-Kalon Corporation, New York, N. Y.
Morgan, G. W., E. I. Du Pont Company, Richmond, Va.
Moseley, F. N., Southwestern Bell Telephone Company, St. Louis, Mo.
Murdock, H. E., Montana Power Company, Bozeman, Mont.
Murray, T. F., United Light and Power Engineering and Construction Company, Davenport, Iowa.
Nebe, H. G., WSMB Radio Station, New Orleans, La.
Nelson, A. E., Jr., Arkansas Power and Light Company, Pine Bluff, Ark.
Nelson, R. D., Line Material Company, South Milwaukee, Wis.
Newton, E. G. (Member) General Electric Company, Pittsfield, Mass.
Nicholson, H. H., Electric Storage Battery Company, Cleveland, Ohio.
Nofrey, C. E., 3014 Clay St., San Francisco, Calif.
Norman, G. H. L., Aerovox Corporation, Brooklyn, N. Y.
Page, F. M., The Reliance Electric & Engineering Company, Cleveland, Ohio.
Paige, H. W. (Member) Peters and Peters, Inc. New York, N. Y.
Patterson, H. M., 825 Union Trust Building Washington, D. C.
Peck, R. R., Kansas City Power and Light Company, Kansas City, Mo.
Rahe, E. P., Western Electric Company, Baltimore, Md.
Rohr, E. K., Iowa State College, Ames.
Rohwer, O. J., Sargent and Lundy, Inc., Chicago, Ill.
Roush, C. G., Westinghouse Electric & Manufacturing Co., Kansas City, Mo.
Safranek, R. C., Washington Water Power Company, Spokane, Wash.
Schatz, G. W., Pennsylvania Power & Light Company, Allentown, Pa.
Scott, J. A., United States Treasury Department, Washington, D. C.
Seels, H. F., R.C.A. Manufacturing Corporation, Harrison, N. J.
Sickel, E. C., Northern States Power Company, West St. Paul, Minn.
Small, A. R. (Member) Underwriters' Laboratories Inc., Chicago, Ill.
Smith, L., Appalachian Electric Power Company, Charleston, W. Va.
Softli, R. R. B., 247 West 63d Street, New York, N. Y.
Spears, V. W., Public Service Company of Indiana, Bedford, Ind.
Stein, A. D. Jr., General Cable Corporation, New York, N. Y.
Stickel, O., A. I. Smith Corporation, Milwaukee, Wis.
Sullivan, D. E. (Member) Westinghouse Electric and Manufacturing Company, New York, N. Y.
Sullivan, J. W., S. S. White Dental Manfacturing Company, Princess Bay, S. I., N. Y.
Summers, S. D., Tri-State College, Angola, Ind.
Targonski, E., Arrow Hart and Hegeman Electric Company, Hartford, Conn.
Taylor, R. W., Tennessee Valley Authority, Knoxville, Tenn.
Thomas, P. E. (Member) Rochester Gas and Electric Corporation, Canandaigua, N. Y.
Thompson, W. B., E. M. Gilbert Engineering Corporation, Reading, Pa.
Tilson, H. MacM. (Member) San Francisco–Oakland Bay Bridge, San Francisco, Calif.
Tindall, H. D., Wagner Electric Corporation, St. Louis, Mo.
Todd, A. W., Westinghouse Electric & Manufacturing Company, East Pittsburgh, Pa.
Tollefson, M. W., Century Electric Company, St. Louis, Mo.
Traves, J. R., Bell Telephone Company of Canada, Toronto, Ont., Canada.
Vitale, R. L., Department of Water Supply, Gas and Electricity, Richmond, N. Y.
Wallace, T. M., General Electric Company, Erie, Pa.
Warfield, W. (Member), Tampa Electric Company, Tampa, Fla.
Westerkamp, P. R., Consolidated Edison Company of New York Inc., New York, N. Y.
White, P., Phoenix Engineering Corporation, New York, N. Y.
Widess, M. B., Western Geophysical Company, Los Angeles, Calif.
112 Domestic

**Foreign**

Accioly, P. B., Rio de Janeiro Tramway Light and Power Company, Brazil, S. A.
Barney, G. C. (Member), American Telegraph and Telephone Company and Bell Telephone Laboratories Inc., London, England.
Johnson, F. J. (Member) Honolulu Rapid Transit Company, Ltd., Honolulu, Hawaii.
Lazarus, V. E., "Sunnyside" Waltair, South India.
4 Foreign

## Addresses Wanted

A list of members whose mail has been returned by the postal authorities is given below, with the addresses as they now appear on the Institute record. Any member knowing of corrections to these addresses will kindly communicate them at once to the office of the secretary at 33 West 39th St., New York, N. Y.

Evans, Maldwyn F., Canadian Comstock Company, Ltd., Star Building, Toronto, Ont., Canada.
Hale, Edward E., Public Service Commission of New York, 80 Centre St., New York, N. Y.
Little, Leroy C., 3414—17th St., N., Cherrydale, Va.
Nash, G. H., 2–A Holland Road, London W.14, England.
Schaefer, Philip E., 5154 St. Paul Avenue, Chicago, Ill.
Wickel, F. A., Pier 42, Dollar S. S. Lines, San Francisco, Calif.
6 Addresses Wanted

# Engineering Literature

## New Books in the Societies Library

Among the new books received at the Engineering Societies Library, New York, recently, are the following which have been selected because of their possible interest to the electrical engineer. Unless otherwise specified, books listed have been presented gratis by the publishers. The Institute assumes no responsibility for statements made in the following outlines, information for which is taken from the preface of the book in question.

VDE-FACHBERICHTE, volume 8, 1936. Berlin-Charlottenburg, Verband Deutscher Elektrotechniker. Illustrated, 12x8 in., paper, 10.20 rm.; bound, 13.50 rm. Contains papers delivered at the 1936 meeting of the Verband Deutscher Elektrotechniker. Discusses many branches of electrical engineering: power generation, distribution, communications, lighting, and high-frequency engineering.

SYMPOSIUM on RADIOGRAPHY and X-RAY DIFFRACTION METHODS, held at the 39th Annual Meeting of the American Society for Testing Materials, Atlantic City, N. J., June 30–July 1, 1936. Philadelphia, American Society for Testing Materials, 1937. 350 pages, illustrated, 9x6 in., cloth, $4.00. A collection of papers on the uses of X rays and gamma rays for testing materials. Provides an account of the available methods and suggests future developments.

PROTECTION of ELECTRIC PLANT. By P. F. Stritzl. London and New York, Pitman Publishing Corporation, 1936. 200 pages, illustrated, 9x6 in., cloth, $6.00. Provides a review of developments in protective devices. Chapters are devoted to the protection of generators, transformers, and high- and low-voltage lines

PERFORMANCE and DESIGN of ALTERNATING CURRENT MACHINES. By M. G. Say and E. N. Pink. London and New York, Pitman Publishing Corporation, 1936. 552 pages, illustrated, 9x6 in., cloth, $6.00. Limited to the principal types of a-c machines; the transformer, the 3-phase induction motor, and the synchronous motor and generator. Outlines the theory of each, and discusses details of performance, control, testing, construction, and design.

MANAGING for PROFIT. By C. E. Knoeppel with the collaboration of E. G. Seybold. New York and London, McGraw-Hill Book Company, 1937. 343 pages, illustrated, 9x6 in., cloth, $3.50. Discusses working methods for profit planning and control and describes recently developed aids to management in the way of profit-making tools and methods.

INDEX to ASTM STANDARDS and TENTATIVE STANDARDS, January 1, 1937. Philadelphia, American Society for Testing Materials. 118 pages, 9x6 in., paper, gratis. Enables the user to ascertain whether the society has issued standard or tentative standards, test methods, or definitions upon any engineering material or subject, and to locate the volume in which the latest information is found.

ELEMENTS of APPLIED ELECTRICITY. 4 volumes. By B. C. Chatterjee. 2 edition. Benares, India, Shiva Narayan Chatterjee, 1 Laksha Road, 1931–1936. 8x5 in., cloth. Volume 1, 412 pages; volume 2, 736 pages; volumes 3–4, 1142 pages, apply. Presents a course in practical engineering intended primarily for students.

HISTORY of the DISCOVERY of PHOTOGRAPHY. By E. Potonniée, translated by E. Epstean. New York, Tennant and Ward, 1936. 272 pages, 10x6 in., cloth, $8.00. Affords an account of the origin of photography and of its development to the end of the Daguerrean period, about 1651.

THEORETICAL ASTROPHYSICS, Atomic Theory and the Analysis of Stellar Atmospheres and Envelopes. By S. Rosseland. Oxford, England, Clarendon Press; New York, Oxford University Press, 1936. 355 pages, illustrated, 10x6 in., cloth, $8.00. Presents a mathematical and physical picture of the constitutions of stellar atmospheres, gaseous nebular and inter-stellar clouds projected to atomic physics as a background.

Introduction to PHYSICAL OPTICS. By J. K. Robertson. 2 editions. New York, D. Van Nostrand Company, 1935. 471 pages, illustrated, 9x6 in., cloth, $4.00. Aims to provide a comprehensive introduction to the subject.

MEN, MONEY, and MOLECULES. By W. Haynes. Garden City, N. Y., Doubleday, Doran and Company, 1936. 214 pages, illustrated, 8x5 in., leather, $1.50. An informal history of the American chemical industry, intended for the general reader.

Deutsches Museum Abhandlungen und Berichte, Jg. 8, Heft. 1. GRÖSZE und MASSE der MOLEKÜLE und ATOME. By E. Rüchardt. Berlin, VDI-Verlag, 1936, 27 pages, illustrated, 8x6 in., paper, 0.90 rm. A brief account of the methods used for investigating the size and mass of molecules and atoms.

74. VDI-HAUPTVERSAMMLUNG DARMSTADT 1936 und 80-Jahrfeier des Vereines Deutscher Ingenieure. FACHVORTRAGE. Berlin, VDI-Verlag, 1936. 406 pages, illustrated, 12x8 in., paper, 6 rm. Contains papers presented at the annual meeting of the Verein Deutscher Ingenieure. Special attention is given to problems connected with national resources in food, raw materials, and power.

PHOTOGRAPHY. By C. E. K. Mees. New York, Macmillan Company, 1937. 226 pages, illustrated, 9x6 in., cloth, $3.00. A review of the whole subject of photography. Based upon a series of Christmas lectures at the Royal Institution, London; simple and popular in style.

ART and the MACHINE, an Account of Industrial Design in 20th-Century America. By S. Cheney and M. C. Cheney. New York, McGraw-Hill Book Company (Whittlesey House), 1936. 307 pages, illustrated, 10x7 in., cloth, $3.75. Discusses the new field of "industrial design." Traces the development of this blending experiment through the last few decades.

DEUTSCHES MUSEUM. Abhandlungen und Berichte, Jg. 6, Heft 5, 1936. ENTWICKLUNG der KINOTECHNIK. By R. Thun. Berlin, VDI-Verlag, pages 111–138, illustrated, 8x6 in., paper, 0.90 rm. Gives a brief, popular outline of the development of moving pictures.

EVERY DAY BUT SUNDAY, the Romantic Age of New England Industry. By J. F. Copeland. Brattleboro, Vt., Stephen Daye Press, 1936. 294 pages, illustrated, 9x6 in., cloth, $2.50. The story of Mansfield, Mass., carried to the end of the nineteenth century. Gives a picture of an early industrial community; of considerable historic interest.

HANDMAIDEN of the SCIENCES. By E. T. Bell. Baltimore, Williams and Wilkins Company, 1937. 216 pages, illustrated, 9x6 in., cloth, $2.00. Shows that mathematics, in one sense queen, is also the servant of the sciences. Explains and demonstrates the usefulness of such concepts as conic sections, fourth and higher dimensions, continuity and discreteness, chance and probability.

COMMUNICATION ENGINEERING. By W. L. Everitt. 2nd edition. New York and London, McGraw-Hill Book Company, 1937. 727 pages, illustrated, 9x6 in., cloth, $5.00. Treats the subject of communication systems as distinct from power systems. Consideration is given only to general and fundamental aspects of network theory and layout. Based on the assumption that the reader already has the necessary groundwork in principles of a-c and d-c systems, and leaves specific applications to be studied in the field. The chapters on complex quantities and medium- and high-requency measurements have been deleted.

DEUTSCHES MUSEUM, Abhandlungen und Berichte, Jg. 8, Heft 6, 1936. Die ENTWICKLUNG der FUNKENTELEGRAPHIE, by J. Zenneck. Berlin, VDI-Verlag, 1936. Pages 139–171, diagrams, 8x6 in., paper, 0.90 rm. Traces the fundamental ideas of wireless telegraphy and the principal steps in its development.

ELECTRICAL MEASUREMENTS, Precise Comparisons of Standards and Absolute Determinations of the Units. By H. L. Curtis. New York and London, McGraw-Hill Book Company, 1937. 302 pages, illustrated, 9x6 in., cloth $4.00. Deals with methods used in absolute measurements of electric units. The introductory chapters cover definitions and the history of electrical units. Discusses each absolute measurement determination given, but considers only the precise ones. Brief appendixes give the computation of elliptic integrals and the results of absolute determinations of electrical units in various countries.

ELEKTRISCHE MESSGERÄTE und MESSEINRICHTUNGEN. By A. Palm. Berlin, Julius Springer, 1937. 231 pages, illustrated, 9x6 in., cloth, 16.50 rm. A textbook for engineers and students, presenting the principles and construction of electrical measuring instruments and their practical applications.

ELEMENTS of ELECTRICITY. By W. H. Timbie. 3rd edition. New York, John Wiley and Sons, 1937. 569 pages, illustrated, 9x6 in., cloth, $3.00. Provides a brief treatment of a few fundamental ideas that a technical student must know well. Presents new material on electronics and vacuum tubes, and covers electrical measurements, batteries, and d-c and a-c machinery.

(The) IDENTITY THEORY. By B. Stevens. 2nd edition, revised and enlarged. Manchester, England, Sherratt & Hughes; New York, C. E. Stechert and Co., 1936. 248 + 16 pages, illustrated, 9x6 in., cloth, 7s. 6d. Presents a mathematical theory of space-time relations as applied to the universe. Text is divided into articles, each one presenting a single argument. The reader is assumed to have had mathematical training.

INDUSTRIAL ELECTRICITY and WIRING. By J. A. Moyer and J. F. Wostrel. 2nd edition. New York and London, McGraw-Hill Book Company, 1937. 502 pages, illustrated, 8x6 in., cloth, $2.75. Based on the latest regulations of the National Electrical Code. Covers fundamental theory and practical wiring information.

INSTRUMENT TRANSFORMERS. By B. Hague. London, Sir Isaac Pitman and Sons; New York, Pitman Publishing Corporation, 1936. 656 pages, illustrated, 9x6 in., cloth, $10.00. An extensive summary of papers and magazine articles, with the object of giving a general view of the complete field covering theory, construction, characteristic features, and testing of instrument transformers.

JONES ANTENNA HANDBOOK, 1937 edition. By F. C. Jones. San Francisco, Pacific Radio Publishing Company, 64 pages, illustrated, 9x6 in., paper, $0.50. Aims to provide practical guidance in the selection and construction of the best type of antenna for any specified purpose and location.

LEHRBUCH der HOCHFREQUENZTECHNIK. By F. Vilbig. Leipzig, Akademische Verlagsgesellschaft, 1937. 775 pages, illustrated, 9x6 in., cloth, 32.80 rm. Aims to provide a review of theory and current practice in the field of high-frequency engineering.

MARINE ELECTRIC POWER. By Q. B. Newman. New York, Simmons-Boardman Publishing Corporation, 1937. 159 pages, illustrated, 9x5 in., cloth, $2.00. A collection of material reprinted from *Marine Engineering* and *Shipping Review*, designed to present simply the basic principles underlying the electrical equipment used on ships. Intended primarily for those who have had little groundwork in physics and mathematics.

MATHEMATICAL RECREATIONS and ESSAYS. By W. W. R. Ball. 10th edition. London and New York, Macmillan and Company, 1931. 366 pages, illustrated, 8x5 in., cloth, $3.50. Covers arithmetical, geometrical, and mechanical problems, magic squares, and chess and playing-card recreations. Contains discussions of cryptographs, ciphers, and various famous calculating prodigies.

NATIONAL ASSOCIATION OF RAILROAD and UTILITIES COMMISSIONERS. PROCEEDINGS of 48th Annual Convention, held at Atlantic City, N. J., November 10 to 13, 1936. New York, State Law Reporting Co., 541 pages, tables, 9x6 in., cloth, $6.00. Contains the discussions on the topics set for this meeting. Includes uniform systems of accounts for gas and electric companies, the operation of the federal motor-carrier act, the regulation of electric utilities and of telephone companies, progress in public-utility regulation, and public-utility rates.


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A collection of modern technical books is available to any member residing in North America at a rental rate of five cents per day per volume, plus transportation charges.

Many other services are obtainable and an inquiry to the director of the library will bring information concerning them.

# Industrial Notes

**Large Generating Units on Order.**—Orders have been placed by the Public Service Electric & Gas Co. (of N. J.) for a 50,000-kw turbine-generator and 2 high pressure steam boilers to be installed at the Essex generating station in Newark. This will increase the station's generating capacity from 193,000 kw to 243,000 kw. Boilers will be operated at 1,400 pounds pressure and at a temperature of 950 F, the highest combined temperature and pressure ever to be utilized in a generating station in this country. The turbine-generator will be built by the General Electric Co., and the steam boilers by the Babcock & Wilcox Co. Boilers will be equipped to burn either oil or pulverized coal and each will have a capacity of 605,000 pounds of steam per hour.

A third 110,000-kw turbine-generator unit will be added to the present River Rouge power plant of the Ford Motor Co. at Detroit, making the total installed capacity 350,000 kw. The new vertical compound turbine will be a duplicate of the second 110,000-kw unit, recently installed, for steam conditions of 1,200 pounds, 900 F. Hydrogen cooling is employed for the generators, which will be the 13th and 14th large turbine-driven units designed for hydrogen cooling to be built at the Schenectady works of the General Electric Co.

**New Equipment for Pennsylvania Railroad.**—After the April 14th directors' meeting of The Pennsylvania Railroad announcement was made that 2,800 new steel freight cars and the chassis for 11 new electric passenger locomotives of the heaviest and most powerful design will be constructed at the railroad's Altoona, Pa., works. The locomotives, known as the GG-1 type, will be assembled at Altoona with electrical parts supplied by the electrical manufacturing companies. The total cost of the equipment will be slightly in excess of $10,750,000. The new locomotives will supplement 58 others of the same type and 28 of a slightly different type already in use for high-speed passenger service in the electrified territory, and will provide part of the additional motive power required for the extension of the electrification now under way westward to Harrisburg, Pa.

**Fansteel Annual Report.**—The recently issued annual report of the Fansteel Metallurgical Corp., No. Chicago, Ill., shows an increase of slightly more than 50 per cent in sales over those for the corresponding period of 1936, despite a "sit-down" strike in February which interrupted all operations for nearly 2 weeks. The products of the company are based upon 4 metals—tantalum, columbium, tungsten and molybdenum having wide application in many industries, including the electrical manufacturing field. Tantalum is used in the production of electronic tubes and is the basis of the Balkite rectifiers and condensers. In addition to its use in lamp filaments tungsten has numerous uses in vacuum tubes, X-ray tubes, and neon signs. One of its principal uses is that for electrical contacts. The most common use for molybdenum is in electronic tubes and incandescent lamps. It is also used extensively in mercury switches and electrical contacts. Development of new metal alloys to be added to the company's line of products is in process and should be completed this year.

**Manufacturers Report Record Orders.**—General Electric Co. reports sales billed for the first quarter of 1937 as $73,412,420, compared with $51,423,071 for the same quarter last year, an increase of 43 per cent. Orders received during the first quarter of this year amounted to $105,747,030, compared with $59,569,879 for the same quarter of 1936, an increase of 78 per cent. This was the largest first quarter in the history of the Company.

Orders booked for the 3 months ending March 31, amounting to $74,242,584, by Westinghouse Electric & Mfg. Co., were the highest for any quarter on record and unfilled orders for the same period were the highest since 1923. The orders booked for the first 3 months of this year show an increase of 75 per cent over the same period in 1936.

**General Electric Opens Exhibit.**—An exhibit of electrical products for industry has been opened in the General Electric Building, 570 Lexington Ave., New York City. It brings together, in 7,000 square feet of floor space, a complete line of representative products of General Electric and its affiliates. Cable, distribution equipment, fractional-horsepower and integral motors, industrial control, industrial heating, lighting, meters and instruments, police radio, switchgear, transportation products, turbines and welding; the products of the incandescent lamp department, air conditioning department, and the construction material division and the plastics division of the appliance and merchandise department; and the products of the Trumbull Electric Co., General Electric X-Ray Corp., Warren Telechron Clock Co., General Electric Vapor Lamp Co., Bailey Meter Co., Locke Insulator Corp., and Carboloy Co., are on display. Much of the equipment is in operation.

# Trade Literature

**Insulators.**—Catalog supplement and 2 articles, 5 pp. Outlines the theory of the design of O-B radio-interference-free pintype insulators, known as "Silentypes;" includes complete descriptions of the units available. Ohio Brass Co., 360 N. Main St., Mansfield, O.

**Relays.**—Folder. Describes a comprehensive line of relays, timing devices, thermostats, electric counters, melting pots, ladles, etc. Struthers Dunn, Inc., 139 North Juniper St., Philadelphia, Pa.

**Recording Instruments.**—Bulletin GEA-1061F, 32 pp. Describes strip-chart recording instruments; illustrates some of the more important improvements that have been made in the complete line of portable and switchboard type CD equipment. General Electric Co., Schenectady, N. Y.

**Circuit Breakers.**—Bulletin 33-226, 8 pp. Describes construction, operation and applications of type F-124 indoor oil circuit breakers for industrial and central station use. Rated at 50,000-kva interrupting capacity, manually and electrically operated, non-automatic and automatic, single throw. Westinghouse Electric & Mfg. Co. E. Pittsburgh, Pa.

**Motor-Control Units.**—Bulletin 67, 16 pp. Describes steel-clad motor-control units, each complete with disconnect switches, bus bars, contactor-type switching mechanisms, safety door-interlocks, meters and all the equipment necessary to meet the requirements of the individual application. The Electric Controller & Mfg. Co., Cleveland, O.

**Magnetic Relays.**—Bulletin 81, 8 pp. Lists more than 100 relays for intermediate duty (10–15 amperes) on d-c and a-c circuits for 2 and 3 wire control. Includes valuable coil and contact data, contact arrangements, enclosures, and illustrates relays assembled from standard parts for use on special applications. Ward Leonard Electric Co., Mount Vernon, N. Y.

**Aerial Cables.**—Bulletin GEA-2215, 52 pp. The book is intended mainly as a treatise on power cable and aims to facilitate selection of insulated cable for overhead transmission and distribution. Tables are presented showing the current carrying capacities of cables in air and also methods of calculating regulation. Some installation data is included in the bulletin. General Electric Co., Schenectady, N. Y.

**Trolley Coaches.**—Bulletin B2088, 32 pp., "The Modern Trolley Coach." Includes the essential data on typical electric-powered coaches of which there are at present over one thousand in use. The booklet traces the development and growth of this means of commutative transportation and studies its field of application. Westinghouse Electric & Mfg. Co., E. Pittsburgh, Pa.

**Utility Distribution Supplies.**—Catalog 37, 166 pp. A comprehensive listing of electrical distribution and transmission underground and street lighting equipment. Items included cover heavy and secondary cable racks, guy guards, anchors, clamps and clevises of many types, cross arms, insulator and pole top pins, brackets, glass and porcelain insulators, fuswitches, mast arms and accessories, etc. Utilities Service Co., Allentown, Pa.

**Street Lighting Equipment.**—Catalog Secs. 60–250,–260,–270,–275,–280,–300,–330,–340 and –450. Describe lighting standards and fittings. These sections include descriptions of cast iron standards, Hollowspun Granite (concrete) standards, Union Metal steel standards, top sections and casings for standards, brackets and equipment for poles, ornamental crooks; also luminaires for street lighting, street lighting glassware, and paragon and octagonal pendants. Westinghouse Electric & Mfg. Co., Lighting Division, Cleveland, O.

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Registered U. S. Patent Office

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## The Cover

**A view, through the stator of a turbo-generator, of the Allis-Chalmers plant at Milwaukee, Wis., which may be visited by attendants at the Institute's 1937 summer convention**



# High Lights

**Radiobroadcasting.** Although radiobroadcasting stations in the United States operate on frequencies assigned so as to provide service to listeners throughout the country, practical limitations make impossible good reception on every one of the 100 frequency channels in the band of medium wave lengths for any one listener (*pages 666–70*). Frequencies of 30 or more megacycles per second have certain characteristics that make them particularly suitable for local broadcasting, and essential for television with present standards, but working frequencies in this region by no means are unlimited. Because such waves are limited in range almost to optical paths, they are unlikely to replace the medium-frequency waves now used for broadcasting over large areas (*pages 662–6*).

**Vibration.** Increasing the speed of machines imposes upon the engineer the necessity for seeking some means of reducing the amount of noise and vibration transmitted to the structures in which the machines are housed. Vibration isolation is one way of accomplishing this (*pages 735–8*). Instruments for precision measurement of vibration must measure amplitude, velocity, and acceleration. Fundamental requirements in the design of a general-purpose measuring instrument determining the useful frequency range, accuracy, amplitude range, and effect of the instrument on the vibrating body (*pages 706–10*).

**Insulation Co-ordination.** For several years a joint committee of Edison Electric Institute and National Electrical Manufacturers Association has been considering the subject of insulation co-ordination. As a result, basic impulse insulation levels now have been agreed upon, which constitutes the first step in the program (*pages 712–14*). A subcommittee has studied the factors that caused divergence in flashover values obtained by different commercial laboratories for the same test piece on impulse testing, and impulse and 60-cycle flashover values for rod gaps and insulators now have been agreed upon (*pages 711–12*).

**Recovery Voltages.** Determination of circuit recovery voltages for many different system conditions by actual tests is expensive and limited in scope. The voltages may be determined by analytical methods, which cannot consider all factors without becoming extremely complex, or by reproducing the system in miniature on an a-c calculating board and actually measuring the desired quantities (*pages 695–705*).

**Distribution Protection.** Investigation of the requirements of distribution systems for protection against surges shows that protectors should have a discharge capacity of 100,000 amperes, although a lower value may be satisfactory, and that a high degree of protection may be obtained in voltage classes up to 13.8 kv with a ratio of 9 to 1 for the protective-device discharge voltage and normal-frequency voltage (*pages 683–8*).

**Transformer Insulation.** For many years the transformer subcommittee of the AIEE committee on electrical machinery has been developing standards for the insulation strength of transformers. Impulse testing of insulation is one of the recent developments, and now the expression of impulse strength in terms of kilovolts instead of gap spacing is authorized (*pages 749–54*).

**Insulation Levels.** Insulation levels of transformers and other power system equipment should be selected according to the performance of the protective equipment such as lightning arresters and gaps; the level selected must be above the maximum surge voltage presumed to be allowed by the protective device on a volt-time basis over the range of time selected (*pages 677–82*).

**Security of Engineering Employment.** Data supplied by some 35,000 engineers shows that the degree of economic security among professional engineers, as evidenced by possession of an employment contract covering some period of time, or by pension privileges, is negligible (*pages 655–61*).

**Insulation Co-ordination.** Economy and the protection of service and equipment are the objectives of insulation co-ordination. Many data on the insulation strength of major equipment and protection available have been collected and are presented in graphical form in this issue (*pages 715–20*).

**Spill Gaps.** Theory and performance of spill gaps for the protection of electric circuits and equipment from lightning, together with a discussion of the selection of insulation levels co-ordinated with this type of protection, are presented in this issue (*pages 689–94*).

**Section and Branch Report.** The annual report of the Section and Branch activities for 1936–37 show that 621 meetings were held by AIEE Sections during the year, 81 more than during the preceding year; Student Branches held 1,363 meetings, by far the most ever held in a fiscal year (*pages 762–5*).

**District Meeting at Buffalo.** Active discussions on electrical equipment for steel mills and power system operation featured the Institute's North Eastern District meeting held recently at Buffalo, N. Y. The meeting included also a Student Branch convention (*pages 758–61*).

**Rotor Balancing.** Small gyro rotors such as are used in airplane flight instruments require balancing in production at speeds of 30,000 or 40,000 rpm. A machine using electrical means to detect unbalance is replacing older methods (*pages 729–34*).

**Oil-Filled Cables.** Improvements in oil-filled cable and associated equipment, have made possible economy and comparatively simple layout for about 100 miles of 66-kv oil-filled single-conductor cable now being installed in Chicago, Ill. (*pages 739–48*).

**Development of Standards.** The AIEE, with its technical committees covering all phases of the electrical art, many of which have active subcommittees, has an ideal setup for the development of material for electrical standards (*pages 653–4*).

**Prize Awards.** National prizes for technical papers presented at Institute meetings during 1936 have been awarded. Prize awards also have been announced by some of the Districts (*page 756*).

**Cathode-Ray Oscillograph.** A historical review of advances in the design of high-speed cathode-ray oscillographs, and a description of a new type of oscillograph, are included in this issue (*pages 721–8*).

**AEC Patent Report.** Action taken by the committee on patents of American Engineering Council during the year 1936 is summarized in the committee's annual report (*pages 766–7*).

**Noninflammable Insulating Oils.** A new type of synthetic insulating oil that obviates several of the problems heretofore associated with the use of mineral oil for insulation has been produced (*pages 671–6*).

**Summer Convention.** Final plans for the Institute's 1937 summer convention to be held at Milwaukee, Wis., June 21–25, are practically complete (*page 755*).

**New Members-for-Life.** Since June 1936, 92 members of the AIEE have become members-for-life (*page 757*).

Statements and opinions given in articles and papers appearing in ELECTRICAL ENGINEERING are the expressions of contributors, for which the Institute assumes no responsibility. Correspondence is invited on all controversial matters. ¶ Subscriptions—$12 per year to United States, Mexico, Cuba, Porto Rico, Hawaii, Philippine Islands, Central and South America, Haiti, Spain, Spanish Colonies; $13 to Canada; $14 elsewhere. Single copy $1.50. ¶ Address changes must be received by the fifteenth of the month to be effective with the succeeding issue. Copies undelivered because of incorrect address cannot be replaced without charge. ¶ ELECTRICAL ENGINEERING is indexed annually by the Institute, weekly and monthly by *Engineering Index*, and monthly by *Industrial Arts Index*; abstracted monthly by *Science Abstracts* (London). ¶ Copyright 1937 by the American Institute of Electrical Engineers. Number of copies this issue—19,800.

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# What Institute Sections Are Doing

## —A Message From the President

FROM my limited viewpoints, a primary activity of other Sections is enthusiastically to receive and delightfully entertain the president. At those meetings where the president was an invited guest, but not the primary speaker, there was the greatest opportunity to learn what the Section was doing "to advance the theory and practice of electrical engineering, and the allied arts and sciences, and to maintain a high professional standing among the members." A meeting each year with a national officer or officers is most desirable, not only that the Section may learn of national activities, but even more that the national officers may be informed as to the Section's viewpoints. Several times this year, the president joined in a luncheon meeting with a Section's executive committee. These meetings were very profitable.

Undoubtedly, the most important factors in a Section's success are the enthusiasm and devotion of the Section's officers. Service to the profession appears to hold the strongest appeal for a representative electrical engineer, and the energy and time devoted to Section affairs by the Section officers is astonishing. Those Sections where this spirit is diffused most widely among the membership are certainly the most successful. Many Sections hold an executive committee meeting prior to each Section meeting, and with excellent results.

I have stressed the opportunity open to the Section to participate in national Institute affairs by nominating one or more members for appointment to the national committees, and by submitting at least one technical paper for publication in ELECTRICAL ENGINEERING. Several Sections have embraced this opportunity. In several cities I have been impressed when I learned that the program for the succeeding year was completely planned prior to the first of July. This practice permits the completion of arrangements for the speakers during the summer months, and further permits the program to be printed and distributed at the first fall meeting of the Section. When the program is so arranged, it is well balanced, best meeting the needs of the various members. If Section finances permit, the membership roster may be combined effectively with program announcements. Those Sections which are following this practice testify to its success.

Usually 9 meetings are held, and integrating the information I have secured throughout my trips, the following seems to be a good classification as to the types of meetings held: 3 meetings are addressed by out-of-Section speakers on recent developments in the field of electrical engineering; 2 inspection trips to local plants, with a short paper by an engineer connected with the plant, outlining what may be observed on the trip; 1 meeting with a paper by a member of the Section on some developments in electrical engineering; 1 meeting attended by a national officer or officers; 1 meeting with a local Student Branch (if there is a Branch in the city or the vicinity); 1 social meeting.

This division of the program has not provided any meeting relating to the broad interest of the engineer beyond his primary professional activity. Such a meeting might replace one of the meetings addressed by a local speaker, and be arranged as a joint meeting with other groups of engineers in the same city or locality. All Sections testify to the difficulty of getting enough speakers from outside the Section to cover all the desired meetings, and those which have developed the practice of securing local speakers testify to the success of this plan. Often the members are much more interested in papers relating to technical activity in their own locality than in those having no bearing on their particular professional interests.

Several Sections sponsor addresses on semi-scientific subjects having a popular appeal, not necessarily related to electrical engineering. At such a meeting it is essential to have an outstandingly interesting speaker; in some places where this plan is followed, the meetings are self-supporting. It seems to me that such a plan is quite con-

sistent with the fundamental purpose of the Institute.

Among the most interesting meetings I have attended, have been those where a Section joined with a local Student Branch. In some cases the technical papers have been presented by members of the Branch. These meetings were well attended by the older Institute members who were glad to have an opportunity to co-operate with the young engineers in training, and to encourage their professional development. In one instance, several neighboring Branches joined in an inspection trip in the morning, were entertained at lunch, held an all-afternoon technical meeting, with 6 Branch papers, and joined with the Section in a dinner followed by an address. In a Western city, an interesting custom has been developed. Each of several devoted Institute members pledged themselves to entertain a Branch member at one of the Section meetings during the year. This resulted in 2 or 3 Branch members being present at each Section meeting as individual guests of some of the older engineers. I talked to some of the student guests, and they were very strong in their expressions of appreciation. I recall another outstanding type of Section meeting where the members of the Section are quite widely distributed, and have only 4 meetings a year; but each meeting starts at 2:30 and continues all afternoon and evening. Papers are presented by both Enrolled Students and members, the total number of papers being 6 or 8. Some members drive between 150 and 200 miles to attend, but those from the more distant points are unable to stay for the evening sessions.

From my observations, the best meeting is likely to be that in which there is the most discussion. Anything that can be done to stimulate discussion is desirable. In one city, the author requested 3 or 4 acquaintances to discuss his paper. Usually it is necessary for only 3 or 4 men to start the discussion and a very wide discussion results. Where 2 or more Sections are fairly close together, joint meetings are inspiring. Such a joint meeting might be preceded by a golf match in the afternoon, both Sections joining in dinner, followed by a technical session. Such a plan permits of a larger audience for some outstanding speaker from outside the Sections participating.

If 2 neighboring Sections each plan their programs considerably in advance, it is possible to arrange for one speaker to address the 2 Sections on succeeding evenings. Such an idea has been under discussion for years, but actually is being applied successfully to only a limited extent. One somewhat remote Section has considerable difficulty in securing outside speakers and has adopted the practice of asking their own members to review the English technical publications and present a digest on one or 2 of the most important contributions.

From all quarters of the country, I have learned that inspection trips are very popular and are largely attended. More meetings of this character are undoubtedly desirable.

I feel that there should be many more members of the Institute among those electrical engineers connected with companies using electric power and electrical equipment, but manufacturing other products. The engineers of such companies desire meetings and papers recording experience with the application of electricity and electrical equipment. It is my belief that if the technical committees would develop more papers of interest to this group of engineers, the organization would be rendering a service that would be greatly appreciated and would stimulate interest. A few of the Sections are holding meetings with this group of engineers particularly in mind. "Application" papers are usually of a broad general interest.

Several of the Sections have a monthly or quarterly publication, recording the activities and plans of the Section. The expense is not very great, and the results are good.

In one or 2 Sections, I find a committee covering the broad activities of the engineer. Each Section may be interested in organizing such a committee. I have observed that the most successful Sections are usually the most social Sections. I am not quite certain as to cause and effect, whether they are most social because they are most successful, or whether they are most successful because they are the most social. Some very light and inexpensive refreshments after meetings do add to sociability. In the West where many attend from a distance, a dinner preceding the meeting is usually held. If it is possible to develop the idea that attendance at the dinner is not necessary, but open to all, good results will follow.

Many Sections have organized specialized technical groups, holding additional meetings. Interest has been good and the meetings well attended. I have heard the statement made that it is not possible to organize such a group in a particular Section because there is not any very specialized industry. To such a Section I would suggest studying the list of technical committees to see if there is not some activity of unusual interest in that locality. For example, it might be desirable in some Sections to organize a general power application technical group, in others a technical education group.

I found one Section giving a great deal of consideration to sponsoring meetings for the benefit of men interested in electrical work, but not necessarily eligible for membership in the AIEE. It certainly seems quite in accord with the fundamental purposes of our organization, that the Institute Section should take the lead in arranging for speakers, and furnishing a meeting place where all the men interested in electrical work could receive information of value to them.

In a Western city, I heard a discussion as to whether it might not be possible to broadcast a Section meeting over short-wave radio. Several members of the Section had operator's licenses. This plan might not be consistent with governmental regulations, but deserves investigation.

One chairman told me that 3 or 4 years ago they wondered what they might do to carry on effectively the work of the AIEE. They decided that no more important meeting could be held than one that would offer the opportunity to every Section member to suggest what he thought might be done. This meeting was held, and since that time the principal problem has been to cover effectively all the suggestions that were made.

Several times I heard the thought expressed that each Section should have a committee on engineering co-operation with other engineering groups in the same city or locality. It seems very desirable that the engineering

activities covering all branches of the profession should be co-ordinated. It certainly is true that many of the questions which should interest the engineer are equally interesting to all types of engineers, whether they be mechanical, civil, electrical, or otherwise. No Institute member should forget the reference in Article 1 of our Constitution to "the allied arts and sciences."

It is my hope that Chairman W. H. Timbie and all members of the Sections committee will sponsor a paper to be printed in ELECTRICAL ENGINEERING next year on the subject "What The Other Sections Are Doing."



# Development of Standards Material

## A discussion of the responsibility of AIEE committees in aiding the development of electrical standards

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FOR an industry that manufactures and uses as large a variety of apparatus as the electrical industry, the problem of the development of standards is a tremendously important one. The purposes of standards are 2-fold: In the first place, they aid in the manufacture of products that are more uniform; in the second place, they form a basis that enables purchasers to obtain bids for new apparatus on a comparable basis.

For many years one of the chief duties of the AIEE has been the formulation and maintenance of standards for all kinds of electrical apparatus and machinery. In the past, purchasers of electrical apparatus have based their purchasing specifications largely on AIEE Standards.

So long as the Institute was the principal body in formulating electrical standards, the duties of its members and committees engaged in standardization were clearly understood. When, because of rapid developments in the art, other organizations—the National Electrical Manufacturers' Association, the Edison Electric Institute, the National Bureau of Standards, the American Society for Testing Materials, and others—found it necessary to formulate standards of their own, usually consisting largely of material not considered within the scope of AIEE Standards, it became desirable to co-ordinate the work of standardization under one central agency so constituted as to assure general acceptance. In 1918, therefore, on the basis of a plan formulated by the AIEE co-operating with the other national engineering societies, the Bureau of Standards, and others, the American Standards Association, or as it then was called, the American Engineering Standards Committee, was established. This organization grew rapidly, and under its procedure were developed many standardization projects outside the electrical field. Further to expedite and correlate electrical standardization under ASA procedure, the Electrical Standards Committee was created. The principal electrical standardization groups have representatives on this electrical standards committee, thus giving assurance that when a standard has the approval of the electrical standards committee it practically has the approval of the entire electrical industry and readily is accorded the status of American Standard by final action of ASA.

With this new setup, the question naturally arises as to what are the duties and responsibilities of the AIEE committees in the formulation and maintenance of electrical standards. The opinion seems to have developed that the ASA has taken over the standards-making obligation and that the Institute no longer has an active duty in the development of standards. This is an erroneous impression which should not exist, and this article aims to show why it still is the Institute's privilege and duty to develop standards material for submission to the ASA through the electrical standards committee. The ASA Council then will decide whether the material is ready for adoption as an American Standard, or whether it is desirable to organize a sectional committee to which it may be referred, with other pertinent material, for review and revision in order to assure general acceptance.

The Institute still has an ideal setup for the development of standards material, namely, the technical committees, covering all phases of the electrical art, many with active subcommittees. The Institute also has means for immediate and wide circulation of information and

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Written especially for ELECTRICAL ENGINEERING.

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data on proposed new developments. This is essential and valuable in keeping the Standards up-to-date and in avoiding long delays in final approval of revisions and of new developments.

To illustrate, the development of a typical new Standard is outlined: Some 6 or 7 years ago the electrical industry decided that consideration should be given to the development of a standard covering impulse testing of transformers. This work was assigned to the AIEE standards committee and by them to the AIEE electrical machinery committee. The machinery committee requested its transformer subcommittee, which was composed of representatives of both operators and manufacturers, to develop the new standards.

Before the standard on impulse tests could be proposed, much research work had to be done in both the laboratory and in the field. As this work went on, the results were published from time to time in ELECTRICAL ENGINEERING. This proved very helpful to the subcommittee. So much ground work had to be done that the subcommittee worked on the problem for 3 or 4 years before standards material could even be proposed, but as soon as the Proposed Standards on impulse testing were published in 1933 the industry accepted them. However, due to the rapid advances in the art and to the accumulation of new data, thought on the subject was not sufficiently crystallized until just recently to justify publication as Tentative American Standards. Publication in this form within the next few months is planned.

Had this work not been assigned to the AIEE, impulse testing of commercial transformers would have been seriously delayed—until the Standards were officially approved. In other words, due to the setup in the AIEE committees, together with the means for obtaining wide publicity for the work of the transformer subcommittee, the industry has been able to make use of the proposed standards material on impulse testing while it was in the developmental stage.

In addition to the formulation of new standards material on impulse testing, the AIEE transformer subcommittee during this time recommended several fundamental changes in the standards, all of which were accepted by the industry as soon as published.

Several years ago, it was decided to seek approval as American Standards for the AIEE Transformer Standards and at the same time to pass along the work done by the transformer subcommittee on proposed changes in those standards. After obtaining approval by the electrical machinery committee and the standards committee, the transformer standards and proposed revisions were turned over to the ASA for consideration as American Standards. To obtain such approval the ASA organized the sectional committee on transformers, *C*-57. While a great deal of work has been done by the sectional committee in getting together the material covered not only in the AIEE standards, but in the standards of other societies to be combined with them, no changes of a fundamental nature have been made by the sectional committee without having them first considered and approved by the AIEE. This is quite logical because, as pointed out hereinbefore, the ASA has no means of getting proposed fundamental changes before the industry until the standards are given final approval. This question of informing the industry of proposed changes in the standards is well illustrated in this case by the publication in ELECTRICAL ENGINEERING since 1933 of 2 reports by the AIEE transformer subcommittee. In many instances, however, it has proved more advantageous to follow a somewhat different procedure; that is, to have the reports published by the standards committee in pamphlet form for general distribution, with an announcement of their availability published in ELECTRICAL ENGINEERING.

The procedure followed by the AIEE and ASA in transformer standardization work is not limited at all to transformer problems, but can and should be followed by other committees working on standards for other types of apparatus. In other words, it is the very definite responsibility and duty of the AIEE technical committees to prepare and formulate standards material, developing it to a point where it is satisfactory to the industry. The current procedure then is for an AIEE technical committee to pass this work on to the AIEE standards committee. The standards committee then approves the material, if satisfactory, either for publication in report form, or for transmittal to the ASA for consideration and approval as American Standards.

There may be exceptions to this procedure, in which event action should be based on the conditions applying to the particular situation.



Photo courtesy Ohio Brass Company

**A transmission line of Fabulosa Mines Consolidated, Bolivia, S. A., high in the Andes Mountains. The peak in the background is Mt. Huayna Potosi, elevation 20,000 feet. The span is 350 meters long and consists of number 4 steel-reinforced aluminum cable**

*Montsinger, Farrer—Standards*

# Security of Engineering Employment

**Data obtained from 35,559 engineers by the United States Bureau of Labor Statistics in its survey of the engineering profession indicate that the degree of economic security among professional engineers, as evidenced by possession of an employment contract covering some period of time, or by pension privileges, was negligible. This is the fourth* in a series of articles reporting the results of the Bureau's survey.**

PRIOR to the onset of the depression in 1929, only nonprofessional workers were primarily concerned with the stability and security of employment. The effects of the depression years, however, were such as to bring about a quickening of interest in the subject of economic security even among professional workers. Because of this, a series of questions relating to this subject was incorporated into the Bureau's study of the engineering profession. Data were requested concerning the employment and separation contract, pension privileges, and the medium used to obtain a position, also whether or not the engineer reporting was under civil service, and what his status was with regard to patent rights.

The present article is based upon data supplied by 35,559 engineers who reported the field of engineering engaged in and who had an engineering job in December 1934.[1] Their reports indicate that 68.4 per cent of all professional engineers used personal contacts and recommendations to obtain their jobs. Those who used this medium, together with those who obtained their positions through the civil service, formed nearly $^4/_5$ of all reporting.

The degree of economic security among professional engineers, as evidenced by possession of an employment contract covering some period of time, or by pension privileges, was negligible.

In general, there appears to be little restriction upon professional engineers with regard to patent rights to inventions made by them. The extent of restriction, however, depended largely upon the engineer's field of employment and the type of work in which engaged.

## Means Used to Obtain Employment

The data furnished by engineers concerning the medium through which they obtained employment are presented in table I. These figures demonstrate that for the engineering profession as a whole, placement was not the function of any particular organization. The vast majority of professional engineers obtained their jobs through personal contacts and recommendations. This was the means used to find the position held in 1934 by no less than 68.4 per cent of the 35,559 engineers who also reported the field of engineering activity in which they were engaged. This medium of employment was reported by $^3/_4$ of the chemical, electrical, and mining and metallurgical engineers, and by slightly more than 70.0 per cent of the mechanical and industrial engineers, but by only 61.7 per cent of the civil engineers. The civil engineers, however, found more positions through civil service agencies; in fact, 2,941, or 80.0 per cent, of the 3,706 engineers who were classified under this medium were civil engineers. This is further emphasized by a consideration of the data for the 5 professional classes. Of the engineers who had engineering jobs in December 1934, 19.8 per cent of the civil engineers stated that these were found through the civil service, whereas among the remaining 4 professional classes, the range was from only 2.5 per cent for the chemical and ceramic to 4.6 per cent for the mining and metallurgical engineers.

It may be noted, however, that personal contacts and recommendations, together with civil service, accounted for 74.2 per cent of the mechanical and industrial engineers. For each of the remaining professional classes, these 2 mediums covered approximately $^4/_5$ of their respective totals, ranging from 78.4 per cent of the chemical and ceramic to 81.5 per cent of the civil engineers. Mechanical and industrial engineers reported relatively higher percentages of jobs obtained through an engineering society, a private employment agency, and newspapers. The most significant differences, however, will be noted for "medium not reported" and "any other medium." Thus, only in the case of civil, and mining and metallurgical engineers did "any other medium" embrace smaller proportions than those classified under "medium not reported." For the other 3 professional classes, this condition was reversed. Any other medium may well include a substantial number placed through their colleges, a point not covered in the questionnaire and one likely to affect the percentage noted in this classification.

Although the percentage distributions for the remaining avenues to employment do not embrace large numbers of each professional class, relatively they do present some striking contrasts. Only 2.4 per cent of all engineers reported that they obtained their positions through an engineering society. Some 3.7 and 2.7 per cent, respec-

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* An article prepared by Andrew Fraser, Jr., of the Division of Hours, Wages, and Working Conditions, Bureau of Labor Statistics, United States Department of Labor, which article was published in the May 1937 issue of *Monthly Labor Review*. Articles reporting other phases of this survey were published in ELECTRICAL ENGINEERING as follows: "Professional Aspects of Engineering Education," August 1936, pages 863–7; "Unemployment in the Engineering Profession," February 1937, pages 216–23; "Employment in the Engineering Profession," May 1937, pages 524–31. A detailed report of the survey will be published later in bulletin form by the Bureau of Labor Statistics.

1. The numbers reported in this article as engaged in engineering work in December 1934 cannot be compared with those shown in the discussion of employment. The former were derived from all of the 35,890 engineers who reported the field of engineering in which they were engaged. The discussion of employment dealt with all those older engineers who reported in the 3 years 1929, 1932, and 1934, and all 1930–32 engineers who reported in the years 1932 and 1934. The grand total, including the 1933–34 engineers, was 35,675.

Of the 35,890 engineers who gave income data in their special field, 331 did not report the year of their birth. Hence, 35,559 constitutes the base for all subsequent relationships with field of engineering engaged in. But 1,458 of these engineers did not report as to type of work engaged in, and hence 34,101 was used as a base figure for all subsequent relationships with functional classification.

tively, of the mechanical and industrial, and mining and metallurgical engineers were so classified. For the 3 remaining professional classes, the percentages ranged from 1.4 to 1.9. Despite the fact that so few engineers reported an engineering society as their employment medium, it must be recognized that such societies are an important factor in obtaining employment for professional engineers. It is obvious that through their members there must inevitably be a pooling of information on employment prospects, both locally and nationally. Furthermore, the officials of the various societies are kept in close touch with local and national employment

**Table I. Distribution of All Engineers Reporting Medium of Obtaining Employment, by Professional Class, at End of 1934**

| Medium Used to Obtain Employment | Engineers Utilizing Each Specified Medium | | | | | |
|---|---|---|---|---|---|---|
| | All Professional Classes | Chemical and Ceramic Engineers | Civil, Agricultural, and Architectural Engineers | Electrical Engineers | Mechanical and Industrial Engineers | Mining and Metallurgical Engineers |
| | Number | | | | | |
| All mediums | 35,559 | 2,538 | 14,861 | 6,816 | 9,833 | 1,511 |
| Personal contacts and recommendations | 24,312 | 1,927 | 9,179 | 5,106 | 6,960 | 1,140 |
| Civil service | 3,706 | 63 | 2,941 | 289 | 343 | 70 |
| Engineering society | 841 | 36 | 274 | 130 | 360 | 41 |
| Private employment agency | 576 | 49 | 113 | 112 | 285 | 17 |
| Newspapers | 567 | 27 | 152 | 120 | 255 | 13 |
| Technical journals | 363 | 54 | 142 | 64 | 85 | 18 |
| United States Employment or Reemployment Service | 264 | 7 | 190 | 14 | 46 | 7 |
| Other public employment service | 268 | 15 | 169 | 26 | 54 | 4 |
| Any other medium | 2,551 | 259 | 706 | 655 | 849 | 82 |
| Medium not reported | 2,111 | 101 | 995 | 300 | 596 | 119 |
| | Per Cent | | | | | |
| All mediums | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 |
| Personal contacts and recommendations | 68.4 | 75.9 | 61.7 | 75.0 | 70.7 | 75.4 |
| Civil service | 10.4 | 2.5 | 19.8 | 4.2 | 3.5 | 4.6 |
| Engineering society | 2.4 | 1.4 | 1.8 | 1.9 | 3.7 | 2.7 |
| Private employment agency | 1.6 | 1.9 | 0.8 | 1.6 | 2.9 | 1.1 |
| Newspapers | 1.6 | 1.1 | 1.0 | 1.8 | 2.6 | 0.9 |
| Technical journals | 1.0 | 2.1 | 1.0 | 0.9 | 0.9 | 1.2 |
| United States Employment or Reemployment Service | 0.7 | 0.3 | 1.3 | 0.2 | 0.5 | 0.5 |
| Other public employment service | 0.8 | 0.6 | 1.1 | 0.4 | 0.5 | 0.3 |
| Any other medium | 7.2 | 10.2 | 4.8 | 9.6 | 8.6 | 5.4 |
| Medium not reported | 5.9 | 4.0 | 6.7 | 4.4 | 6.1 | 7.9 |

conditions as a result of their meetings and conventions; but such appointments as are made would depend rather upon personal contacts and recommendations than upon contacts made through the society's employment service. The fact, therefore, that only 2.4 per cent of all engineers reported the engineering society as their medium of employment must be interpreted in the light of these conditions.

The securing of employment through newspapers and technical journals was reported by 1.6 and 1.0 per cent, respectively, of all engineers making returns. It will be noted however that, relatively, electrical and mechanical and industrial engineers found more jobs through newspapers than did any of the other professional classes; this medium was reported by 1.8 per cent of the electrical and 2.6 per cent of the mechanical and industrial engineers, whereas, among the other classes the highest percentage was 1.1. On the other hand, technical journals as a medium of employment were of more assistance to chemical and ceramic engineers (2.1 per cent); among the remaining professional classes percentages ranged from 0.9 to 1.2.

Private employment agencies were used by only 1.6 per cent of all engineers reported. When considered together, the 2 public employment agencies embraced approximately the same proportion, namely, 1.5 per cent. A similar comparison among the 5 professional classes showed that, relatively, public agencies were of more importance to civil engineers, of whom 2.4 per cent so reported, whereas the next highest percentage was 1.0 per cent for mechanical and industrial engineers. Only 0.8 per cent of the civil engineers used private employment agencies to obtain jobs, but 2.9 per cent of the mechanical and industrial engineers did so; for the remaining professional classes, the percentages ranged from 1.1 to 1.9 per cent.

## Economic Security in the Engineering Profession

A written contract of employment and pension privileges are 2 important criteria of economic security. The efficacy of any such schemes, however, depends to a marked extent upon the nature of the employment. This is demonstrated by a comparison of the data concerning economic security among professional engineers who reported being engaged in public engineering, personal service, and private engineering.

### Civil-Service Status

The importance of civil-service status as a factor in stability of employment is shown in table II. Despite the fact that, in all, 11,177 of the engineers reporting were in the employ of public authorities in December 1934, only 45.0 per cent reported being under civil service. The proportion of all engineers with civil-service status was 48.4 per cent for positions under the Federal Government, and for employment with state and county, and municipal and other public authorities, 36.1 and 45.6 per cent, respectively. This percentage under civil service of these engineers employed by the Federal Government was higher than in the 2 other public employments, despite the enormous increase in Federal Government employment by December 1934, because of the amount of temporary employment under the work-relief programs; it may be assumed that relatively few engineers so employed would be classified under civil service. Consequently, under normal circumstances, the proportion of all engineers under civil service with the Federal Govern-

ment would be higher than 48.4 per cent. With regard to the other 2 classes of public engineering, it may be recalled that the numbers of engineers so engaged remained comparatively stable over the period 1930–34. Hence, the proportions reported being under civil service are representative of the situation.

The relative proportions of each professional class under civil service differed very markedly among the 3 classes of public engineering employment. The smallest range occurred in Federal positions—from 45.1 per cent for electrical engineers to 62.0 per cent for mining and metallurgical engineers. These 2 professional classes also constituted the extremes of the range of the proportions embraced by municipal governments, but in reverse order. Thus, of the mining and metallurgical engineers in municipal employment, 30.4 per cent, and of the electrical engineers, 57.1 per cent, had civil-service status. Relatively, the smallest numbers of each professional class under civil service were found in state and county governments. This is best exemplified by the comparative data for civil engineers; of their number 47.9 and 43.8 per cent, respectively, in Federal and municipal employments but only 38.0 per cent in state and county positions had civil-service status. But since the civil engineers comprised approximately 80.0 per cent of the 5,038 engineers under civil service, obviously such a status is a significant contributory factor to the stability of employment.

**Table II. Distribution of All Engineers Reporting as to Civil-Service Status, by Field of Activity and Professional Class, at End of 1934**

| Field of Employment and Professional Class | Number | | | | Per Cent | | | |
|---|---|---|---|---|---|---|---|---|
| | Total | Without Status | With Status | Not Reporting | Total | Without Status | With Status | Not Reporting |
| Federal Government | 4,649 | 2,084 | 2,250 | 315 | 100.0 | 44.8 | 48.4 | 6.8 |
| Chemical and ceramic | 74 | 22 | 44 | 8 | 100.0 | 29.7 | 59.5 | 10.8 |
| Civil, agricultural, and architectural | 3,620 | 1,649 | 1,734 | 237 | 100.0 | 45.6 | 47.9 | 6.5 |
| Electrical | 306 | 143 | 138 | 25 | 100.0 | 46.7 | 45.1 | 8.2 |
| Mechanical and industrial | 549 | 240 | 272 | 37 | 100.0 | 43.7 | 49.6 | 6.7 |
| Mining and metallurgical | 100 | 30 | 62 | 8 | 100.0 | 30.0 | 62.0 | 8.0 |
| State and county governments | 4,438 | 2,487 | 1,604 | 347 | 100.0 | 56.1 | 36.1 | 7.8 |
| Chemical and ceramic | 37 | 30 | 3 | 4 | 100.0 | 81.1 | 8.1 | 10.8 |
| Civil, agricultural, and architectural | 4,044 | 2,203 | 1,535 | 306 | 100.0 | 54.4 | 38.0 | 7.6 |
| Electrical | 134 | 91 | 33 | 10 | 100.0 | 67.9 | 24.6 | 7.5 |
| Mechanical and industrial | 170 | 123 | 28 | 19 | 100.0 | 72.3 | 16.5 | 11.2 |
| Mining and metallurgical | 53 | 40 | 5 | 8 | 100.0 | 75.5 | 9.4 | 15.1 |
| Municipal governments | 2,090 | 1,028 | 952 | 110 | 100.0 | 49.1 | 45.6 | 5.3 |
| Chemical and ceramic | 54 | 28 | 23 | 3 | 100.0 | 51.8 | 42.6 | 5.6 |
| Civil, agricultural, and architectural | 1,617 | 829 | 709 | 79 | 100.0 | 51.3 | 43.8 | 4.9 |
| Electrical | 238 | 88 | 136 | 14 | 100.0 | 37.0 | 57.1 | 5.9 |
| Mechanical and industrial | 158 | 70 | 77 | 11 | 100.0 | 44.3 | 48.7 | 7.0 |
| Mining and metallurgical | 23 | 13 | 7 | 3 | 100.0 | 56.6 | 30.4 | 13.0 |

## The Employment Contract

For the engineering profession as a whole, the data in table III clearly evidence a lack of economic security in terms of a written contract which would secure employment over a substantial period of time. In all, only 3,169, or 8.9 per cent, of the 35,559 engineers who reported employment in an engineering field[2] were covered by a written contract. Of these, some 0.8 per cent had a contract for less than 1 year, 3.5 per cent a contract for between 1 and 2 years, and only 0.9 per cent for 2 years or more. Engineers who did not report as to period of contract formed 3.7 per cent of the whole. No less than 91.1 per cent either answered "no" or did not furnish specific information.

Comparison of the positive returns on employment contract from all engineers in the 3 broad fields of engineering activity shows that use of the contract was most common in personal service—primarily education.

For engineers under contract in the personal-service field the most common contract period (reported by 25.6 per cent of the 2,778 engineers so engaged) was from 1 to 2 years. Some 4.0 per cent were under contract for periods of 2 years or longer. Although the corresponding percentages for public engineering were much lower than for personal service, they were higher than for private engineering. For employment contracts under 1 year, however, private exceeded public engineering (1.0 per cent, as against 0.5 per cent). Of all reporting engineers engaged in public engineering, 2.0 per cent had contracts for 1 and under 2 years, and 1.1 per cent for periods of 2 years and over. The corresponding percentages for private engineering were 1.4 and 0.5 per cent.

For the separate fields of activity under private engineering, relatively the largest proportion of engineers under contract in their jobs occurred in manufacturing, with 408, or 3.8 per cent, of the 10,888 reporting as so engaged. In the construction and extractive industries 3.0 and 2.0 per cent, respectively, had written contracts. The smallest proportions under contract were reported by engineers in the employ of public utilities or engaged in transportation (1.1 and 0.9 per cent, respectively). In public engineering, there was a marked contrast in contract status between Federal positions and those in the 2 other categories of public engineering. Thus, while only 2.3 per cent of the 4,649 reporting engineers in Federal employ were on con-

2. Throughout the whole of this discussion, only engineering employment is considered. Consequently, no cognizance has been taken of the economic security of engineers engaged in nonengineering employment.

## Table III. Distribution of All Engineers Reporting Employment Contract, by Field of Employment at End of 1934

| Field of Employment | Number | | | | | | Per Cent | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Under Contract for— | | | Under Contract, No Period Reported | Not Reporting* | | Under Contract for— | | | Under Contract, No Period Reported | Not Reporting* |
| | Total | Under 1 Year | 1 and Under 2 Years | 2 Years and Over | | | Total | Under 1 Year | 1 and Under 2 Years | 2 Years and Over | | |
| All fields | 35,559 | 295 | 1,234 | 330 | 1,310 | 32,390 | 100.0 | 0.8 | 3.5 | 0.9 | 3.7 | 91.1 |
| Private engineering | 21,604 | 212 | 298 | 99 | 637 | 20,358 | 100.0 | 1.0 | 1.4 | 0.5 | 2.9 | 94.2 |
| Construction | 3,437 | 32 | 63 | 12 | 113 | 3,217 | 100.0 | 0.9 | 1.8 | 0.3 | 3.3 | 93.7 |
| Extractive industries | 1,841 | 11 | 21 | 6 | 60 | 1,743 | 100.0 | 0.6 | 1.1 | 0.3 | 3.3 | 94.7 |
| Public utilities | 4,183 | 16 | 21 | 8 | 50 | 4,088 | 100.0 | 0.4 | 0.5 | 0.2 | 1.2 | 97.7 |
| Transportation | 1,255 | 5 | 4 | 2 | 17 | 1,227 | 100.0 | 0.4 | 0.3 | 0.2 | 1.4 | 97.7 |
| Manufacturing | 10,888 | 148 | 189 | 71 | 397 | 10,083 | 100.0 | 1.4 | 1.7 | 0.7 | 3.6 | 92.6 |
| Public engineering | 11,177 | 53 | 224 | 121 | 295 | 10,484 | 100.0 | 0.5 | 2.0 | 1.1 | 2.6 | 93.8 |
| Federal Government | 4,649 | 33 | 42 | 34 | 181 | 4,359 | 100.0 | 0.7 | 0.9 | 0.7 | 3.9 | 93.8 |
| State and county governments | 4,438 | 15 | 125 | 50 | 81 | 4,167 | 100.0 | 0.3 | 2.8 | 1.1 | 1.8 | 94.0 |
| Municipal governments | 2,090 | 5 | 57 | 37 | 33 | 1,958 | 100.0 | 0.2 | 2.7 | 1.8 | 1.6 | 93.7 |
| Personal service | 2,778 | 30 | 712 | 110 | 378 | 1,548 | 100.0 | 1.1 | 25.6 | 4.0 | 13.6 | 55.7 |

* Also includes those who reported "no," which number could not be separated in the tabulation.

tract, the proportion working on this basis for state and county, and municipal governments formed, respectively, 4.2 and 4.7 per cent of their grand totals.

The type of work in which engineers under contract were engaged is presented in table IV. In general, the distribution followed the same trend as shown in table III, that is to say, the largest groups had written contracts for periods from 1 and under 2 years. Table IV also confirms the previous finding that engineers engaged in teaching are relatively more secure with regard to employment than other members of the engineering profession: 33.8 per cent of their number reported written contracts for periods of from 1 to 2 years. Sales employments, next in order, had under contract for a similar period only 3.9 per cent of their 1,513 reporting engineers, and general administration and management only 2.3 per cent. Each of the other functional classes had less than 2.0 per cent. Even for the contract periods of 2 years and over, teaching covered 4.8 per cent of the total reported for this functional class. The next highest percentage, namely, 1.5, was reported for general administration and management. In no one of the remaining employments did the percentage of engineers with written contracts for 2 years and over exceed 0.8 per cent.

Thus, with regard to fields of activity or the functional classes within them, the engineering profession cannot be said to have any substantial security of employment provided through a written contract for a period of time. However, professional engineers are not generally restricted with regard to the seeking of employment similar to that in which they may be engaged. This is evidenced by a consideration of the data furnished by professional engineers concerning their separation-contract status (tables V and VI).

Only 1.4 per cent of all the reporting engineers stated that they were under a contract for a definite period of time during which they bound themselves not to seek similar employment. This included 0.8 per cent whose separation contracts were for less than 1 year, 0.2 per cent for a period of from 1 to 2 years, and 0.4 per cent for 2 years and over. Clearly, restrictions upon professional engineers with regard to new employment were few.

It may be noted in table V, however, that 2.1 per cent of the reporting engineers in personal service were under separation contracts for less than one year, whereas the proportion in extractive industries and manufacturing was 1.0 per cent each. The reason for the relatively greater use of the separation contract in personal service is not clear. In extractive industries and manufacturing, the use of secret processes probably makes necessary some

## Table IV. Distribution of All Engineers Reporting Employment Contract, by Type of Work Engaged in at End of 1934

| Type of Work | Number | | | | | | Per Cent | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Under Contract for— | | | Under Contract No Period Reported | Not Reporting* | | Under Contract for— | | | Under Contract No Period Reported | Not Reporting* |
| | Total | Under 1 Year | 1 and Under 2 Years | 2 Years and Over | | | Total | Under 1 Year | 1 and Under 2 Years | 2 Years and Over | | |
| All types | 34,101 | 288 | 1,196 | 311 | 1,236 | 31,070 | 100.0 | 0.8 | 3.5 | 0.9 | 3.6 | 91.2 |
| Design and research | 9,050 | 106 | 119 | 52 | 305 | 8,468 | 100.0 | 1.2 | 1.3 | 0.6 | 3.4 | 93.5 |
| Construction | 8,233 | 39 | 153 | 63 | 209 | 7,769 | 100.0 | 0.5 | 1.9 | 0.8 | 2.5 | 94.3 |
| Operation | 8,276 | 57 | 79 | 38 | 148 | 7,954 | 100.0 | 0.7 | 1.0 | 0.5 | 1.8 | 96.0 |
| Consulting | 2,146 | 26 | 30 | 11 | 80 | 1,999 | 100.0 | 1.2 | 1.4 | 0.5 | 3.7 | 93.2 |
| Teaching | 2,050 | 24 | 692 | 98 | 350 | 886 | 100.0 | 1.2 | 33.8 | 4.8 | 17.1 | 43.1 |
| Sales | 1,513 | 15 | 59 | 7 | 56 | 1,376 | 100.0 | 1.0 | 3.9 | 0.5 | 3.7 | 90.9 |
| General administration and management | 2,833 | 21 | 64 | 42 | 88 | 2,618 | 100.0 | 0.7 | 2.3 | 1.5 | 3.1 | 92.4 |

* Also includes those who reported "no," which number could not be separated in the tabulation.

## Table V. Distribution of All Engineers Reporting Separation Contract, by Field of Employment at End of 1934

| Field of Employment | Number | | | | | | Per Cent | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Under Contract for— | | | Under Contract, No Period Reported | Not Reporting* | | Under Contract for— | | | Under Contract, No Period Reported | Not Reporting* |
| | Total | Under 1 Year | 1 and Under 2 Years | 2 Years and Over | | | Total | Under 1 Year | 1 and Under 2 Years | 2 Years and Over | | |
| All employments | 35,559 | 287 | 77 | 128 | 95 | 34,972 | 100.0 | 0.8 | 0.2 | 0.4 | 0.3 | 98.3 |
| Private engineering | 21,604 | 180 | 67 | 124 | 38 | 21,195 | 100.0 | 0.8 | 0.3 | 0.6 | 0.2 | 98.1 |
| Construction | 3,437 | 32 | 5 | 8 | 10 | 3,382 | 100.0 | 0.9 | 0.1 | 0.2 | 0.3 | 98.5 |
| Extractive industries | 1,841 | 19 | 1 | 2 | 4 | 1,815 | 100.0 | 1.0 | 0.1 | 0.1 | 0.2 | 98.6 |
| Public utilities | 4,183 | 16 | 2 | 2 | 4 | 4,159 | 100.0 | 0.4 | (†) | (†) | 0.1 | 99.5 |
| Transportation | 1,255 | 2 | | | 2 | 1,251 | 100.0 | 0.2 | | | 0.2 | 99.6 |
| Manufacturing | 10,888 | 111 | 59 | 112 | 18 | 10,588 | 100.0 | 1.0 | 0.5 | 1.0 | 0.2 | 97.3 |
| Public engineering | 11,177 | 50 | 3 | 2 | 26 | 11,096 | 100.0 | 0.4 | (†) | (†) | 0.2 | 99.4 |
| Federal Government | 4,649 | 16 | 1 | 2 | 8 | 4,622 | 100.0 | 0.3 | (†) | (†) | 0.2 | 99.5 |
| State and county governments | 4,438 | 27 | 1 | | 10 | 4,400 | 100.0 | 0.6 | (†) | | 0.2 | 99.2 |
| Municipal governments | 2,090 | 7 | 1 | | 8 | 2,074 | 100.0 | 0.3 | (†) | | 0.4 | 99.3 |
| Personal service | 2,778 | 57 | 7 | 2 | 31 | 2,681 | 100.0 | 2.1 | 0.3 | 0.1 | 0.1 | 96.4 |

* Also includes those who reported "no," which number could not be separated in the tabulation.
† Less than 1/10 of 1 per cent.

protection for the employer. It is evident, however, that even for these fields such a contract is seldom required. This freedom from restriction with regard to other employment is also apparent from table VI. Only 2 functional classes—teaching and sales—covered more than 1.0 per cent of their respective totals, and in neither did the period of contract exceed one year. In the teaching profession 2.5 per cent of the engineers were under separation contract and in sales 1.9 per cent; none of the other groups exceeded 0.8 per cent. Notwithstanding, it is significant that some 0.7 per cent of the engineers engaged in design and research were under separation contract for periods for 2 years and more.

### Provision for Retirement on Pension

An analysis of the data furnished by professional engineers concerning their pension privileges is presented in table VII. As of December 1934, 10,641, or almost 1/3, of the 35,559 professional engineers reporting who had engineering jobs at that time stated that they had pension privileges. Of this number, 6,684, or 18.8 per cent, were covered by contributory pension schemes, and 3,957, or 11.1 per cent by noncontributory schemes. Some 57.8 per cent were in employments for which no pension provision had been made. About 12.3 per cent did not furnish information.

Of the engineers in pensionable positions, the smallest relative proportion, 26.2 per cent, were engaged in private engineering. By contrast, 37.4 per cent of the engineers engaged in public engineering and 29.0 per cent of those in personal service had pension privileges. It may be noted also that for public engineering and personal service the contributory scheme predominated. Of the engineers engaged in private engineering, the largest proportion was covered by noncontributory systems. However, within the private-engineering group marked differences were shown; the same was true of the 3 categories of public engineering.

The largest number of professional engineers covered by a pension plan were those in the employ of the Federal Government. Out of a total employment of 4,649 engineers reporting, 43.2 per cent were under a contributory and only 5.3 per cent under a noncontributory plan. The corresponding proportions in positions with state and

## Table VI. Distribution of All Engineers Reporting Separation Contract, by Type of Work Engaged in at End of 1934

| Type of Work | Number | | | | | | Per Cent | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Under Contract for— | | | Under Contract, No Period Reported | Not Reporting* | | Under Contract for— | | | Under Contract, No Period Reported | Not Reporting* |
| | Total | Under 1 Year | 1 and Under 2 Years | 2 Years and Over | | | Total | Under 1 Year | 1 and Under 2 Years | 2 Years and Over | | |
| All types | 34,101 | 274 | 72 | 122 | 93 | 33,540 | 100.0 | 0.8 | 0.2 | 0.4 | 0.3 | 98.3 |
| Design and research | 9,050 | 68 | 33 | 62 | 15 | 8,872 | 100.0 | 0.8 | 0.4 | 0.7 | 0.2 | 97.9 |
| Construction | 8,233 | 45 | 9 | 2 | 18 | 8,159 | 100.0 | 0.5 | 0.1 | (†) | 0.2 | 99.2 |
| Operation | 8,276 | 52 | 12 | 33 | 16 | 8,163 | 100.0 | 0.6 | 0.1 | 0.4 | 0.2 | 98.7 |
| Consulting | 2,146 | 10 | | 9 | 8 | 2,119 | 100.0 | 0.5 | | 0.4 | 0.4 | 98.7 |
| Teaching | 2,050 | 51 | 6 | | 31 | 1,962 | 100.0 | 2.5 | 0.3 | | 1.5 | 95.7 |
| Sales | 1,513 | 28 | 6 | 5 | 1 | 1,473 | 100.0 | 1.9 | 0.4 | 0.3 | 0.1 | 97.3 |
| General administration and management | 2,833 | 20 | 6 | 11 | 4 | 2,792 | 100.0 | 0.7 | 0.2 | 0.4 | 0.1 | 98.6 |

* Also includes those who reported "no," which number could not be separated in the tabulation.
† Less than 1/10 of 1 per cent.

county, and municipal governments were very much less—26.9 and 1.3 per cent, respectively. For municipal-government employment the figures were 29.9 and 2.4 per cent. This order of difference parallels that of the proportions of engineers under civil service in these 3 classes of employment, but only in the case of the Federal Government are the 2 proportions closely related. This arises from the fact that, whereas all persons under Federal civil service must contribute to the retirement fund, this is not true to the same extent for employments under state and county, and municipal governments, where age, length of service, and salary are also taken into consideration.

Among the remaining fields of activity, public utilities and transportation reported the next highest proportions (after Federal employment) as having pension privileges. Public utilities and transportation used the noncontributory scheme; this type of plan covered 37.2 per cent in utilities and 33.1 per cent in transportation; contributory systems covered only 8.2 and 9.6 per cent, respectively, of those reporting. For the 3 remaining pursuits shown under private engineering, the largest number of engineers with pension privileges did not exceed 25.7 per cent, and in all cases contributory schemes predominated.

From the preceding discussion of the pension privileges it is quite evident that the kind of employment has a marked effect upon the question of the installation of a pension scheme. In no type of engineering employment was a majority of the reporting engineers protected by such a plan.

**Table VII. Distribution of All Engineers Reporting Pension Privileges, by Field of Employment at End of 1934**

| Field of Employment | Number | | | | | Per Cent | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | Pension Privilege | | | | | Pension Privilege | | |
| | Total | No Pension | Contributory Plan | Non-contributory Plan | Not Reporting | Total | No Pension | Contributory Plan | Non-contributory Plan | Not Reporting |
| All employments | 35,559 | 20,556 | 6,684 | 3,957 | 4,362 | 100.0 | 57.8 | 18.8 | 11.1 | 12.3 |
| Private engineering | 21,604 | 13,207 | 2,265 | 3,387 | 2,745 | 100.0 | 61.1 | 10.5 | 15.7 | 12.7 |
| Construction | 3,437 | 2,445 | 174 | 138 | 680 | 100.0 | 71.1 | 5.1 | 4.0 | 19.8 |
| Extractive industries | 1,841 | 1,109 | 272 | 200 | 260 | 100.0 | 60.2 | 14.8 | 10.9 | 14.1 |
| Public utilities | 4,183 | 1,833 | 341 | 1,555 | 454 | 100.0 | 43.7 | 8.2 | 37.2 | 10.9 |
| Transportation | 1,255 | 576 | 120 | 416 | 143 | 100.0 | 45.9 | 9.6 | 33.1 | 11.4 |
| Manufacturing | 10,888 | 7,244 | 1,358 | 1,078 | 1,208 | 100.0 | 66.5 | 12.5 | 9.9 | 11.1 |
| Public engineering | 11,177 | 5,791 | 3,827 | 357 | 1,202 | 100.0 | 51.8 | 34.2 | 3.2 | 10.8 |
| Federal Government | 4,649 | 1,850 | 2,009 | 248 | 542 | 100.0 | 39.8 | 43.2 | 5.3 | 11.7 |
| State and county governments | 4,438 | 2,723 | 1,193 | 58 | 464 | 100.0 | 61.3 | 26.9 | 1.3 | 10.5 |
| Municipal governments | 2,090 | 1,218 | 625 | 51 | 196 | 100.0 | 58.3 | 29.9 | 2.4 | 9.4 |
| Personal service | 2,778 | 1,558 | 592 | 213 | 415 | 100.0 | 56.1 | 21.3 | 7.7 | 14.9 |

## Patent Privileges in the Engineering Profession

Information as to patent privileges was furnished by 61.6 per cent of the 35,559 reporting engineers with engineering jobs at the end of 1934 (table VIII). Of all engineers covered, 31.7 per cent reported retention of the patent rights for all inventions made either in the course of their work or in fields not directly related to their work. Among the nine separate fields of employment this was true of the largest group in each case, except in manufacturing where the highest proportion (30.1 per cent) reported that they had no rights to patents relating to their work, but did retain their rights to those not directly related to their work. This latter combination ["(1) no; (2) yes," in table VIII] ranked second in importance and included 16.9 per cent of the 35,559 engineers. The third group in importance (including 4,575, or 12.9 per cent) was that reporting complete restriction on both aspects of patent privileges. Only 42 engineers, less than 0.1 per cent of the total, reported that they retained the rights to inventions connected with their duties but not to those not so connected.

It would seem that, comparatively, there is only slight restriction on the retention of patent rights among professional engineers, although its extent varies in the different fields of employment. Thus, relatively the greatest restriction was placed upon engineers engaged in manufacturing 19.0 per cent of whom reported complete restriction, 30.1 per cent the right to patent inventions not directly related to their work but not to those made in the course of their work, and only 23.1 per cent no restrictions. In the extractive industries the limitations, while less severe than in manufacturing, were nevertheless greater than in any of the other branches of private engineering. Complete restriction was reported by 15.6 per cent of the engineers in the extractive industries, by 11.8 per cent of those in construction, and by 11.4 per cent of those in transportation; the smallest proportion, 8.9 per cent, was reported for engineers in the employ of public utilities.

It has already been noted that in manufacturing, some 30.1 per cent of the engineers so engaged had the right to patent inventions not directly related to their work, but not to those made in the course of their work. This partial restriction was very much less for the remaining fields of activity in private engineering. In extractive industries, only 18.6 per cent so reported, in transportation 17.3 per cent, and in public utilities 16.0 per cent. Partial restriction affected only 8.6 per cent of the engineers engaged in construction. These same 4 fields of activity,

however, did report larger proportions as being unrestricted with regard to patent privileges. These ranged from 32.6 for extractive industries to 42.4 per cent for public utilities. In this regard, it may be recalled that only 23.1 per cent of the engineers in manufacturing so reported.

In the 3 classes of public engineering, there was a marked divergence in the restrictions placed upon patent privileges. This was greatest for engineers in the employ of the Federal Government, 12.2 per cent of whom had no patent privileges whatsoever, whereas in state and country, and municipal governments only some 9.0 per cent were under complete restriction. Partial restriction affected 12.5 per cent of the Federal Government engineers, but only about 5.5 per cent of those in the other 2 public employments. The greatest divergence occurred for those engineers who reported they had the right to patents made in the course of their work and also to those not directly related to their work. This group included only 21.7 per cent of Federal Government engineers, whereas

## Table VIII. Distribution of All Engineers Reporting Patent Rights, by Field of Employment

| Field of Employment | Total | Right Retained to Inventions (1) Made in the Course of Work, and (2) Not Directly Related to the Work: (1) Yes; (2) Yes | (1) Yes; (2) No | (1) No; (2) Yes | (1) No; (2) No | Not Reporting |
|---|---|---|---|---|---|---|
| | | | Number | | | |
| All employments | 35,559 | 11,263 | 42 | 6,017 | 4,575 | 13,662 |
| Private engineering | 21,604 | 6,499 | 29 | 4,801 | 3,279 | 6,996 |
| Construction | 3,437 | 1,178 | 5 | 294 | 405 | 1,555 |
| Extractive industries | 1,841 | 601 | 2 | 342 | 288 | 608 |
| Public utilities | 4,183 | 1,771 | 6 | 670 | 374 | 1,362 |
| Transportation | 1,255 | 434 | 3 | 217 | 143 | 458 |
| Manufacturing | 10,888 | 2,515 | 13 | 3,278 | 2,069 | 3,013 |
| Public engineering | 11,177 | 3,364 | 10 | 946 | 1,150 | 5,707 |
| Federal Government | 4,649 | 1,009 | 3 | 582 | 567 | 2,488 |
| State and county governments | 4,438 | 1,587 | 5 | 249 | 386 | 2,211 |
| Municipal governments | 2,090 | 768 | 2 | 115 | 197 | 1,008 |
| Personal service | 2,778 | 1,400 | 3 | 270 | 146 | 959 |
| | | | Per Cent | | | |
| Total, United States | 100.0 | 31.7 | 0.1 | 16.9 | 12.9 | 38.4 |
| Private engineering | 100.0 | 30.1 | 0.1 | 22.2 | 15.2 | 32.4 |
| Construction | 100.0 | 34.3 | 0.1 | 8.6 | 11.8 | 45.2 |
| Extractive industries | 100.0 | 32.6 | 0.1 | 18.6 | 15.6 | 33.1 |
| Public utilities | 100.0 | 42.4 | 0.1 | 16.0 | 8.9 | 32.6 |
| Transportation | 100.0 | 34.6 | 0.2 | 17.3 | 11.4 | 36.5 |
| Manufacturing | 100.0 | 23.1 | 0.1 | 30.1 | 19.0 | 27.7 |
| Public engineering | 100.0 | 30.1 | 0.1 | 8.5 | 10.3 | 51.0 |
| Federal Governments | 100.0 | 21.7 | 0.1 | 12.5 | 12.2 | 53.5 |
| State and county governments | 100.0 | 35.8 | 0.1 | 5.6 | 8.7 | 49.8 |
| Municipal governments | 100.0 | 36.7 | 0.1 | 5.5 | 9.4 | 48.3 |
| Personal service | 100.0 | 50.4 | 0.1 | 9.7 | 5.3 | 34.5 |

for state and county, and municipal governments the percentages reported were, respectively, 35.8 and 36.7.

Relative to all other fields of activity, the least restrictions were found in personal service, where 50.4 per cent reported unrestricted patent rights, 9.7 per cent partial restriction, and only 5.3 per cent no patent privileges. This freedom from restriction in the retention of patent rights for engineers in the personal-service group was due to the preponderance of teachers in this group, as examination of table IX shows.

Engineers engaged in teaching were under the least restriction as to the retention of patent rights, and

## Table IX. Distribution of All Engineers Reporting Patent Rights, by Type of Work Engaged in at End of 1934

| Type of Work | Total | Right Retained to Inventions (1) Made in the Course of Work, and (2) Not Directly Related to the Work: (1) Yes; (2) Yes | (1) Yes; (2) No | (1) No; (2) Yes | (1) No; (2) No | Not Reporting |
|---|---|---|---|---|---|---|
| | | | Number | | | |
| All types | 34,101 | 10,828 | 40 | 5,779 | 4,401 | 13,053 |
| Design and research | 9,050 | 2,128 | 13 | 2,404 | 1,430 | 3,075 |
| Construction | 8,233 | 2,730 | 8 | 717 | 892 | 3,886 |
| Operation | 8,276 | 2,737 | 10 | 1,494 | 1,108 | 2,927 |
| Consulting | 2,146 | 695 | 3 | 202 | 246 | 1,000 |
| Teaching | 2,050 | 1,132 | 3 | 199 | 90 | 626 |
| Sales | 1,513 | 453 | 2 | 310 | 293 | 455 |
| General administration and management | 2,833 | 953 | 1 | 453 | 342 | 1,084 |
| | | | Per Cent | | | |
| All types | 100.0 | 31.8 | 0.1 | 16.9 | 12.9 | 38.3 |
| Design and research | 100.0 | 23.5 | 0.1 | 26.6 | 15.8 | 34.0 |
| Construction | 100.0 | 33.2 | 0.1 | 8.7 | 10.8 | 47.2 |
| Operation | 100.0 | 33.1 | 0.1 | 18.1 | 13.4 | 35.3 |
| Consulting | 100.0 | 32.4 | 0.1 | 9.4 | 11.5 | 46.6 |
| Teaching | 100.0 | 55.3 | 0.1 | 9.7 | 4.4 | 30.5 |
| Sales | 100.0 | 29.9 | 0.1 | 20.5 | 19.4 | 30.1 |
| General administration and management | 100.0 | 33.6 | † | 16.0 | 12.1 | 38.3 |

† Less than 1/10 of 1 per cent.

engineers in design and research were under the greatest restriction. Of the 9,050 engineers classified as working in design and research, only 23.5 per cent had the right both to patents made in the course of their work and those not directly related to their work. As many as 55.3 per cent of the engineers engaged in the teaching of engineering subjects so reported. For the remaining 5 lines of work, the proportions with full rights to patents ranged from 29.9 per cent in sales to 33.6 per cent in general administration and management.

Relatively, the largest proportion of engineers who were partially restricted in regard to patent rights (26.6 per cent) was reported for design and research. Even in the case of sales, some 20.5 per cent were classified under this "no–yes" combination. By contrast, only 18.1 per cent of the engineers engaged in operation and 16.0 per cent in general administration and management were restricted only as to patents relating to their work. The corresponding proportions in construction, consulting, and teaching were very much less, ranging from 8.7 in construction to 9.7 in teaching.

The largest relative percentage completely restricted was 19.4—for the engineers engaged in sales—with design and research following next in order (15.8 per cent). From this point the proportion ranged downward to 13.4 per cent in operation, 12.1 per cent in general administration and management, 11.5 per cent in consulting, and 10.8 per cent in construction. The lowest percentage under complete restriction, namely 4.4, was noted in teaching.

# The Ultrahigh-Frequency Domain

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**Use of ultrahigh frequencies for educational broadcasting has been thought to offer attractive possibilities because of the supposedly almost unlimited number of channels; however, the demands of other radio services, particularly television, may be expected to congest this newly opened region. Ultrahigh-frequency waves behave somewhat like light waves, and give reliable and steady communication over short distances. The 6-megacycle band width required for television can be accommodated only in this region, but short range precludes, for the present, coverage of rural areas with these frequencies.**

THE ultrahigh-frequency waves have attracted considerable attention of late. It is but natural that educators have frequently considered the possible application of these waves for local educational broadcasting. In some quarters the optimistic thought has been expressed that in this new domain there will be space for the establishment of almost any number of local educational broadcasting stations. It will be attempted later in this presentation to analyze the probability of the successful execution of such a plan.

## Frequency Regions for Broadcasting

The radio waves referred to as lying in the "ultrahigh-frequency domain" are, broadly speaking, those having a wave length less than 10 meters. They result from electrical oscillations having frequencies greater than the extremely high value of 30,000,000 cycles or oscillations in each second. The waves in the existing broadcasting band—that is, the so-called "medium waves"—have lengths lying between about 200 and 550 meters, and correspond to electric oscillations of a frequency in the general neighborhood of 1,000,000 cycles per second. Lying between the medium waves for broadcasting and the ultrahigh-frequency domain are the short waves which are so effectively used, among other purposes, for trans-oceanic and transcontinental communication.

There is one additional region used for broadcasting, namely, that of the longer waves in the neighborhood of 1,500 meters, having a frequency of about 200,000 cycles per second. These waves are not used for broadcasting in America although they have had considerable application in Europe.

Thus there are, so to speak, 4 domains of possible interest for modern broadcasting. These are the long waves, having frequencies of the order of 200,000 cycles per second; the medium waves (so widely used in the United States), having frequencies of the general order of 1,000,000 cycles per second; the short waves, having frequencies of the order of 10,000,000 cycles per second; and, finally, the ultrashort waves, which have the ultrahigh frequencies of from 30,000,000 to several hundred million cycles per second or even more.

It was hinted that the short waves were not widely useful for national broadcasting. They do serve admirably to cover the great distances required to span oceans, but they give a relatively poor local service and create so considerable an amount of interference at distant points in other countries when they are used for primarily local broadcasting that it seems inappropriate to regard them as a proper means for completely carrying out national broadcasting in such countries as the United States.

Accordingly, so far as future expansion of the broadcasting realm is concerned, attention must be concentrated on the ultrahigh-frequency domain. The nature of these waves is worth considering more fully. To begin with, they are a good deal more like visible light than are the short, medium, or long radio waves hitherto used. By this is meant that these waves are more readily blocked by obstacles which would stop light; are reflected by objects somewhat like those which would reflect light; and have somewhat of the reliability and steadiness of transmission which light waves attain in the absence of fog or material obstacles.

## Ultrahigh-Frequency Transmission

Broadly considered, an ultrahigh-frequency transmitting station acts like a sort of radio lighthouse. Its rays travel outward in all directions toward the horizon and are best received along the "line of sight." For this reason it is common and approved practice to place the ultrahigh-frequency transmitting stations on the top of the tallest structure which may be available and also to place them, as nearly as practicable, in the center of the region which they are intended to serve. The higher the location of the transmitting station, the greater the range of satisfactory transmission.

It is true that the ultrahigh-frequency waves do not stop completely at the horizon but can be received, though with diminished strength and increased unsteadiness, at distances considerably beyond the optical horizon. It is also true that occasionally these waves may "fade" beyond their normal range, that is, fluctuate rapidly in their strength at the receiving station.

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It has been reported that the occasional range of transmission and reception of the ultrahigh-frequency waves may be very considerable. Distances from 100 to several thousand miles have been cited in this connection. How frequently such extreme ranges may occur and upon what physical factors they depend are not yet known with certainty. Accordingly, a proper precaution is to suspend judgment as to the extent to which these facts will influence the allocation of the ultrahigh frequencies.

Nevertheless, taken by and large, the ultrahigh-frequency waves work best to distances little beyond the visible horizon, produce a steady and reliable signal with a minimum of distortion of the material transmitted (whether televisual or telephonic), and are relatively free from erratic changes in transmission. It is fair to state that, as a rule, the ultrahigh-frequency waves are transmitted with somewhat of the steadiness and constancy to be attained in a properly designed wire or cable system operating under the most favorable conditions.

Another fortunate aspect of the ultrahigh-frequency waves is the relatively low level of natural interference. It is well known that atmospheric electrical disturbances trouble radio listeners on the medium waves during the summer months, even in the northern portions of the United States. The ultrahigh-frequency waves, on the contrary, are little troubled from this source, though a number of man-made devices (such as the ignition systems of some automobiles and medical diathermal equipment) may cause serious interference with the reception of these waves at points near the outer limits of their service range. Fortunately automobile ignition systems can be shielded, and there is little doubt, should ultrahigh-frequency waves become widely used for broadcasting to the public, that the automobile industry will likely co-operate by taking such measures as will reduce ignition interference. Possibly diathermal outfits will be given their own assigned frequency, thus preventing most of the interference caused by them.

While the ultrahigh-frequency waves give reliable and steady communication, their service range, as indicated, is usually limited to distances of the order of several tens of miles from the transmitter. The questions will naturally be asked: Why should these waves be used in broadcasting? With their limited range what compensating advantages do they display? What can be accomplished by their use which cannot be otherwise accomplished? What broadcasting opportunities are thus offered? And what broadcasting methods, of special interest to educators, can thus be realized?

## Widths of Frequency Bands for Communication

Before answering these questions it is necessary to consider briefly the demands made upon radio transmission capabilities by the various forms of communication. The simplest form of communication is telegraphy—by dots and dashes. This requires a limited band of frequencies or "space in the air." Actually a few tens, or at most hundreds, of cycles per second are required next to one or both sides of the so-called carrier wave by telegraphic communication. Telephonic communication—the transmission of speech or music—makes more severe demands. In this case the frequency band required (that is, the so-called "side band") is about 10,000 cycles wide. The demands of facsimile communication—the transmission of drawings, printed text, writing, or photographs in the form of a record—requires perhaps a half or a third as much space for the corresponding frequency band as telephony. Then there is television, which is the most difficult of the communication arts. This is the transmission of pictures in motion, in transient form (that is, not recorded). The side band in this case rises in width to millions of cycles. For example, a side band about 2,500,000 cycles wide is believed to be required for really acceptable television pictures.

The difficulty of each of these methods of communication is somewhat proportionate to the side-band width required as previously indicated. This must not be taken too literally. However, it is fair to say that television is much more difficult than either telephony or facsimile which, in turn, exceed telegraphic communication in their technical requirements.

As hinted in the foregoing discussion, every transmission of intelligence by radio is accomplished by using a carrier wave for transmission and by modulating or controlling this carrier wave in such fashion as to convey the intelligence in question. The result of this modulation, in the simplest case, is to add new side bands on each side of a carrier wave; these side bands occupy frequencies to the exclusion of the interference-free reception of other communications of comparable strength on the same frequencies in the same general locality. (For the moment, the capabilities and advantages of directional reception are not under consideration.)

That television cannot be carried out, with adequate picture quality, on the medium broadcast waves becomes at once evident. Finding space on such waves, having an average frequency of a million cycles, for side bands several million cycles wide such as are required by television is not possible. It becomes necessary to go to the ultrahigh frequencies. If the carrier frequency has the ultrahigh value of say 50 megacycles there is obviously room on each side of this frequency for the side bands required by television, wide though such side bands be.

## Beam Transmission of Ultrahigh Frequencies

It is also desirable, before answering the questions which have been posed, to consider one other useful characteristic of the ultrahigh-frequency waves. These waves are quite short and are accordingly readily focused, if desired, so that they may be transmitted primarily in a given direction in a narrow beam. This is important whenever directional transmission and reception are required. A proposal has been made to use the ultrahigh-frequency waves for relay communications. In this process the transmission from a given station of these waves is picked up at a distant point by a corresponding receiving station, and the received signals are amplified powerfully by one means or another and then sent into a nearby second

transmitter which carries them along on their way to a further receiving station where the process of automatic relaying is carried out. Several such ultrahigh-frequency relay stations, each picking up its signal from the preceding and sending it forward along the relay system, would constitute a sort of network.

The difficulty experienced in using medium or long waves for the purpose of radio relaying involves the problem of efficient transmission and accurate reception. In this respect the ultrahigh-frequency waves are nearly ideal. They can be readily concentrated in a given direction toward the next relay station; and the amount of interference experienced in reception because of natural electrical disturbances is, as has previously been stated, relatively very slight and unimportant. For these reasons the ultrahigh-frequency waves lend themselves well to radio relay systems.

## Use of Ultrahigh Frequencies for Broadcasting

To some extent the questions which have been previously set forth can now be answered. First, as to the question: Why should the ultrahigh-frequency waves be used in broadcasting? The answer is that they show reduced distortion of quality, diminished interference from natural electrical disturbances, and a high degree of reliability of service within their normal range, which range is quite adequate to cover most urban and suburban areas or areas of corresponding size in rural regions. They require only reasonable amounts of power to accomplish such results provided the transmitting station is centrally located on the top of a high structure. Under usual conditions these waves do not cause severe distant interference and have only a limited "nuisance range," in contradistinction to the short and medium waves which sometimes cause interference at distances far beyond their range of useful reception. Further, the fact that the utilization of these waves might, if judiciously carried out and with due control, somewhat relieve the worst congestion now existing on the medium broadcasting waves cannot be overlooked. In the foregoing statement it is believed that there has similarly been answered the question: With their limited range what compensating advantages do they display?

The next question is: What can be accomplished by their use which cannot otherwise be accomplished? Through the use of ultrahigh-frequency waves it is possible to have more local stations which would be substantially noninterfering than would be the case if the medium waves were used. It is possible to establish more nearly constant day and night quality of service than is now the case. It is also feasible to maintain winter and summer reception on more nearly the same level of freedom from natural electrical disturbances. While it is true that man-made devices, such as automobile ignition systems and medical diathermal equipment, can interfere with ultrahigh-frequency reception, yet the reduction of such types of interference by organized planning, regulation, and industrial co-ordination offers greater possibilities than the elimination of natural disturbances—which latter have proved extremely stubborn as to their elimination by any methods of conventional sort requiring no increased width of frequency band for the corresponding transmission and reception. By the use of the ultrahigh-frequency waves it becomes at once possible to transmit telephone programs (that is, speech and music) on an extremely high-fidelity basis and, similarly, to receive these programs with such accuracy of reproduction in the home as will greatly enhance the clarity of speech and the naturalness of reproduction of music. Present-day broadcasting on the medium waves is greatly handicapped in its struggle to obtain high fidelity transmission and reception by the congestion of stations on neighboring channels only 10,000 cycles (10 kilocycles) apart. Actually 3 times this separation could be used to advantage were it available—which it emphatically is not in a country like the United States where great areas must be covered, where numerous broadcasters insist on the privilege of transmission, and where occasionally political considerations may be urged in connection with the allocation of transmission frequencies. Broadly stated, more reliable local transmission, less interference from natural disturbances, a partial relief from certain types of congestion of transmission facilities, high-fidelity telephonic operation, and a steady and reasonably uniform all-day and all-year service can be anticipated from the ultrahigh frequencies.

## Use of Ultrahigh Frequencies for Television

Perhaps the greatest opportunity offered by the ultrahigh-frequency waves, namely, the introduction of television, has not as yet been analyzed. Here is one service, at least, which could not conceivably be carried out according to present knowledge on any but the ultrahigh-frequencies. Its side-band demands for an extraordinarily wide band of frequencies can be met only in this new domain. Since the visual services can reasonably be expected to add a great deal to the value of broadcasting as an educational medium in the broadest sense, there is no question but that the ultrahigh frequencies will find a wide and successful application for that purpose.

Only very recently was reasonably good agreement reached among experts as to what constitutes an acceptable type of television. In a broad way the television picture is described as having "a certain number of lines," the lines being the parallel and adjacent paths over which moves the spot of light that creates the television picture. Initially as few as 24 lines were suggested for an acceptable television picture. Actually such a picture would be of the utmost crudity and capable of giving an extremely rough impression of only the simplest objects. As time went on, 45-line pictures and then 60-line pictures were proposed. In each case the almost pitiful inadequacy of such television pictures, so far as any educational or entertainment value was concerned, became fully evident. There then followed attempts to use 120 and 180 lines of television pictures and, for the first time, a slightly useful television picture was produced. However, present-day experimental practice here and abroad involves pictures having 343 lines or 405 lines, respectively (although some

attempts are still made to use 240-line pictures). The proposed standard for the United States is a 441-line picture. At its best such a picture may be described, crudely enough, as definitely better than a projected motion picture from 8-millimeter film and perhaps nearly or quite as good as a motion picture projected from 16-millimeter film. The television standards so far proposed as practicable cannot be expected to give results equal to those obtained in an auditorium, for example, by the projection of 35-millimeter film. The pictures are monochrome—that is, essentially in black and white. Practical color television is a rather remote possibility and hardly one with which to be concerned for some time to come.

If television pictures having numbers of lines of between 300 and 500 are taken as a reasonable standard for the present, the side bands required for the corresponding transmissions are found to be extraordinarily wide as compared to those used for telephony. The proposed width for the side bands in the American television transmissions will be about 2,500,000 cycles per second. Only in the ultrahigh-frequency domain of waves can be found a practicable resting place for such transmissions. Accordingly television must necessarily embrace the capabilities and accept the limitations which have been previously described as associated with ultrahigh-frequency transmission and reception.

The establishment of a television transmitting station on the highest location in the region which is to be served is, nevertheless, unlikely to enable coverage over a range of more than a few tens of miles in each direction. While this is entirely adequate for most cities and their suburbs, it is certainly not adequate for the coverage of large rural areas where the concentration of lookers will be small and the distances to be covered will be great.

It may be judged from this that methods should be found, if possible, to give to television services an adequate rural coverage although it must be admitted that, up to the present, the problem of so doing is formidable both technically and economically. One may also conclude that the medium-frequency telephone broadcasting stations of today, while unable to render television service because of the limitations of medium-frequency transmission as pointed out previously, will nevertheless necessarily remain the backbone, so to speak, of the broadcasting structure in so vast a country as the United States, at least for many years to come. From this the comforting thought may be extracted that the present broadcasters do not face an abrupt obsolescence of their stations which, so far as can now be told, will still render a useful rural service in the future. No present means of replacing the rural service in question by technically correct and economically feasible utilization of ultrahigh-frequency transmissions is known. However, even these problems may in time be solved to the advantage of ultrahigh-frequency methods.

## Facsimile Broadcasting

Facsimile broadcasting is perhaps of particular interest to the educator since it is the only form of broadcasting which offers a permanent record of textual and graphic material. It is a sort of radio printing press located in the home and capable of producing pages (and even books, if given reasonable time). Facsimile broadcasting could technically be carried out on the existing broadcast frequencies, that is, the medium frequencies. The side bands required are little different from those necessary for telephony. However, the congestion in the present broadcasting band is so extreme that it would be out of the question at this time to add other services in the present broadcasting band. The interesting suggestion has been made that facsimile broadcasting might be carried out during the early morning hours on the existing broadcasting band, the reproduced material on sheets of paper being available to the recipient as he awakens in the morning. Such a service has distinct limitations and would likely be useful, if at all, only during an interim stage of development and as a facsimile service to rural areas not readily reached by ultrahigh-frequency transmissions.

If more or less continuous facsimile broadcasting is to be established in urban and suburban areas, it is more logical to expect that it will be associated with its related visual service—television. That is, facsimile broadcasting also finds a natural location in the ultrahigh-frequency domain. It must be left to the imagination of the educator to envisage the numerous attractive possibilities of instruction and examination which are afforded by this type of broadcasting. However, the limitations of range of the ultrahigh-frequency waves must be kept in mind here, as well as in the case of television broadcasting.

## Availability of Channels in the Ultrahigh-Frequency Domain

The likelihood of the successful establishment of a substantially unlimited number of ultrahigh-frequency educational stations for local broadcasting in a given neighborhood can now be analyzed. The television experts have reached the conclusion that the television-telephone channels must, for effective picture and sound transmission, be about 6,000,000 cycles (6 megacycles) wide. In studying television standards the committee on television of the Radio Manufacturers Association has proposed the use of the frequencies between 42 and 90 megacycles for television transmission (excluding the amateur band between 56 and 60 megacycles). In view of the impression which may exist that an indefinitely large number of television transmissions can be placed within this region it is interesting to know that there are only 7 available channels, each 6 megacycles wide, in this whole requested band of frequencies! Where 2 cities, like New York and Philadelphia, are about 100 miles apart, it is possible that television allocations would be so restricted as to provide say 4 television transmissions for New York City and 3 for Philadelphia. Otherwise stated—and this is a rather startling and discouraging fact—there appears to be space at this time in the ultrahigh-frequency domain for fewer television-telephone transmissions in a given locality than there is space for the usual telephone broadcasting channels in the existing medium-frequency band. Accordingly,

until even higher frequencies than 100 megacycles are available for satisfactory broadcasting of telephone, television, or facsimile material, it is unlikely that the average city can enjoy the privilege of simultaneous operation of more than a limited number of television-telephone transmissions. It has been the unhappy experience in radio broadcasting that the opening of a new domain always appeared to offer an almost limitless opportunity for simultaneous and noninterfering transmissions but, after practical examination and test, it has turned out to offer extremely few opportunities in comparison with the number anticipated. In fact, no radio domain so far rendered available has, after a reasonable time of development, been free from marked congestion at some time. Unfortunately there is no present reason for believing that the ultrahigh-frequency domain will be an exception to this experience of the past, and whatever congestion now exists in broadcasting may be expected to continue when the ultrahigh-frequency waves are used.

It would probably be good counsel to the educators of the United States to advise them to keep fully informed on the technical and industrial developments in the ultra-high-frequency domain and to study carefully in advance what may probably be accomplished by the use of the radio and visual broadcasting services which can be established in this domain. It would also be well if carefully planned broadcasting of educational material were carried out, using these new frequencies and the novel forms of transmission, such as facsimile and television, which they render possible. However, if education is to derive its full benefit from these new instrumentalities of science, it will involve much sober thought, co-operative effort, and systematic planning on the part of educators. The field is too complex and its problems too numerous to make an unplanned success at all probable or to reward casual, meager, or purely selfish efforts.

Beyond a doubt, engineers will do their utmost to perfect the approaching art of television and facsimile broadcasting and of telephone broadcasting as well, all on the ultrahigh frequencies. It is hoped that the educators of America, fully awakened to the interesting civic possibilities which these communication media offer, will similarly avail themselves of their potentialities systematically and effectively.

## Practical Limitations of
# The Broadcast Allocation Structure

By C. B. JOLLIFFE
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**To give the radiobroadcast listener maximum service is an important problem in which the frequencies available, characteristics of the receiving set, phenomena of transmission of radio waves, area to be served, and density of population in the area must be considered. Broadcast stations in the United States are of 2 main classes, clear channel and duplicated channel, and are allocated in frequency to prevent interference between stations in the same area. Short-wave broadcasting has additional limitations because of natural phenomena.**

BROADCASTING, as it is known today, is a newcomer in radio communication. Consequently, since its start in 1921 when a single frequency was made available for the service, radiobroadcasting has had to make its own place in the radio spectrum purely on the basis of public interest and public acceptance. It has been estimated that at the end of 1936 approximately 30,000,000 radio receiving sets were in use in the United States. This alone is ample proof that the public has accepted broadcasting. If nothing else were considered, the huge investment of the public in this industry is sufficient to give broadcasting a position of commanding importance. Because of its great importance to the public, a thorough understanding of the underlying principles of broadcast allocation is necessary in order to judge the effectiveness of any allocation or in order to make constructive suggestions concerning improvements.

In the frequency spectrum, broadcasting of the United States has been allocated the space from 550 to 1,600 kilocycles for domestic service and several frequency bands between 6,000 and 22,000 kilocycles (6,000–6,150; 9,500–9,600; 11,700–11,900; 15,100–15,350; 17,750–17,800; 21,450–21,550) for international service. This discussion will be limited to these bands of frequencies.

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In the band from 550 to 1,600 kilocycles the principles of broadcast allocation have become fairly definitely stabilized. However, the average listener who tunes across the dial of his receiving set may well wonder if there is system and order behind what he hears. Why is he able to receive on some points of the dial while at other points he hears a mixture of signals from many stations? Why is not every point or every channel on the radio dial available to give him perfect service? What should a listener expect to hear on his receiving set? The answers to these questions are not immediately obvious, but the answers are relatively simple when one studies the bases of allocation used in the United States and the severe limitations imposed on the allocation of frequencies to broadcast stations. It is the purpose of this article to discuss these limitations of broadcast allocation and give a brief picture of the structure under which the broadcasting industry operates at the present time.

## Medium-Frequency Broadcasting Service

### Number of Frequency Channels Available

The fundamental limitation to every radio service is the frequency space available for that service. All the radio communication services of the world work in a common transmission medium referred to as the ether. Radio waves of all frequencies can exist in this medium and retain their separate identities, that is, there is no mutual interference between radio waves in space. There is projected into this medium all types of signals—point-to-point telegraph communications, telephone communications, communication between police cars and headquarters, military communications, communication between amateurs, ship to shore telegraph and telephone, and so forth. If a receiving set which had no frequency discrimination were used, all these communications would be heard simultaneously as a jumble. Fortunately, receiving sets can discriminate with respect to frequencies and it is possible to pick out one band of frequencies and reject all others.

Consequently, it is necessary first to arrange the various kinds of communications in different frequency bands in such a way that receiving sets can pick out the band desired. Different groups of frequencies are assigned for use by different services and receiving sets are used which are designed to accept frequencies of a particular service.

At international conferences in which all nations of the world participate, the common communication medium has been carved into frequency bands which have been allocated to various classes of services.* Broadcasting has been allocated frequency space which the nations of the world believe to be its proportionate share of these frequencies. In North America there has been allocated the band of frequencies from 550 to 1,500 kilocycles for the exclusive use of broadcasting for the purpose of providing domestic broadcast service as it is known today. Because no interference to other parts of the world will be caused, the nations of North America have further agreed to use the space from 1,500 to 1,600 kilocycles for broadcasting. Similarly, the nations of Europe have agreed among themselves to use other frequencies (below 400 kilocycles) for broadcasting which do not cause interference in North America. The agreements concerning use of frequencies have been made by the duly accredited representatives of all nations of the world, including the United States, and are a part of the fundamental law.

The United States, then, has one of the pieces of the frequency spectrum, 550–1,600 kilocycles, available for broadcasting. The size of this piece is not likely to be changed. The duty of the Federal Communications Commission, which is the agency of the government charged with the administration of the radio laws and the assignment of frequencies to stations, is to assign frequencies in this space to broadcast stations in such a manner as to provide the best broadcast service possible to the people of the United States.

The Commission has decided that stations will be allocated at intervals of 10 kilocycles through the space 550–1,500 kilocycles. This provides, then, using channels at both ends of a block of frequencies, 96 channels of communication for use in North America. Assuming that the frequency space from 1,500 to 1,600 kilocycles will be assigned eventually on the same basis, 10 more channels may be added, making a total of 106 for use by broadcast stations in this band. By agreement between the United States and Canada, 6 frequencies have been allocated for the exclusive use of the latter. Thus a total of 100 channels remains for use by stations of the United States. This then is the first limitation of broadcast allocation.

### Performance of Receiving Set

The radio receiving set used by the listener constitutes the second limitation on allocation. Broadcast stations are assigned at intervals of 10 kilocycles. In order to have satisfactory radio reception it is necessary that but one program be reproduced in the output of the receiving set. The antenna which is used to pick up a minute amount of power from the transmission medium has flowing in it currents of all frequencies produced by transmitting stations of corresponding frequencies. The function of the receiving set is to pick out, amplify, and reproduce the currents produced by the one transmitting station desired and reject all others.† If 2 transmitting stations separated by 10 kilocycles produce in the receiving antenna approximately equal currents, most receiving sets can receive one station and reject the other. If the 2 stations are separated by 20 kilocycles the unwanted station can be approximately 20 times the strength of the wanted station and the receiving set can select one from the other. If the ratio is greater than this then the average receiving set cannot make a clear distinction This ability of the receiving set to accept one station and reject another is referred to as the selectivity of the receiving set, and is the factor which makes possible the

* Article 7, General Radio Regulations annexed to the International Telecommunication Convention, Madrid, 1932, Treaty Series No. 867.

† "Characteristics of American Broadcast Receivers as Related to the Power and Frequency of Transmitters," Arthur Van Dyck and D. E. Foster. IRE *Proceedings*, volume 25, April 1937, page 387.

operation of many stations at the same time.

Some may remember in the early days of broadcasting that reception of one station without at the same time receiving signals from several other stations was extremely difficult. The development of the modern receiving set has been one of increasing its selectivity and approaching that ideal by which it is possible to accept one signal and reject all others regardless of their intensity.

Technical limitations make impossible the complete accomplishment of the ideal in the present state of the art. It is sufficient to state that with the present development it is possible to receive a signal on a given frequency and reject all others separated by 50 kilocycles or more regardless of their intensity. At less frequency separation than 50 kilocycles with modern receivers rejection of adjacent frequencies is possible provided they do not exceed certain values, the value which may be present decreasing as the frequency separation decreases.

A modern receiving set is a marvel of ingenuity which is accepted and used with little thought of the amount of work which has gone into its design and production. It is the best that engineers have been able to design and produce at a cost which can be borne by the listener. It does, however, represent the second limitation in allocation.

## Transmission of Radio Waves

The third limitation is the most fundamental and one which is imposed by nature; that is, the ability of radio waves once radiated to travel through space. When an alternating current of high frequency flows in an elevated conductor there is set up around it an electromagnetic field which moves through space with the speed of light. Variations in the intensity of the current flowing in the conductor produce similar variations in the electromagnetic field which make it possible for these electromagnetic waves to carry a message through space. Once these electromagnetic waves have left the antenna there is nothing which man has conceived to date that can be done to alter their course. The intensity of these waves at any given point is proportional to the amount of current flowing in the elevated conductor or antenna, and falls off rapidly as the distance between the antenna and the receiving point is increased.

At night a further complication is introduced. There is no simple transmission along the ground. The waves which leave the antenna at an angle from the ground and which in the daytime are usually lost in space, at night encounter what appears to be an electrical mirror at a height of some 50 to 100 miles above the surface of the earth. This electrical mirror returns the waves to earth and they are then capable of producing currents in the antenna of the receiving set even though the distance be very great.

This electrical mirror is not uniform and the waves which return are consequently not of uniform intensity. This gives rise to the phenomenon which has been called "fading." There are 2 types, one of which is produced when the reflected wave and the wave that is propagated along the ground both are of sufficient intensity to produce currents in the antenna. These waves having arrived over different distances and being of different phase interfere with each other and produce variations in the current produced in the receiving antenna. Irregularities in the reflecting medium vary the intensity and phase of the reflected wave while the intensity of the ground wave remains constant. This is the first type of fading which is encountered as one proceeds from the transmitting station. This fading is usually quite severe and one of its characteristics is that it is selective so that certain parts of the speech or music may cancel out entirely and other parts remain or are augmented. This results in severe distortion and very unsatisfactory reception. There is no known practical remedy for this type of fading and it is the limit of good service of many broadcast stations.

Beyond this region of interference between "ground" and "sky" wave the sky wave predominates and fading is due to irregularities in the reflection of the waves. This fading, the second of the 2 types, is usually not selective and all portions of the program change equally. This type of fading is substantially corrected by the modern receiving set by means of automatic control of the amount of amplification used by means of the intensity of the incoming signal.

The phenomenon of transmission of radio waves is extremely complex and in order to understand the laws governing it a large amount of experimental data must be obtained. These data have been accumulated over a period of years and it is believed that what to expect under any given set of circumstances is now known. The laws governing these transmissions are as exact and as certain to operate as the laws of gravitation. Man cannot alter them, he can only learn the fundamental bases and adapt himself to these bases. He may be able to apply apparatus and equipment which make better use of the transmitted signal, but he must always recognize that nature has set this limitation.

A corollary to this limitation of transmission is that of interference. When 2 radio waves of approximately the same frequency exist simultaneously in space they will produce in the antenna of the receiving set alternating currents of approximately the same frequency. The receiving set which depends on differences in frequency in order to select between 2 stations can make no selection when the frequencies it receives are the same. Consequently the signals carried by both radio waves will produce signals in the output of the receiving set. In order that one signal may be heard above the other it must be of sufficient strength that it can completely mask the other so that the receiving set appears to reproduce only one signal; in short, a shout drowns out a whisper.

Nature is also a broadcaster and produces radio waves which travel through space as do other radio waves. Every discharge of electricity in the form of a spark sets up electromagnetic waves. The noise produced by thunderstorms, which is usually referred to as static or atmospherics is familiar to all. The general accumulation of electrical discharges in space between clouds and between clouds and ground sets up a background of radio noise which

is picked up by the receiving antenna. Added to this there are the spark discharges produced in all types of electrical apparatus such as motors, generators, and flashing signs. This group of transmitters produces radio noise which is usually referred to as background noise. It is always present in a greater or lesser degree. In highly congested centers of population the background noise produced by electrical machinery may be extremely high while in a rural section with little electrification it may be practically zero. The natural noise produced by natural discharges is usually very high in the summer, particularly in the tropics, and practically nothing in the winter. The minimum amount of signal considered necessary to render good service under varying conditions is a measure of the amount of noise present on the average.

### Area and Distribution of Population

The final limitation of allocation is the size of the United States and the distribution of its population. The population of the United States is distributed over an area of approximately a rectangle 3,000 by 1,500 miles. The distribution of population varies from many thousands per square mile in highly concentrated centers of population to an average of less than one per square mile in wide open spaces. The time at which people are listening to broadcast programs varies, depending on time zones and habits of the various classes of people. It is not possible to change these factors, but it is possible to know what they are and act accordingly.

These are the technical limitations. None of them has been gone into exhaustively in this paper; any one of them is a subject for a paper itself. When broadcasting started there was little information available. As broadcasting has developed it has developed its instruments and measurements and accumulated its data. That which it is necessary to know concerning all of these limitations may be said now to be known. They can be analyzed and used in building and improving an allocation structure. They cannot be ignored simply because what they produce is not liked. Legislation and regulation may dictate or limit how these principles can be applied but they cannot change the fundamental technical laws.

### Plan of Allocation

How these limitations have been recognized and applied may now be briefly considered. That these applications are the only methods which might be used is not inferred, but they are used as illustrations of what has been done and what is familiar to everyone.

Stations of the United States have been classified into 2 different main classes: stations operating on clear channels, that is, one station only permitted to operate at night using the maximum amount of power; and stations operating on duplicated channels, that is, 2 stations or more permitted to operate simultaneously on each channel.

Stations of different classifications are distributed throughout the United States in such a manner that stations operating on adjacent frequencies are separated geographically from each other, thus recognizing the limitation in selectivity of the receiving sets. So when a listener is near one station, stations on channels 10, 20, 30, and 40 kilocycles removed therefrom are at distances from the listener so that the signals from them should always be below the values necessary to cause interference to the nearby station.

The Commission and station operators have recognized that the service area of a station is of 2 kinds, primary service and secondary service. The primary service is that area in which all listeners get service free of interference. The secondary area is that area in which the listeners get some amount of satisfactory service, but which is not always free of interference. For clear channel stations the primary area may extend for 100 to 150 miles up to the point of severe and selective fading. Beyond this area of severe and selective fading there exists a secondary area which extends to the limit of useful signal produced by the station. This useful limit of the secondary area is fixed by the amount of natural noise and consequently changes from day to day and season to season.

It should not be expected that everywhere within this secondary area there is freedom from interference and that the whole of the United States is within the secondary area of every clear channel. The limitation of radio-wave propagation limits the distance for which it will be useful. Also, the strength of signals from stations on adjacent frequencies will make the signal of no use in certain areas. If the secondary area of a clear channel station were charted it would consist of a map of the United States with many areas removed, the amount removed depending on the location of the stations on adjacent channels and the noise intensities in various areas.

Stations which operate on duplicated channels have their night service area limited by interference from the other stations operating on the same channel. At night these stations have very little, if any, secondary service and their primary service can be very accurately defined; in fact, so accurately defined that its use as a basis for estimating the number of people who can be served by the station is possible.

A station operating on a duplicated channel, therefore, is used to serve a center of population and is not expected to have any service at night beyond its normal service area limited by interference from other stations on the same channel.

The result of the allocation is, therefore, that clear channel stations serve centers of population with primary service up to the beginning of fading and then have a very extended secondary area, and stations operating on duplicated channels serve centers of population but have no secondary service, the entire service lying within an area relatively close to the station.

### Service Received by the Listener

From the listener's standpoint, then, if he lives in the good service area of either a clear-channel station or a station operating on a duplicated channel, he should obtain excellent service free of interference from these stations. In addition he should be able to receive the secondary service from many of the clear channel stations. This secondary service is usually less satisfactory than the pri-

mary service from a local station. However, program content may cause him to listen to a less satisfactory signal rather than his local signal free of interference.

Turning now to the questions which were asked in opening this paper, the answer is that the distribution of population over the United States, and consequently distribution of radio stations, makes it necessary that persons in some localities be deprived of service on certain channels in order that persons in other localities can have primary service. If, for example, the people of Washington, D. C., had perfect service on all 100 channels then the people in all cities beyond approximately 100 miles from Washington, D. C., would have to depend entirely on secondary service. This example can be carried to any center of population.

A person in a given locality should be able to hear all the stations which have their primary service area covering his locality, plus the secondary service from clear channels. Persons who do not live in a center of population having local service must depend entirely on the secondary service from clear channel stations. On duplicated channels on which no station gives primary service in his area he will simply hear a mixture of signals. These channels are giving primary service to other areas.

## High-Frequency Broadcast Service

The limitations and use of the frequencies used for international broadcasting, that is, frequencies between 6,000 and 22,000 kilocycles may now be discussed very briefly. These frequencies by their very nature are capable of world-wide interference and a type of world-wide service. In the frequency band above 6,000 kilocycles practically all of the radio commerce of the world is carried; communication between ship and shore, between the United States and all other countries of the world, and among the other countries of the world. This communication service puts a severe load on the frequency spectrum. Because of this large load of commercial traffic only a very small portion of the frequency spectrum has been allotted to broadcasting.

The transmission characteristics of these frequencies change very markedly as the frequency range is changed, as the transmission path changes from daylight to dark, and as the seasons change. These characteristics are well known.

A frequency of the order of 15,000 kilocycles for example, used for transmission from a station produces very little service in its immediate neighborhood, but does produce in the daytime a very strong signal at distances of greater than approximately 1,000 miles away. In other words, if an observer were to travel out from a station with a receiving set he would find that its service fell off very rapidly in the first few miles, then disappeared for several hundred miles, and then began to reappear again. This distance in which the signal vanishes is called the "skip" distances for that frequency. Skip distance varies from a few miles for the lower frequencies in the daytime to thousands of miles for the higher frequencies at night. In fact, frequencies above approximately 10,000 kilocycles are useless at night because their skip distance is greater than half way around the world. Because of this characteristic of transmission, in order to serve a particular point or a particular area at a distance from the station, it is necessary to use a different frequency in the daytime than at night and also a different frequency in winter than is used in summer. Consequently, to permit continuous service to be given to a country, such as Argentina in South America, would require from 3 to 5 frequencies spaced properly between 6,000 and 20,000 kilocycles, the proper frequency being used in accordance with its known propagation characteristics.

It has been suggested that these frequencies be used for the purpose of covering portions of the United States. In order to do this each station would be required to use from 3 to 5 different frequencies throughout the period of propagation in order to cover given areas. If each country in the world tried to give this kind of a service it would require more than all the frequencies above 6,000 kilocycles to meet the needs of all nations. Instead of a station being assigned a single frequency, as is done in domestic broadcasting, each station would have to be assigned a multiplicity of frequencies, and instead of the allocation problem being confined to the United States, the interference limitations imposed by stations of the entire world would need to be met.

The nations of the world, realizing this lack of adequate supply of frequencies, have practically all confined their use of these frequencies to broadcast programs destined for reception in other countries. Unfortunately, this has not been confined to the propagation of entertainment programs only, but these programs have also included propaganda and much might be said as to the improper use of such frequencies. However, this is not a technical question.

These frequencies likewise have the same limitations with respect to fading as do the lower frequencies used in broadcasting. The entire service of these frequencies is secondary service and consequently subject to fading and interference from electrical noises. The service can never be as good as the service given by a steady signal from a local station. The limitations of selectivity of receiving sets and distribution of population also apply to this band of frequencies.

From an engineering standpoint it is known what these frequencies can do and what limitations they have. The limitations are natural phenomena and there is nothing that can be done to change the phenomena. By technical advances the characteristics of the devices which transmit and receive them, may be changed but at present there appears no way by which the laws of nature can be changed. With these frequencies, as with the broadcast frequencies, the utmost information concerning the laws of nature must be obtained and applied to the best of our ability to the problems in hand.

Man may not like the consequences of natural laws and the natural limitations of radio propagation, but he must accept them. Man can make and unmake his own laws and limitations, and change them as he desires, but nature makes her laws and they are final; man can learn what they are and use them, but he cannot change them.

# The Dielectric Strength of Noninflammable Synthetic Insulating Oils

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THE SUBSTITUTION of chlorine for hydrogen in the hydrocarbon molecule produces marked effect not only on the physical and chemical properties, but on the electrical characteristics as well. The compounds so produced present to the electrical engineer a new type of insulating liquid which eliminates many of the problems heretofore inevitably associated with the use of mineral oil. It is the object of this paper to demonstrate the dielectric strength characteristics of such synthetic liquids both alone and in combination with cellulosic insulation.

Although the use of chlorine-containing compounds in the electrical industry is not new, the application of such liquid materials has been limited because of chemical instability. Under the conditions of voltage stress and high temperature normally encountered in the service of transformers, capacitors, cables, and the like, compounds of the chlorinated paraffin hydrocarbon type have not been found to be very satisfactory. With the development of the chlorinated liquid compounds of the cyclic hydrocarbons,[1,2] dielectric compositions have been made available which fully meet the stability requirements. Because of the desire to obtain noninflammability of the liquid as well as to eliminate the explosiveness of the arc-formed gases, the compounds of this type have at least half of the hydrogen atoms present in the original hydrocarbon replaced by chlorine.[3] Only such compounds are discussed in the present paper.

## The General Characteristics of Noninflammable Synthetic Insulating Liquids

The noninflammable synthetic dielectric liquids at present commercially available are, in general, chlorinated derivatives of cyclic organic hydrocarbons. In order to obtain suitable physical characteristics, such as viscosity and low congealing point, blends of chlorinated organic compounds are frequently employed. Among the compounds in commercial use or available for use are the chlorinated derivatives of diphenyl, diphenyl oxide, benzophenone, diphenyl methane, dibenzyl, and benzene. Each of these has its advantages.[4] At present, however, the chief commercial interest lies in compositions containing chlorinated diphenyl and mixtures of chlorinated diphenyl with trichlorbenzene. The properties of 2 such compositions in commercial use as impregnants for capacitors and cables, and as the dielectric and cooling medium for transformers are given in table I. Such compositions are not only noninflammable in themselves, but when decomposed by the electric arc evolve only noninflammable gaseous mixtures.

## The Dielectric Strength of the Liquids

The factors which determine the dielectric strength of insulating liquids are not clearly recognized. Liquid density is without doubt of importance in any homologous series of organic compounds. The difference in density as between two different chemical types of organic liquids, however, does not appear to be of significance in determining the relative dielectric strengths. It has been suggested[5] that the dielectric strength of mineral oils varies with those changes which produce a variation in the dissolved gas content of the liquid. Such a suggestion does not attempt to explain the high dielectric strength of the noninflammable synthetic dielectric liquids described in table I as compared to mineral oil of similar viscosity.

While it is recognized that the dielectric strength of any insulating liquid is distinctly a function of the care used in its preparation and test, the normally expected value for new and unoxidized mineral oil, tested in accordance with the usual practice, is about 30 kv at room temperature. The synthetic liquid dielectrics of table I tested under similar conditions are characterized by a dielectric strength which is from 40 to 50 per cent higher. Such a high dielectric strength becomes only of academic interest unless it can be maintained at a correspondingly higher than oil value during use. Accumulated service and laboratory experience clearly indicates such behavior.

Consideration of the dielectric adaptability of a liquid for any specific application must inevitably include a survey of its chemistry.[8] Detailed chemical analysis of the noninflammable synthetic dielectrics is beyond the scope of this paper, yet for the proper understanding of the materials, consideration of their chemical reactivity cannot be avoided. One of the major factors leading to decreased dielectric strength in liquids is the presence of moisture, moist fibers, gas bubbles, and suspended solids. It is unfortunate that in most of the dielectric applications of mineral oils, oxidation cannot be entirely eliminated. The oxidation of the oil hydrocarbon produces those types of materials which lead to decreased dielectric strength, as for example carbon dioxide gas, water, organic acids, and, if the oxidation is severe, suspended oil sludge. Water coming in contact with oxidized mineral oil may even form a semipermanent emulsion with dangerously low dielectric strength. The noninflammable synthetic

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1. For all numbered references, see list at end of paper.

**Table I. Properties of Noninflammable Synthetic Liquid Dielectrics**

| Type | Viscous | Nonviscous |
|---|---|---|
| Use | Capacitors and cables | Transformers |
| Color | Pale yellow | Pale yellow |
| Specific gravity | 1.500 (60/15.5 degrees centigrade) | 1.565 (15.5/15.5 degrees centigrade) |
| Saybolt universal viscosity | 48 seconds at 98.9 degrees centigrade | 54 seconds at 37.8 degrees centigrade |
| Pour point | +10 degrees centigrade | Lower than −32 degrees centigrade |
| Burn point | None | None |

liquids are in marked contrast. Exposed to an oxidizing atmosphere under the most severe conditions, little if any chemical change can be observed. The color and original neutrality are essentially unchanged. No water, gas, or sludge is formed. The initially high resistance to water emulsification is retained with resultant high dielectric stability.

Figure 1 illustrates the marked difference in the dielectric stability of a typical transformer noninflammable synthetic dielectric liquid as compared to the usual mineral transformer oil. The materials were placed each in a clear glass, 5-gallon bottle, maintained at atmospheric temperature, and equipped with an inverted breathing tube open to the atmosphere in such a manner that the direct entrance of water (moisture or rain) was prevented, although free breathing produced as a result of atmospheric temperature changes was allowed. Clear glass bottles were used in order to promote any possible chemical change due to sunlight. Free breathing to the atmosphere was allowed in order that atmospheric moisture might slowly be accumulated in each liquid. Since chemical changes, if present, would include acid formation, liquid darkening, sludge formation, and water accumulation, the relative dielectric stability of the 2 liquids was expected to be demonstrated. As shown in figure 1, the nonoxidizing synthetic liquid gave practically no change in dielectric strength throughout the test exposure. The oxidizable mineral oil showed a slow drop in dielectric strength during the first 16 days of exposure, followed by a severe drop in dielectric strength between the sixteenth and the thirtieth day. At this time, the chemical changes in the oil were sufficiently advanced such that oil acid and sludge had accumulated in the liquid. In both the oil and the noninflammable liquid containers, water had accumulated, on the top of the synthetic liquid and at the bottom of the mineral oil. The test was discontinued after 182 days.

Organic hydrocarbon liquids, if exposed for long periods at high temperature to air and moisture, will oxidize and deteriorate. Under such conditions, the noninflammable synthetic liquids described in this paper show negligible change, either chemically or electrically. Typical results are illustrated in figure 2. The setup consisted of a glass vessel containing the synthetic liquid and connected to a reflux water condenser. Distilled water was added in an amount equal to about 10 per cent of the volume of the synthetic liquid which was heated sufficiently to maintain a slow refluxing of the water. The liquid temperature was approximately 100 degrees centigrade. Metallic aluminum was placed in the body of the liquid dielectric in order to detect any generation of corrosive chlorine formed from the long-time moisture contact in the presence of air. None was observed. The liquid showed no substantial increase in color or acidity. As shown in figure 2, the high dielectric strength of the liquid was maintained.

The superior dielectric strength characteristics of the noninflammable synthetic liquids, when tested with the usual oil-testing procedure, using a 0.1-inch liquid gap, is maintained with greater gap distances. Tests up to a gap distance of 2 inches are illustrated in the data of figure 3.

The dielectric strength of both the noninflammable synthetic liquid dielectric and mineral oil is a logarithmic function of the gap distance. The logarithmic relation, however, changes with increasing gap distance above approximately one inch. This change is illustrated in figure 4. Its technical significance is at present under investigation. For the larger gap distances above one

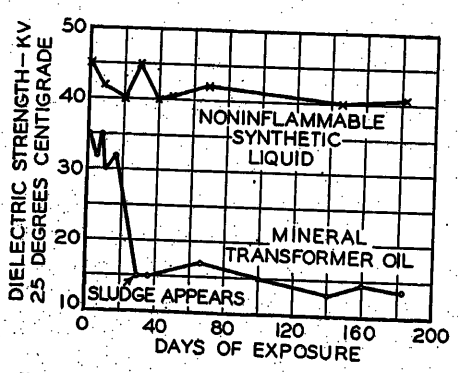



**Figure 1. Comparative stability in dielectric strength of mineral transformer oil and a synthetic noninflammable liquid of similar viscosity**

Dielectric strength tested in accordance with the usual rapidly applied voltage procedure using one-inch brass-disk electrodes spaced 1/10 inch apart

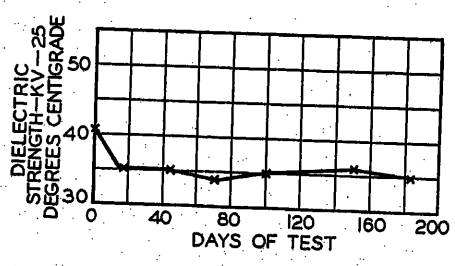



**Figure 2. The dielectric stability of noninflammable synthetic insulating liquids**

Setup: Liquid refluxed with water in presence of aluminum and air. Dielectric strength determined with rapidly applied voltage application using one-inch brass-disk electrodes spaced 1/10 inch apart

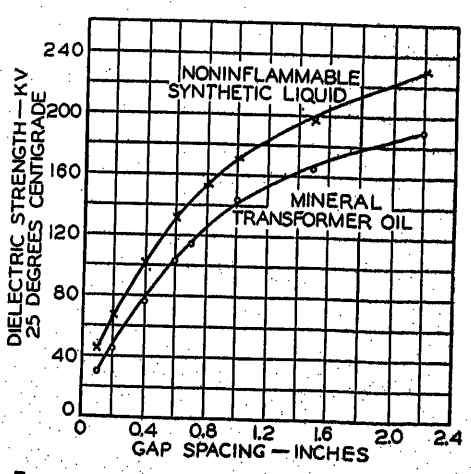



**Figure 3. The dielectric strength-gap distance relation for mineral transformer oil and a noninflammable synthetic insulating liquid of similar viscosity**

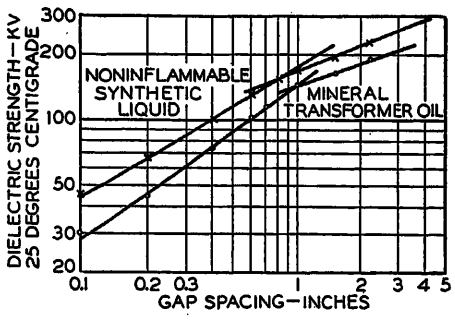



**Figure 4. Showng the logarithmic relation between dielectric strength and gap distance for mineral transformer oil and a noninflammable synthetic liquid of similar viscosity**

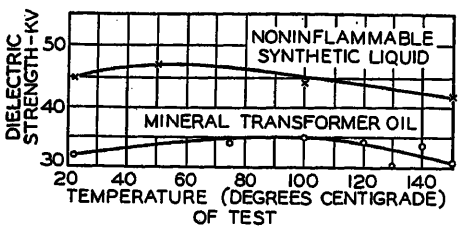



**Figure 5. The comparative dielectric strength of mineral transformer oil and noninflammable synthetic liquid of like viscosity as a function of the testing temperature**

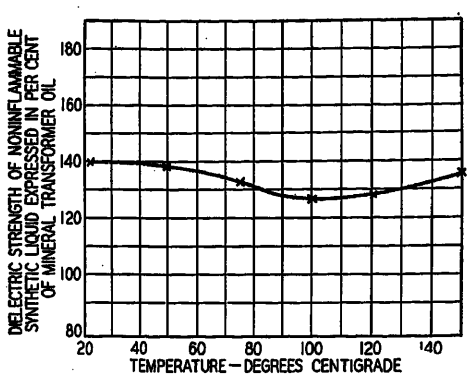



**Figure 6. The increased dielectric strength obtained with the noninflammable synthetic transformer insulating liquid expressed in terms of the dielectric strength of mineral transformer oil as a function of the testing temperature**

inch, the noninflammable synthetic dielectric liquid shows a dielectric strength about 20 per cent higher than that obtained with mineral transformer oil. For the smaller gap distances below one inch, the superiority in dielectric strength of the noninflammable synthetic liquid varies from approximately 20 per cent to as high as 50 per cent as the gap distance is continuously decreased.

Expressed logarithmically for the tests of this survey, the dielectric strength of oil and noninflammable synthetic liquids varies with the gap distance in accordance with equations 1, 2, and 3, in which $T$ indicates gap distance.

For mineral oil below one-inch gap distance:

$$Kv = AT^{0.70} \quad (1)$$

For noninflammable synthetic liquid dielectrics below one-inch gap distance:

$$Kv = AT^{0.59} \quad (2)$$

For both oil and noninflammable synthetic liquid dielectrics above one-inch gap distance:

$$Kv = AT^{0.37} \quad (3)$$

Figure 5 illustrates the effect of temperature change on the dielectric strength of a typical transformer noninflammable synthetic liquid dielectric and mineral transformer oil, each tested with rapidly applied voltage application between one-inch brass disk electrodes spaced $^1/_{10}$ inch apart. As already described in previous papers[6] the dielectric strength of mineral transformer oil increases with increase in temperature to 100 degrees centigrade. The noninflammable synthetic dielectric liquid shows a similar change in dielectric strength with increase in temperature, but reaches its maximum value at about 55 degrees centigrade, above which temperature its dielectric strength decreases in an approximately linear relation to the temperature increase. While at room temperature, the synthetic liquid is approximately 40 per cent higher in dielectric strength than mineral transformer oil, at 100 degrees centigrade the advantage has been reduced to 27 per cent. Above 100 degrees centigrade, the superiority of the noninflammable synthetic liquid again increases due to the more rapid drop in dielectric strength of mineral transformer oil as the temperature is further increased. The relationship is illustrated in figure 6.

It has already been suggested[6] that the change in the dielectric strength of insulating liquids with temperature reflects changes in the liquid-dissolved air content. It is to be observed that the changes in the dissolved air content of the noninflammable synthetic liquid dielectric discussed in these paragraphs predict the change in dielectric strength observed. The dissolved air content at normal atmospheric pressure and the corresponding dielectric strength at 25 degrees centigrade and 100 degrees centigrade for the noninflammable synthetic dielectric liquid under discussion are indicated in the following tabulation:

| | Dissolved Air Content | | Dielectric Strength | |
|---|---|---|---|---|
| | 25°C | 100°C | 25°C | 100°C |
| Mineral transformer oil | 10.0 | 11.3 | 32.0 | 35.0 |
| Noninflammable synthetic liquid | 6.3 | 6.0 | 45.5 | 44.5 |

## The Dielectric Strength of Treated Insulation

The ability of an insulating liquid to impart a high dielectric strength to cellulosic insulation is one measure of its usefulness. It is frequently considered that all insulating liquids possess equal ability to impart dielectric strength to solid insulation unless prevented by exceptional physical characteristics. Since most liquids heretofore investigated have been of petroleum origin, this generalization has been apparently well-founded. With the noninflammable synthetic liquid dielectrics of the type under discussion, however, 2 important changes have been introduced. The first is that the characteristic dielectric strength of the liquid has been raised by more than 20 per cent, depending upon the testing temperature and gap spacing. The second is that the dielectric constant has been materially increased. Over the range of temperature from 25 degrees centigrade to 100 degrees centigrade, the dielectric constant of the noninflammable synthetic

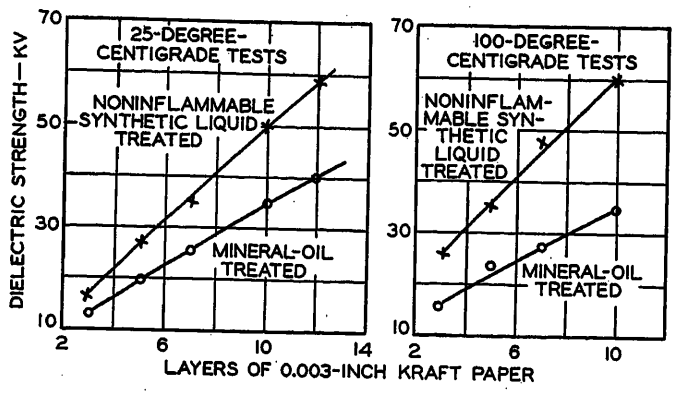



**Figure 7. The comparative dielectric strength of mineral oil and noninflammable synthetic-liquid-impregnated kraft paper**

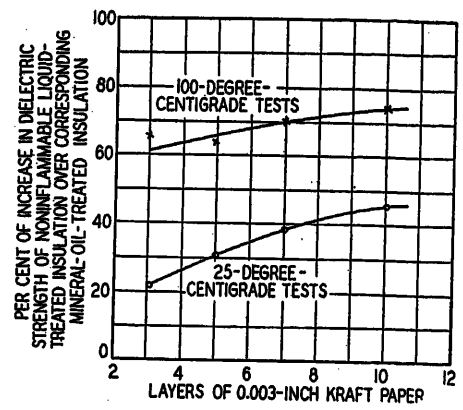



**Figure 8. The superiority of the noninflammable synthetic-liquid-impregnated 0.003-inch-kraft-paper dielectric expressed in terms of the corresponding mineral-oil-treated dielectric**

Testing temperature —25 degrees centigrade and 100 degrees centigrade, as indicated

Testing procedure—Minute test

Insulation thickness —0.004 inch (8 sheets of insulation)

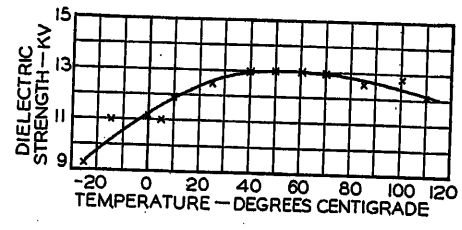



**Figure 9. The dielectric strength-temperature relation for 0.0005-inch-kraft-paper insulation impregnated with the transformer type of noninflammable synthetic insulating liquid**

liquid under discussion varies from 5 to 4, a value more closely approximating that of the cellulose material itself than does the dielectric constant of mineral oil or related hydrocarbon mixtures, the characteristic dielectric constant of which is approximately 2.2. Since liquid-impregnated cellulosic insulation in laminated structures, such as is normally used in commercial dielectrics, is essentially a series arrangement of liquid and solid, the advantage of an equalized dielectric constant as between the liquid and solid is immediately evident. Higher breakdown values for the noninflammable synthetic liquid impregnated cellulosic insulation are to be expected, not only because of the increased dielectric strength of the liquid itself as compared to mineral oil but also because of the more equal stress distribution resulting from the equalization of the dielectric constant of the liquid and the cellulosic base.

Figure 7 illustrates the dielectric strength of 0.003-inch kraft paper impregnated insulation, tested by the "minute test" voltage procedure, both at 25 degrees centigrade and at 100 degrees centigrade. The presence of the synthetic liquid increases the breakdown of the paper insulation as compared to the corresponding oil-treated value, the increase in breakdown increasing as the total thickness of the pad tested is increased. This is illustrated in figure 8.

Figure 9 illustrates the temperature effect on dielectric strength for noninflammable synthetic liquid-impregnated insulation, tested by the "minute test" procedure from −20 degrees centigrade to +100 degrees centigrade. The insulation in this case consists of 8 layers of 0.0005-inch kraft capacitor paper.

The advantageous dielectric strength characteristic of insulation impregnated with the noninflammable synthetic insulating liquid is undoubtedly related to thermal phenomena. Under conditions which prevent serious heat accumulation effects, the dielectric strength of mineral oil-treated insulation or untreated insulation is a logarithmic function of the thickness and approaches the first power function of the thickness factor. With test conditions which allow greater thermal effect, although the logarithmic relation is sustained, the dielectric strength increases at a decreased function of the insulation thickness.[7] The following relationships have been established for insulation tested in the form of flat pads:

Untreated kraft paper at 25 degrees centigrade, rapidly applied voltage

$$Kv = AT^{0.92 \text{ to } 1.0} \quad (4)$$

Untreated kraft paper at 25 degrees centigrade, minute test voltage

$$Kv = AT^{0.92 \text{ to } 1.0} \quad (5)$$

Mineral-oil-treated kraft paper at 25 degrees centigrade, rapidly applied voltage

$$Kv = AT^{0.90 \text{ to } 0.95} \quad (6)$$

Mineral-oil-treated kraft paper at 25 degrees centigrade, minute test voltage

$$Kv = AT^{0.75} \quad (7)$$

The dielectric strength data of figure 7 are also a logarithmic function of the insulation thickness. The "minute test" breakdown at 25 degrees centigrade for 0.003-inch mineral-oil-treated kraft paper agrees well with the previously established relation (equation 7), breakdown varying with thickness in accordance with equation 8:

$$Kv = AT^{0.75} \quad (8)$$

The previous publication,[7] however, did not demonstrate that when the temperature of the test is increased, the logarithmic relation correlating breakdown and insulation thickness changes, again reflecting the effect of heat accumulation. The data of figure 7 and figure 10 describing the dielectric strength-thickness relation for mineral-oil-treated kraft paper at 100 degrees centigrade indicate the following expression:

$$Kv = AT^{0.66} \quad (9)$$

In table II, rapidly applied test breakdown data are given for impregnated kraft paper tested at 25 degrees centigrade. Complete data covering a wide range of insulation thicknesses are not illustrated. Such studies, however, clearly substantiate the logarithmic relation between dielectric strength and insulation thickness whether the kraft paper be impregnated and tested under mineral oil or the synthetic noninflammable liquid. The formula established from these studies relating the dielectric strength under rapidly applied tests at 25 degrees centigrade for both types of impregnants is given in equation 10:

$$Kv = AT^{0.90 \text{ to } 0.95} \qquad (10)$$

The similarity in the dielectric strength-thickness relation for kraft paper insulation impregnated with mineral oil and the synthetic liquid when tested at 25 degrees centigrade with rapidly applied voltage procedure is to be expected since under these conditions heat effects are negligible. When, however, longer time voltage tests are used the kraft paper insulation impregnated with the noninflammable synthetic liquid dielectric shows a closer approach to a linear relation of thickness and dielectric strength than that established for mineral oil-treated insulation. This is illustrated in figure 10. While in this instance the dielectric strength at high temperature is a decreased logarithmic function of thickness, the effect of change in insulation thickness for the synthetic liquid treated insulation always more closely approximates a linear relation than that observed for the corresponding mineral-oil-treated dielectric. This is indicated in the following formulas set up for 0.003-inch kraft paper impregnated with the noninflammable synthetic liquid dielectric and tested in accordance with minute test voltage application procedure:

$$\text{At 25 degrees centigrade, } Kv = AT^{0.04} \qquad (11)$$

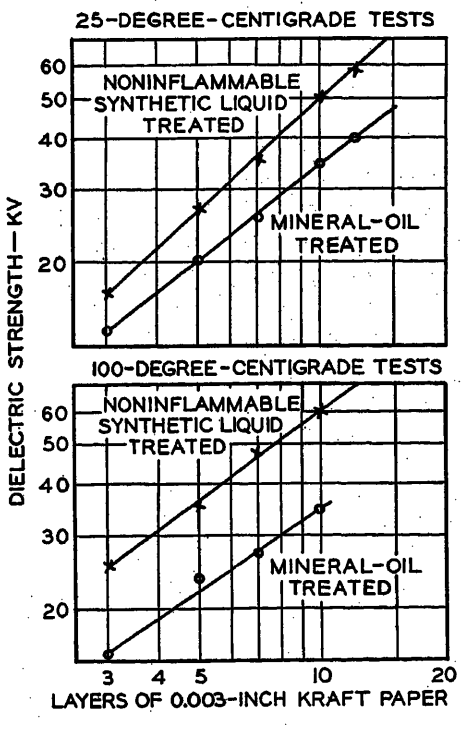



**Figure 10. Illustrating the logarithmic relation between dielectric strength and thickness for 0.003-inch-kraft-paper insulation impregnated with mineral transformer oil and synthetic noninflammable dielectric liquid of like viscosity**

Testing procedure—Minute test (data based on figure 7)

**Table II. The Comparative Rapidly Applied and Minute-Test Dielectric Strength of Impregnated Kraft Paper**

Test temperature—25 degrees centigrade
Voltage applied—60 cycles
Insulation—0.003-inch impregnated kraft paper
Test medium—Same as impregnating medium

| | Average Dielectric Strength | | |
|---|---|---|---|
| | Rapidly Applied Voltage, (Kv) | Minute Test Voltage, (Kv) | Per Cent Decrease Due to Extended Time |
| Oil impregnated—10 layers | 41.0 | 35.0 | 14.7 |
| Noninflammable synthetic-liquid-impregnated—10 layers | 55.5 | 50.0 | 9.7 |
| Oil impregnated—15 layers | 59.0 | 47.0 | 20.3 |
| Noninflammable synthetic-liquid-impregnated—15 layers | 80.0 | 72.0 | 10.0 |

$$\text{At 100 degrees centigrade, } Kv = AT^{0.71} \qquad (12)$$

The dielectric strength of mineral-oil-treated insulation decreases with the duration of voltage application. With the so-called "life test," in which the voltage application extends over weeks and months, this effect may be produced by voltage or by heat accumulation, both of which result in chemical deterioration in the dielectric assembly. Such effects are not susceptible to easy demonstration under laboratory conditions. Data available, however, indicate clearly that the marked chemical stability of the noninflammable synthetic dielectric liquids as compared to the susceptibility of the hydrocarbon oils to oxidation and other forms of chemical change is reflected in the greater electrical stability of the treated insulation.

Test temperature—25 degrees centigrade
Voltage application—Minute test procedure
Test form—Flat pads
Electrodes—Aluminum foil

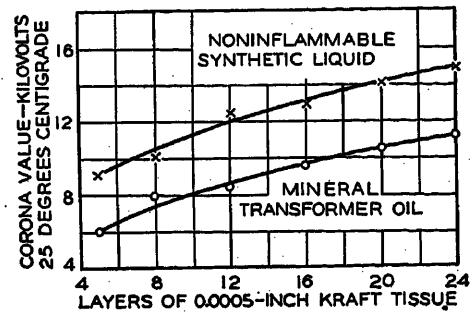



**Figure 11. The visual corona-formation point for mineral-transformer-oil-treated and synthetic-liquid-treated 0.0005-inch-kraft-paper dielectric**

Voltage application—Minute test procedure
Dielectric thickness—0.004 inch
Electrodes—Aluminum foil

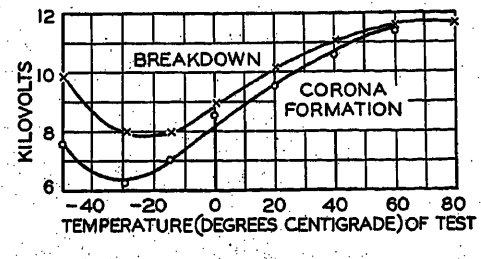



**Figure 12. Corona formation and breakdown of noninflammable synthetic-liquid-treated 0.0005-inch-kraft paper as a function of the testing temperature**

The dielectric superiority of the noninflammable synthetic-liquid-treated insulation is indicated even under conditions of test in which air and oxygen are carefully excluded in order to eliminate mineral-oil-oxidation effects. Thus in one typical group of tests, dielectric assemblies were prepared each consisting of aluminum electrodes separated by 3 sheets of 0.0004-inch kraft tissue. The electrodes were $2^7/_8$ inches wide and 94 feet long. The rolled assembly was vacuum dried, impregnated and tested in a gas-free hermetically-sealed container. The following results clearly indicate the superiority of the synthetic-liquid-treated insulation even when tested under the most favorable mineral oil conditions:

| Dielectric Treated With | Mineral Oil | Noninflammable Synthetic Liquid |
|---|---|---|
| Number assemblies tested | 40 | 40 |
| Voltage applied (60 cycles) | 880 | 880 |
| Volts per mil | 733 | 733 |
| Ambient testing temperature | 30 degrees centigrade | 30 degrees centigrade |
| First dielectric failure | 1 day | 17 days |
| Total dielectric failures in 10 days | 7 (17½ per cent) | 0 (0 per cent) |
| Total dielectric failures in 25 days | 12 (30 per cent) | 1 (2½ per cent) |
| Total dielectric failures in 50 days | 15 (37½ per cent) | 2 (5 per cent) |
| Total dielectric failures in 70 days | 16 (40 per cent) | 2 (5 per cent) |

Laboratory demonstration of the greater time-voltage stability of the noninflammable liquid as compared to the mineral-oil-treated dielectric is also illustrated by the usual time-voltage relation in which the voltage is continuously applied for periods from one second to 1 or 2 hours. Reference to data already presented will serve to indicate the comparison. In table II, the 10-second breakdown (called "rapidly applied test") is compared to the so-called "minute test" procedure, in which the voltage is slowly raised over a period of about 10 minutes. In general, the effect of lengthened time of voltage application is less on the noninflammable synthetic liquid-treated insulation. Under the conditions outlined, a decrease in breakdown value of 10 per cent appears to be characteristic of kraft paper insulation impregnated with the noninflammable synthetic liquid dielectric. This compares to a corresponding average decrease of 17 per cent characteristic of the same dielectric when mineral-oil impregnated.

## Visual Corona Formation in the Treated Dielectric

The dielectric failure of insulation is inevitably preceded by the formation of corona in the liquid layer. With mineral-oil-treated insulation, because of the difference in the dielectric constants of the oil and the cellulosic insulation, coupled with the breakdown characteristic of the oil itself, corona may appear at relatively low voltage stress. With 0.0005-inch kraft-paper tested by the "minute test" procedure, the corona formation point of the noninflammable synthetic liquid-treated dielectric, depending upon the thickness of insulation tested, is from 30 per cent to 50 per cent higher than the corresponding corona formation point in the mineral-oil-treated dielectric. Figure 11 illustrates the corona formation value for mineral-oil-treated 0.0005-inch kraft paper as compared to similar insulation impregnated with noninflammable synthetic liquid of similar viscosity. The corona formation point is described as the voltage at which visual discharge appears at the edges of the aluminum foil electrodes used in this test setup, all tests being carried out under the same medium used for the impregnation of the kraft paper. With temperature increase, the corona formation of the noninflammable synthetic liquid-treated dielectric increases. Figure 12 shows the corona formation value in its relation to the ultimate "minute test" breakdown as the temperature is changed from −50 degrees centigrade to +80 degrees centigrade. With temperatures higher than 60 degrees centigrade to 80 degrees centigrade, the corona-formation voltage increases to the extent that it blends with the breakdown voltage and is visually indistinguishable therefrom. As the temperature is decreased below room temperature, the breakdown and the corona formation voltage do not decrease indefinitely but reach a minimum value in the range of about −30 degrees centigrade. Both values increase with further decrease in temperature. Such changes invariably accompany a change in physical state, liquid to solid, and are normal behavior of mineral oils as well as other dielectric liquids.

## Summary

The development of synthetic noninflammable chlorinated liquids of the aromatic hydrocarbon type places in the hands of the engineer a chemically stable material of high dielectric strength and possessing a dielectric constant approximately equal in value to that of cellulose itself. This insures a more equitable stress distribution in the composite insulation assembly normally used in commercial practice. The result is an increase in dielectric breakdown and related phenomena. No fixed relation defining the superiority of the synthetic noninflammable liquid or liquid-treated insulation is possible, since variation in test conditions changes the relative dielectric values. In general, however, the data indicate an advantage in favor of the synthetic liquid and liquid-treated insulation equal to at least 20 per cent of the corresponding mineral-oil value.

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# Application of Arresters and the Selection of Insulation Levels

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FOR many years, the insulation strength of power transformers and other electrical equipment was determined chiefly by the performance in service. When failures occurred, the insulation was made heavier at the points of weakness, and gradually the number of weak points was reduced in the particular lines of equipment and ratings involved. When new lines or ratings were initiated, operating experience was frequently necessary to perfect the design. Little information was available regarding the insulation strength of equipment under impulse conditions, and there was practically no selected co-ordination between the equipment strength and the performance of surge protective equipment.

The principal cause of equipment failures has been lightning, and much attention has been given during the past few years to the study of lightning phenomena and the behavior of insulation material under lightning stress. At the same time, the study of protective equipment has made available a knowledge of its behavior under lightning surge conditions. Great strides have been made in this direction, so that it is now possible to select insulation levels with a degree of confidence as to subsequent performance, provided that proper correlation of these phenomena and behavior characteristics is effected.

This paper describes a method of selecting the required insulation levels of transformers and other power system equipment according to the performance of the protective equipment.

A brief review of some of the important phases of the problem will first be given in order that the method proposed for the selection of insulation levels may be readily understood.

The most important factors are:

(*a*) The magnitude and duration of the overvoltages to which the equipment may be subjected

(*b*) The volt-time insulation characteristics of the equipment

(*c*) The performance characteristics of available protective equipment

## Overvoltages

Transformers and other power system equipment may be subjected to overvoltages due to:

(*a*) Switching surges and abnormal power system conditions

(*b*) Lightning

Switching surges are usually of relatively long duration, but their magnitudes generally do not exceed 3.5 times normal voltage.[1] On many systems, they are less than 2 times normal voltage. Dynamic overvoltage due to hydroelectric generator runaway or other abnormal unloading conditions may reach values as high as 2 times normal. Apparatus designed in accordance with AIEE alternating voltage dielectric tests has proved to be entirely adequate for such overvoltages arising from system operation.

Lightning is considered to be the principal source of insulation failure because of the very high values of voltage and the steep wave fronts involved. Lightning voltages may be the result either of a direct stroke or a traveling wave, and the effect on insulation depends upon the magnitude, the duration, and the rate of rise and decay of the surge potential. It is apparently more economical and practical to take advantage of the protective equipment available and to utilize apparatus of an insulation strength properly co-ordinated with this protective equipment than to attempt to build apparatus in the present operating voltage ranges which will be able to withstand lightning surges without the use of some auxiliary protective device, either separate from or integral with the apparatus.

## Protective Equipment

The fundamental duty of a surge voltage protective device is to discharge any surge successfully and to limit the voltage to values well within the impulse strength of the equipment. In this discussion, the protective equipment will be assumed to include lightning arresters properly applied, supplemented by gaps on line terminals and by direct stroke shielding.

### Lightning Arresters

A lightning arrester is a device which has the property of reducing the voltage of surges applied to its terminals, is capable of interrupting follow current (if present), and restores itself to its original operating condition without causing a disturbance on the system. A lightning arrester, due to its rapid breakdown or gap flashover and the relatively low voltage across it during discharge provides both short time and long time protection to insulation except for some direct strokes.

Typical protective characteristics of modern lightning arresters, based on information as available and including impulse breakdown voltages and the voltage across the arrester during discharge of surge currents of various magnitudes, are presented in table I. Complete performance characteristics of line-type arresters are presented in the report of the AIEE lightning arrester subcommittee.[2]

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1. For all numbered references see list at end of paper.

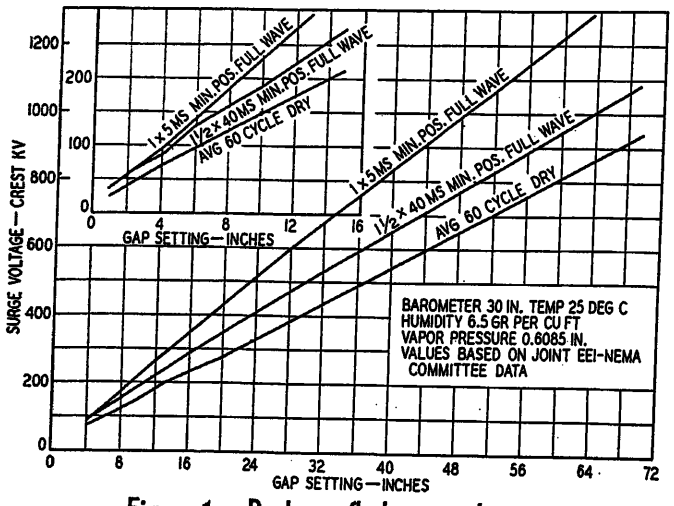



**Figure 1. Rod gap flashover voltages**

### Gaps

Various types of special gaps, such as the control gap, deion gap, and expulsion gap, have been developed. These have particular operating characteristics which govern their application and give varying degrees of protection.

The rod gap which has been extensively used in the past few years as a device for applying impulse tests on transformers and for co-ordination work in the laboratories, is defined as one consisting of $^1/_2$-inch square-cornered square-cut rods coaxially spaced and overhanging their supports at least one-half the gap spacing, and mounted on conventional insulators giving a height of 1.3 times the gap spacing plus 4 inches (±10 per cent tolerance) above the ground plane. Figure 1 shows the 1.5x40 microsecond, the 1x5 microsecond minimum flashover, and the 60-cycle characteristics of this rod gap. Figure 2 shows the approximate volt-time characteristics at various spacings. The protection afforded by rod gaps is discussed in another paper presented at this symposium.[3]

### Direct Stroke Protection

Shield wires or ground wires have proved themselves very effective for direct stroke protection when properly located and adequately grounded.[4] Shielding is of principal value in the protection of high-voltage lines and equipment against direct strokes and may be justified when the investment is proportionately high.

## Insulation Characteristics of Equipment

Various materials having markedly different insulation strength characteristics are used in electrical equipment. For example, a transformer consists of laminated insulation, solid insulation, oil, porcelain, and clearances in air. The volt-time characteristics of laminated and solid insulation are relatively flat, approaching the characteristics of a sphere gap. On the other hand, the volt-time characteristics of porcelain are approximately the same as rod gaps and show time lags at short time intervals. This is illustrated by figure 3. This disparity between the characteristics of the solid insulation and the bushing or rod gap necessitates that an insulation co-ordination study be made on a volt-time basis with full recognition of short time as well as long time phenomena.

Volt-time characteristics of apparatus insulation are not as yet generally available. It has, therefore, been necessary to study insulation levels largely in terms of voltages corresponding to some particular specified test wave condition. As a matter of convenience, the manufacturers have been expressing these insulation levels largely in terms of rod gaps, corresponding to some particular specified test wave condition. This has proved inadequate and basic insulation levels have recently been set up in terms of the minimum impulse flashover voltage on a $1^1/_2$x40 microsecond wave under standard conditions.[5] The latest authentic data available regarding the impulse strength of transformers is presented in reports by the AIEE transformer subcommittee.[6,7]

## Selection of Insulation Levels

An electrical station is composed of a number of component parts, i.e., transformers, circuit breakers, bus, etc., each including various types of insulation—air, oil, porcelain, and other materials. In order to render such a station as immune as practicable to transient voltage disturbances there must be a definite relationship between

**Table I. Typical Performance of Modern Lightning Arresters**

| Arrester Rating (RMS Kv) | Arrester Gap Breakdown (Surge Crest Kv) | Voltage Across Arrester During Discharge (Crest Kv) 1,500 Amp | 3,000 Amp | 5,000 Amp |
|---|---|---|---|---|
| **Protective Ability** | | | | |
| **Line Type** | | | | |
| 3 | 17 | 11 | 13 | 15 |
| 6 | 35 | 21 | 24 | 27 |
| 9 | 49 | 31 | 36 | 40 |
| 12 | 58 | 40 | 47 | 52 |
| 15 | 66 | 51 | 59 | 65 |
| 20 | 80 | 70 | 78 | |
| 25 | 100 | 88 | 97 | |
| 30 | 115 | 105 | 115 | |
| 37 | 140 | 130 | 145 | |
| 50 | 180 | 175 | 195 | |
| 60 | 215 | 215 | 235 | |
| 73 | 270 | 260 | 285 | |
| **Station Type** | | | | |
| 3 | 14 | 9 | 10 | 11 |
| 6 | 24 | 18 | 20 | 21 |
| 9 | 36 | 27 | 30 | 32 |
| 12 | 41 | 36 | 43 | 50 |
| 15 | 51 | 45 | 55 | 63 |
| 20 | 70 | 50 | 66 | 75 |
| 25 | 85 | 74 | 86 | 100 |
| 30 | 100 | 91 | 110 | 127 |
| 37 | 125 | 110 | 130 | 150 |
| 50 | 170 | 149 | 175 | 200 |
| 60 | 205 | 182 | 220 | 250 |
| 73 | 250 | 220 | 265 | 300 |
| 97 | 330 | 290 | 350 | 400 |
| 121 | 410 | 360 | 440 | 500 |
| 145 | 490 | 430 | 530 | 600 |
| 169 | 570 | 500 | 620 | 700 |
| 242 | 820 | 720 | 890 | 1,000 |

**Thermal Ability**

The thermal ability is a function of the magnitude of the current and its duration. The line type arresters can withstand surge currents of 2,000–3,000 amperes crest and the station type arresters 10,000 amperes crest with surges of relatively long tails. These arresters can withstand a limited number of surges of higher current values provided they are of shorter duration.

the characteristics of the protective devices and the insulation strength of the equipment. Since overvoltages due to lightning are conceded to be the most serious source of trouble, then logically the characteristics of the surge protective equipment will form the criterion. *The insulation level of apparatus must be above the maximum surge voltage presumed to be allowed by the protective device on a volt-time basis over the range of time selected.*

The transformer is usually the most important piece of equipment in a station, both from the standpoint of cost and of service continuity. Furthermore, the major insulation in a transformer has practically a flat time-lag characteristic (figure 3) and this tends to make its protection from surges having high amplitudes and steep fronts a more serious problem than that of air, oil, or porcelain insulation. The protection of the transformer insulation has, therefore, been considered to be of prime importance in determining a proper insulation level.

Having available performance data on protective equipment and having evaluated the marginal factors, the determination of insulation levels is chiefly a matter of the selection and application of the protective equipment. The protective performance of modern lightning arresters has been selected as a suitable basis for the initial establishment of a series of protected insulation levels. Arresters generally have the following characteristics which are of value in this connection:

(*a*) A regular series of voltage ratings, including the distribution voltages, have been standardized.

(*b*) The performance characteristics as indicated in table I have been determined as typical, and it is assumed that the devices produced by the principal manufacturers have characteristics sufficiently similar to render them suitable for general application.

(*c*) The performance characteristics are such as to approximate the volt-time characteristics of transformer insulation.

(*d*) The performance characteristics are unaffected by weather and do not greatly change in general character with considerable change in voltage rating.

## Application of Lightning Arresters

The principal factors in the selection of the rating of a surge protective device, such as a lightning arrester or a gap, are:

(*a*) The maximum dynamic voltage which may occur between sound phase and ground under any fault conditions. The device must withstand this voltage without failure.

(*b*) The efficacy of the protective device in maintaining a low protected level and at the same time meeting satisfactorily the system operating requirements. The impulse volt-time characteristics must be below that of the equipment to be protected.

(*c*) The surge current which must be satisfactorily discharged. The thermal ability must be adequate for the currents expected.

The voltage rating of an arrester represents the maximum dynamic voltage which the arrester can withstand continuously and which it can interrupt after discharge. The arrester rating must, therefore, be greater than the maximum dynamic voltage which may occur between the arrester terminals during disturbances, allowing for the power system neutral being isolated, or grounded, as the case may be, and considering the actual maximum operating voltage. Allowance must also be made for the voltage recovery rate and any overvoltage conditions which may exist due to the overspeeding of hydroelectric generators, etc. The protection afforded by a lightning arrester is approximately proportional to its voltage rating and, therefore, it is important to use an arrester of as low a voltage rating as possible. Table II presents the general

**Table II. Typical Application of Lightning Arresters**

| System Voltage Classification | Approx. Range System Operating Voltage | Preferred Arrester Rating (Maximum Line-Ground Voltage, Kv) Neutral Not Effectively Grounded | Neutral Effectively Grounded |
|---|---|---|---|
| 2,400 | 2,200– 2,650 | 3 | 3 |
| 4,160Y | 3,800– 4,600 | 6 | 3 |
| 4,800 | 4,400– 5,300 | 6 | 6 |
| 7,200 | 6,600– 7,950 | 9 | 6 |
| 8,660Y | 7,600– 9,200 | 12 | 6, 9 |
| 12,000 | 11,000–13,000 | 12, 15 | 9, 12 |
| 13,200 | 12,100–14,300 | 15 | 12 |
| 14,400 | 13,200–15,000 | 15 | 12 |
| 23,000 | 20– 25 kv | 25 | 20 |
| 34,500 | 30– 37 kv | 37 | 30 |
| 46,000 | 40 –48 kv | 50 | 37 |
| 69,000 | 60– 72 kv | 73 | 50, 60 |
| 115,000 | 100–120 kv | 121, 132 | 97 |
| 138,000 | 120–144 kv | 145, 156 | 121 |
| 161,000 | 140–168 kv | 169, 180 | 121, 145 |
| 230,000 | 200–240 kv | 242 | 200 |

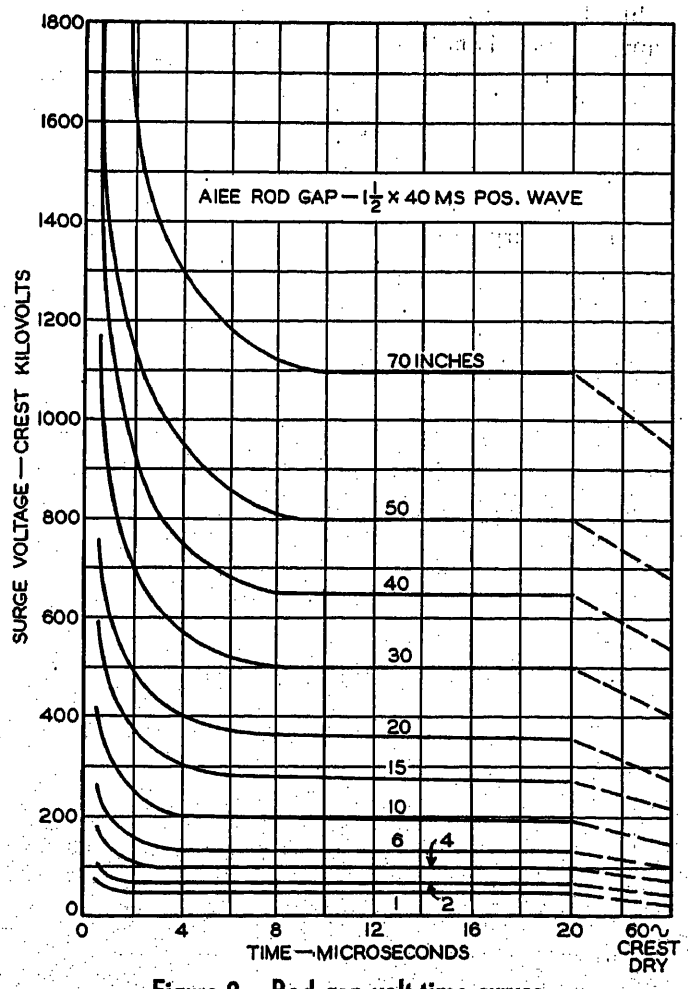



**Figure 2. Rod gap volt-time curves**

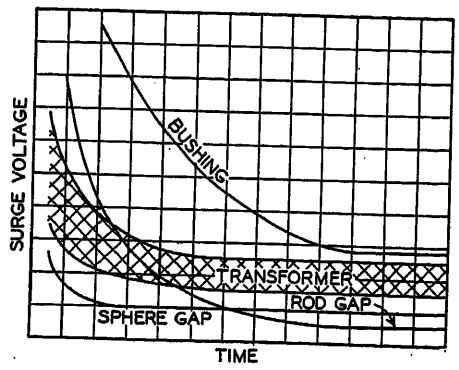



Figure 3. Relative volt-time curves

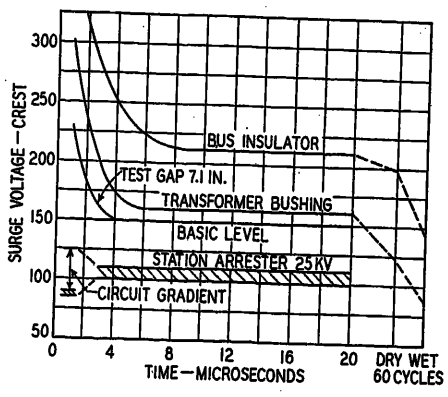



Figure 4. Station insulation—25-kv class—volt-time curves

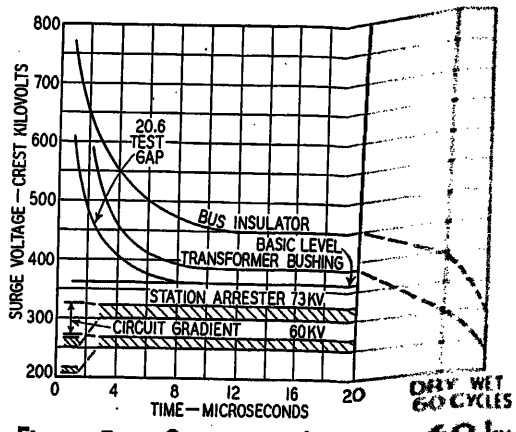



Figure 5. Station insulation—69-kv class—volt-time curves

application of arresters to systems in the various voltage classifications.

### Dynamic Voltage

The normal "full voltage" rated arrester is designed to operate on an ungrounded or isolated neutral system where the voltage existing between line and ground may at times equal the normal line-to-line voltage. The arrester rating is generally 5 per cent or more above the maximum operating voltage. Under favorable conditions where the system neutral is effectively grounded, better protection may be obtained by the use of an arrester having a reduced voltage rating, provided the upper limit of dynamic voltage is not exceeded under any operating condition. In the past "grounded neutral" arresters have had voltage ratings approximately 80 per cent of the "full rated" arresters. This gave a wide margin above the normal system line-to-neutral voltage to allow for fault voltages, etc.

For the purpose of determining the allowable arrester voltage rating, the maximum dynamic voltage which may occur during fault conditions between the sound phases and ground may be calculated by the method of symmetrical components. Under certain conditions, a 2-line-to-ground fault may be slightly more severe than a single line-to-ground fault.

For a single line-to-ground fault, Wagner and Evans[8] have shown that:

$$E_b = \frac{\sqrt{3}E_g}{2}\left[\frac{\sqrt{3}(Z_0 + R) + j(Z_0 + 2Z_2 + 3R)}{Z_0 + Z_1 + Z_2 + 3R}\right]$$

where

$E_b$ = voltage between sound phase and ground
$E_g$ = normal line to neutral voltage
$Z_1, Z_2, Z_0$ = sequence impedance to point of fault
$R$ = fault resistance

Arresters of reduced voltage rating should not be applied except where the neutral is "effectively grounded" and the following conditions are met:

(*a*) The neutral of that portion of the system must be grounded at all times and under all operating conditions.

(*b*) The ratio of zero-sequence impedance (including neutral impedance and fault resistance) to positive-sequence impedance or negative-sequence impedance ($Z_0/Z_1$ or $Z_0/Z_2$) must be equal to 2 or less under maximum fault conditions. Due consideration must be given to the circuit impedance as affected by sequential operation of circuit breakers at the ends of a line.

(*c*) The arrester voltage rating must be at least 10 per cent above the calculated maximum sound phase voltage to ground. In general it will be found that

if $Z_0/Z_1 = 2$ or less, an 80 per cent arrester may be used
if $Z_0/Z_1 = 1$ or less, a 70 per cent arrester may be used

These latter percentages should be applied to the *maximum* line-to-line operating voltage in determining the allowable arrester rating.

### Surge Currents

Considering traveling wave phenomena, it would be possible to calculate the magnitude of the surge discharge currents through the arrester for the various combinations of line and station insulation which may be encountered. These calculations, however, involve a number of indeterminate factors, including the surge impedance to ground, the magnitude and the wave shape of the surge, etc., and it is not generally considered feasible to make such calculations for each individual case. In the present discussion, the surge discharge current through station type arresters has been taken at 5,000 amperes crest and for line type arresters at 3,000 amperes crest. These values appear to be reasonably moderate in view of available field data[9,10] regarding lightning arrester surge currents. Furthermore, the voltage across the arrester during discharge does not increase in proportion to the surge current.

### Marginal Requirements

The typical performance of arresters, as given in table I, applies only to the arresters themselves, without any tolerances or margins. It must be realized, however, that with any protective device, an adequate margin must be provided above its performance characteristic to allow for manufacturing tolerances, different types of installations and to insure proper selectivity between the protective performance of the device and the apparatus insulation. The necessary margin is thus affected by a number of factors and should cover both long time im-

pulses and short waves of steep front and high crest.

The following tolerances and marginal items have been considered in this analysis with values as indicated:

(*a*) *Tolerances* in performance characteristics of arrester. Based upon manufacturer's information, these have been taken as:

Gap breakdown voltage = plus 5 per cent to 25 per cent

*IZ* drop across arrester during discharge of specified current = plus 5 kv + (5 per cent to 15 per cent)

(*b*) Effect of *distance and potential gradient* during surge conditions which may generally exist between the protective device and the apparatus on the basis of modern station layouts. The capacitance of station equipment will be effective in reducing the slope of the incoming surge wave. In the larger high-voltage stations this mitigates against the higher reflected surge voltages and complete double voltage reflections would not be expected unless the station capacity were very small and the station located at the terminal of a line.

The possibility of flashover occurring on the front of the wave, rather than on the tail of the wave as considered in the recent AIEE test procedure using waves of moderate crest, has been taken into account by considering steep wave fronts and both the short time and long time characteristics of insulation and protective devices. Considering the magnitudes of surge voltages and the reflection effects which may reasonably be expected, it appeared that a short time potential gradient of one kv per foot should be adequate allowance for distance, arrester connections, etc. Arresters to be effective should be located as close as possible to the apparatus being protected. In the case of 2,400-volt and 4,800-volt pole-mounted units, the distance between the arrester and the equipment has been taken as 4 circuit feet, with a gradual increase up to 150 circuit feet for the 240-kv class installed in stations.

(*c*) *Selectivity Margin.* It is necessary to provide an adequate margin, both with respect to time and voltage, to insure that the protective device shall function properly before insulation breakdown or damage may occur. There is apparently little definite information available pertaining to the margins which may be necessary. After reviewing past operating experience and correlating the performance of arresters in service with the information available regarding existing insulation levels, it has been concluded that a selectivity margin of some 30 kv to 40 kv (in addition to manufacturing tolerances and circuit gradient) is the minimum which may be used in the transmission-voltage classes.

## Protected Levels

In this analysis, arresters have been utilized on the basis of the voltage rating being approximately equal to the system line-to-line voltage, i.e., the use of a full rated arrester. The actual application of an arrester on a particular power system should ordinarily be on the basis of using one rated as low as permitted by the maximum dynamic voltage which might exist between sound phases and ground as previously described and the protection would be proportional to the voltage ratings shown.

Table III presents an analysis of the performance characteristics of station and line type arresters and includes the various marginal values which have been described. The terms "short" and "long" coupling have been used to designate the location of the arrester relative to the transformer being protected.

Figures 4 and 5 illustrate the arrester performance and station equipment insulation levels on a volt-time basis with a $1^1/_2 \times 40$ microsecond minimum positive wave. Figure 4 assumes a 23-kv system requiring a 25-kv arrester. This arrester will have a gap breakdown potential of 85–89 kv, and the breakdown will take place in approximately one-half microsecond. The voltage across the arrester when discharging 5,000 amperes will be 100–110 kv. With manufacturing tolerances and with the circuit gradient given in table III, there exists a net selective margin between the basic insulation level and the arrester performance of 27 kv to 40 kv. In figure 5 the performances of 60-kv and 73-kv arresters are compared with the volt-time characteristics of 69-kv equipment, basic level, and with the AIEE test rod gap of 20.6 inches. It will be noted that the net selective margins between the basic level and the arrester amount to 35 kv to 40 kv for the full rated 73-kv arrester and 80 kv to 92 kv for the 60-kv arrester.

Figure 6 shows the relation between the recently agreed upon basic insula-

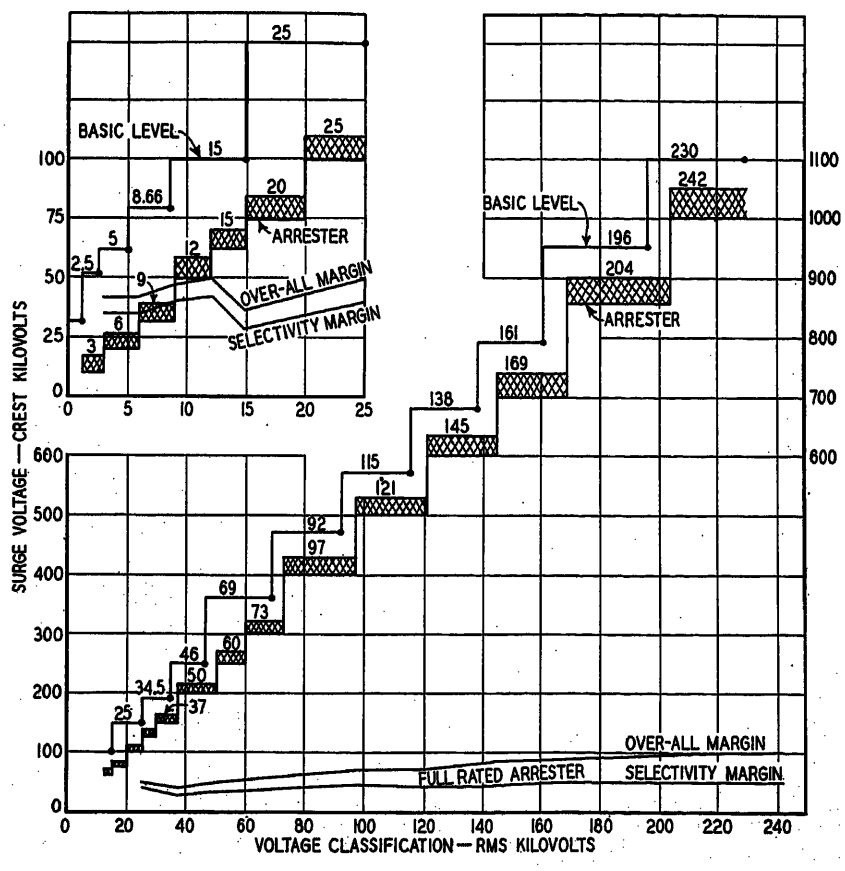



**Figure 6. Margin between arrester and basic insulation level**

Station-type arrester; current = 5,000 amperes

tion levels[5] and arrester performance when discharging 5,000 amperes surge current. The margin between the arrester performance and the long time insulation level of equipment will generally be greater than is indicated by this analysis because the surge currents will not be maintained at high values for long periods of time. Incoming surges which produce these heavy currents will generally have caused flashovers out on the line and will thus be chopped. The margin at short time intervals will also be somewhat greater than indicated because the insulation strength of apparatus is inherently higher than the basic level at short time intervals. These margins between the arrester performances and the basic levels generally range from 30 kv to 100 kv in the various voltage classifications, as shown in table III. In certain cases, such as in the 15-kv classification, the margins are relatively small. In cases where arresters do not have as favorable characteristics as have been considered herein, or where conditions are unusually severe, the margins will be still smaller or even nonexistent.

**Table III. Analysis of Arrester Protection**

| Basic Insulation | | Short Time | | | | Long Time | |
|---|---|---|---|---|---|---|---|
| Voltage Class (Kv) | Level (Crest Kv) | Arrester Rating (RMS Kv) | Breakdown Incl. Toler. (Crest Kv) | Circuit Gradient at 1 Kv/Ft | Selectivity Margin† (Kv) | IZ Drop Incl. Toler. (Crest Kv) | Selectivity Margin† (Kv) |
| **Line Type—Close Coupled Installation** | | | | | | | |
| 2.5 | 53 | 3 | 21 | 4 | 28 | 20 | 33 |
| 5.0 | 63 | 6 | 44 | 4 | 15 | 34 | 29 |
| 8.66 | 80 | 9 | 61 | 5 | 14 | 49 | 31 |
| | | 12 | 73 | 6 | 21* | 63 | 37* |
| 15 | 100 | 15 | 83 | 6 | 11 | 74 | 26 |
| | | 20 | 88 | 7 | 55* | 87 | 63* |
| 25 | 150 | 25 | 110 | 8 | 32 | 107 | 43 |
| | | 30 | 127 | 9 | 54* | 126 | 64* |
| 34.5 | 190 | 37 | 154 | 9 | 27 | 157 | 33 |
| 46 | 250 | 50 | 198 | 11 | 41 | 210 | 40 |
| | | 60 | 237 | 13 | 110* | 252 | 108* |
| 69 | 360 | 73 | 297 | 15 | 48 | 304 | 56 |
| **Line Type—Long Coupled Installation** | | | | | | | |
| 2.5 | 53 | 3 | 21 | 15 | 17 | 20 | 33 |
| 5.0 | 63 | 6 | 44 | 15 | 4 | 34 | 29 |
| 8.66 | 80 | 9 | 61 | 17 | 2 | 49 | 31 |
| | | 12 | 73 | 18 | 9* | 63 | 37* |
| 15 | 100 | 15 | 83 | 21 | —3 | 74 | 26 |
| | | 20 | 88 | 23 | 39* | 87 | 63* |
| 25 | 150 | 25 | 110 | 26 | 14 | 107 | 43 |
| | | 30 | 127 | 28 | 35* | 126 | 64* |
| 34.5 | 190 | 37 | 154 | 32 | 4 | 157 | 33 |
| 46 | 250 | 50 | 198 | 38 | 14 | 210 | 40 |
| **Station Type—Long Coupled Installation** | | | | | | | |
| 2.5 | 53 | 3 | 15 | 20 | 18 | 17 | 36 |
| 5.0 | 63 | 6 | 25 | 20 | 18 | 27 | 36 |
| 8.66 | 80 | 9 | 38 | 24 | 18 | 39 | 41 |
| | | 12 | 43 | 26 | 31* | 58 | 42* |
| 15 | 100 | 15 | 54 | 29 | 17 | 71 | 29 |
| | | 20 | 74 | 31 | 45* | 84 | 66* |
| 25 | 150 | 25 | 89 | 34 | 27 | 110 | 40 |
| | | 30 | 105 | 37 | 48* | 138 | 52* |
| 34.5 | 190 | 37 | 131 | 42 | 17 | 163 | 27 |
| 46 | 250 | 50 | 179 | 49 | 22 | 215 | 35 |
| | | 60 | 215 | 55 | 80* | 268 | 92* |
| 69 | 360 | 73 | 263 | 62 | 35 | 320 | 40 |
| 92 | 470 | 97 | 347 | 78 | 45 | 425 | 45 |
| 115 | 570 | 121 | 430 | 90 | 50 | 530 | 40 |
| 138 | 680 | 145 | 515 | 100 | 65 | 635 | 45 |
| 161 | 790 | 169 | 600 | 115 | 75 | 740 | 50 |
| 196 | 950 | 204 | 714 | 130 | 106 | 900 | 50 |
| 230 | 1,100 | 242 | 860 | 150 | 90 | 1,050 | 50 |

† Basic level minus (arrester performance + tolerance, etc.)
* Margin obtained on grounded neutral system where arrester voltage rating is below basic insulation level classification voltage.

## Conclusions

Insulation co-ordination requires a study of the entire surge protective scheme and, among others, the following items should be considered.

(*a*) Lightning arresters of suitable characteristics connected metallicly and as closely as possible to the equipment to be protected.

(*b*) Protective gaps having suitable flashover voltage characteristics and located on the line side of oil circuit breakers connected to overhead lines. Gaps should not be mounted directly on transformer or breaker bushings.

(*c*) Ground wires properly installed on overhead lines and extending an adequate distance out from the station.

This study of the co-ordination of insulation indicated that insulation levels for various operating voltages could be assigned, depending upon the class of service, the performance of the surge protective equipment utilized, and the economics of the situation. This has been substantiated by years of operating experience with apparatus installed in stations wherein the insulation was designed in accordance with these principles.

Furthermore, it may be concluded that:

(*a*) Full rated lightning arresters which have suitable performance characteristics and which are properly located will provide protection for the basic insulation levels[5] listed in table III (except the 15-kv level) down to extremely short time intervals, except for some direct strokes or unusually severe conditions.

(*b*) Lightning arresters of less than full voltage rating can be utilized on systems having the neutral effectively grounded and will give a greater margin of protection than will full rated arresters. In such installations, apparatus having impulse insulation strength levels one step below the basic level will be protected if the arresters have suitable characteristics.

(*c*) The impulse insulation strengths of electrical apparatus in the various voltage classifications should be equal to or greater than the corresponding basic insulation levels.

(*d*) The alternating voltage dielectric tests for particular conditions should be in conformity with the operating requirements and the insulation level selected. Under particularly favorable operating conditions, it seems reasonable that the alternating voltage dielectric tests may be reduced below present levels.

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# Surge Protection of Distribution Systems

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ASSOCIATE AIEE

## Synopsis

A quantitative investigation of the surge protective requirements of distribution systems and the power frequency voltage requirements of protectors for these systems, has been made which leads to the conclusions that:

1. The surge current discharge capacity of protectors should be 100,000 amperes to prevent damage from lightning. In general, 50,000 amperes capacity will give satisfactory results.

2. The surge voltage breakdown characteristics should be similar in shape and lower in value than the transformer insulation.

3. Field experience, as well as laboratory tests, have proved that a high degree of protection is obtained with a ratio of protective device initial discharge voltage to normal frequency voltage of 9 to 1 in voltage classes up to 13.8 kv, compared to the present conventional arrester rates up to 3.5 to 1.

4. Testing of protective devices under conditions more nearly representative of their service requirements should be considered.

## I. Function and Operation of Surge Protective Apparatus

THE MENACE of lightning to electrical power lines and apparatus is the high surge voltage produced on them which breaks down insulation and renders the line unfit for service. Following such breakdowns, current will flow from the line to ground in order to discharge the energy induced in the line by the lightning stroke. This current may reach extremely high values, and since an arc is usually associated with its conduction to ground, burning and physical destruction may be severe. Finally, large magnetic forces are caused which may damage lines and associated apparatus.

The highly concentrated energy discharge associated with the lightning stroke may be transmitted to the power line in either of 2 ways. First, the lightning discharge may terminate directly on a line conductor, in which case the entire current of the lightning stroke must pass through the line and associated apparatus to ground. This is called a direct stroke. Second, if lightning strikes in the vicinity of a power line, the electrostatic field is raised to such a high value that a considerable overvoltage is induced in it.[1,8] Such surges are called induced surges or indirect strokes. As a result of either direct or indirect strokes, the surge on the line will travel along it in both directions with very high velocity. The wave shape of the surge will change, however, and the traveling wave will be attenuated, so that in the course of even a short distance, the overvoltage will be considerably smaller and the length of the wave considerably greater than at the point where the surge originated.

Protective apparatus connected to power lines for the purposes of minimizing lightning damage must provide a short and direct path to ground in the event of a surge, so that the induced voltage on the line will be held to a value lower than its insulation level. The simplest means of protecting the line and connected apparatus is to suddenly ground it in the event of a lightning discharge. A spark gap is the simplest form of device which can be used for this purpose. The gap will be broken down by the overvoltage introduced on the line and will very quickly pass sufficient current so that the voltage on the insulation will be limited to a small value.

This simple expedient is not ideal, however, since the voltage at which the gap will be broken down increases with increasing rates of voltage rise, and consequently the protection provided is not uniformly good. The volt-time characteristics of such a device are shown in figure 2, curve *D*. Furthermore, the breakdown voltage of a simple gap is erratic and not subject to close control.

A simple gap also has the very great disadvantage that after the lightning phenomenon is over, the line is left grounded. This means that short-circuit current will flow in most cases, and circuit breakers must be opened in order to clear the gap. Consequently, there is a line outage. It becomes then a required characteristic of the lightning protective device that it automatically opens the established circuit between line and ground after complete discharge of the lightning stroke energy.

To accomplish this result it is essential that the simple gap be fundamentally modified. There are 2 known ways of making lightning protectors self-clearing. One principle is to connect a valve element in series with a gap from line to ground. This valve element is so constructed that the impedance drop across it is substantially constant and somewhat greater than the crest of the normal line to ground power voltage. The lightning surge voltage will then be limited to this impedance drop and the "valve" together with its series gap will pass current sufficiently freely to so limit the voltage. After the surge energy of the lightning stroke is discharged only a small current will pass through the valve due to the high impedance which is reached as the surge current decreases. Since it has been impossible to construct a theoretically perfect valve element, the series gap has been introduced to serve the dual purpose of "interrupting" the small residual current which remains after the surge discharge and of isolating the valve from power voltage under normal conditions.

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1. For all numbered references see list at end of paper.

The second principle is to enclose the gap in walls of fiber which evolve gas under the action of an arc so that high interrupting capacity is obtained. In this device under some conditions a larger power follow current may flow just after the surge discharge, but it is interrupted at the first current zero. A series resistor is used to limit the magnitude of this power current.

Qualitatively, the common requirements of a satisfactory lightning protective device are:

1. The device must be capable of passing without damage any lightning current to which it is subjected.

2. Its voltage breakdown characteristics should be as nearly linear with time as possible, and under all conditions lower than the apparatus which it is desired to protect.

3. Its impedance drop when passing such currents should be well below the insulation breakdown level of the apparatus to be protected.

4. After passing surge currents, the device must be capable of cutting off any flow of power current even with full power frequency voltage across it.

5. In order to prevent undue operation, the power frequency voltage required to "breakdown" the protective device should be substantially above the normally impressed voltage.

These requirements will be expressed quantitatively in the following sections.

## II. Surge Current Requirements of Protective Devices

For a number of years, engineers have been collecting quantitative data on the nature of lightning strokes—their magnitude, duration, polarity, probability of occurrence, etc., Measurements on transmission lines, distribution lines, and general field measurements have yielded valuable information on this subject. Direct and indirect measurements have been made. The latter have as their basis some physical effects such as mechanical forces, fusion effects, magnetic effects, etc., which are related to or calibrated by laboratory measurements. Indirect measurements have yielded much data on the magnitude and polarity of surge currents. More direct measurements are required to ascertain the shape and duration of surge currents and the nature of repetitive strokes.

The data available indicate the following:[1]

1. The most severe strokes from the standpoint of rate of voltage rise and magnitude of surge current are uni-directional single strokes negative in polarity.

2. Approximately 95 per cent of lightning strokes measured on transmission lines are negative in polarity.

3. Approximately 20 per cent of lightning strokes measured are repetitive.

4. The number of individual discharges in a repetitive stroke ranges from 2 to 10, or more, with the average number 3 to 4.

5. The total time duration of repetitive strokes is from a few hundred microseconds to one or more seconds with the impulses spaced about 0.03 seconds or more.

6. The rate of voltage rise of direct strokes is probably 1,000 to 3,000 kv per microsecond.

7. Measurements indicate a probable maximum surge current of about 200,000 amperes in rare cases.

8. The duration of individual surges varies up to 50 to 100 microseconds maximum with the average probably not over 25 microseconds.

Some of the data available are summarized in figure 1 for comparison. These data represent different methods of measurement. Curve *A* is determined from the fusion effect of lightning currents on metal electrodes of deion gaps and represents data on 4,000 transformer years.[2] From this curve, it appears that from 1/2 to 1 per cent of transformers in suburban and rural areas are subjected to surge currents of 10,000 amperes or higher, and approximately 1/4 per cent are subjected to surge currents of 50,000 amperes or higher.

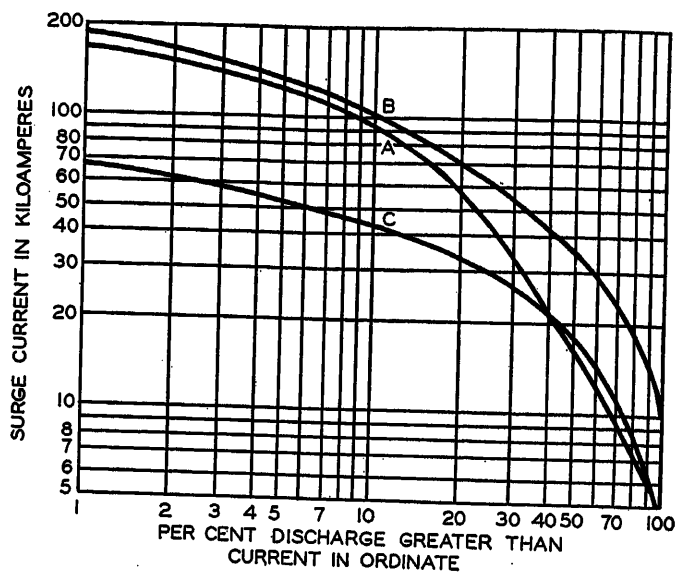



**Figure 1. Magnitude of lightning currents recorded by different methods of measurement**

*A*—Lightning currents at suburban or rural distribution transformers as indicated by fusion effects. 4,000 transformer years[2]

*B*—Lightning currents computed in tower legs on surge-crest ammeter. 911 tower years[3]

*C*—Lightning currents in towers above 5,000 amperes—surge-crest ammeter. 911 tower years[3]

Curve *B* of the same figure, shows the surge current in transmission towers above 5,000 amperes. These measurements represent 911 station years and 235 records in excess of 5,000 amperes were obtained. They indicate 19 per cent per year in excess of 10,000 amperes and 1 1/2 per cent per year in excess of 50,000 amperes.

Curve *C* is the computed currents in tower legs.[3] They are based on 911 tower years and 113 measurements, all of which are in excess of 10,000 amperes or a probability of 12 1/2 per cent per year at the particular location. The probability of currents of 50,000 amperes and higher as indicated by this curve, is 3.7 per cent.

Measurements by another method were made by H. W. Collins.[4] Out of approximately 500 measurements, in excess of one per cent were above 10,000 amperes with the maximum measured 20,000 amperes.

Additional valuable data on distribution lines has been contributed by McEachron and Halperin[5] on the probability of surge currents in shielded urban areas and by McEachron and McMorris[6] on more exposed lines. These data indicate that the probability of surge currents in excess of 10,000 to 20,000 amperes in shielded urban areas is very remote indeed. In rural areas, however, 1 per cent of the surges were found to exceed 15,000 amperes.

A summary of the data indicates that at least 1 per cent of the surge discharges will exceed 10,000 amperes and an appreciable fraction of 1 per cent will reach 50,000 amperes. An efficient and satisfactory protective device should be capable of handling surge currents of this order of magnitude.[7]

In analyzing data of this nature, it is necessary to take into account the natural difficulties of measurements. Due to the numerous points of low insulation level of distribution lines, diversion of current through multiple paths takes place easily, so that measurement at any one point may not be indicative of the maximum currents to be expected. From the physical concept of the problem, it would be expected that the maximum currents would be of the same order as those obtained on high voltage transmission lines, particularly in exposed circuits.

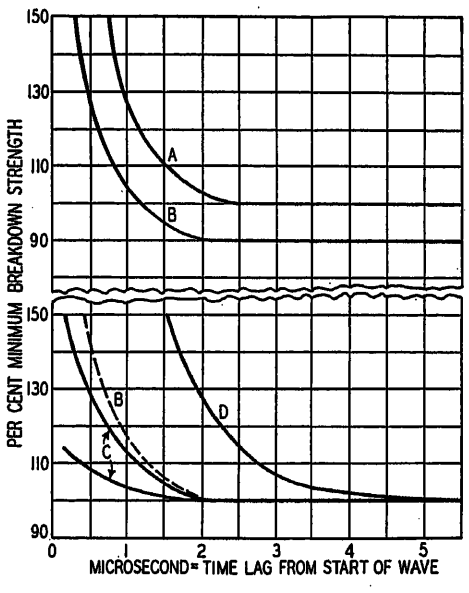



**Figure 2. Comparison of impulse characteristics of distribution transformer insulation and protective devices**

*A*—Breakdown characteristics of distribution transformer insulation

*B*—Probable voltage and time curve at which deterioration begins

*C*—Flashover characteristics of deion gaps and arrester gaps compared with *A* and *B*

*D*—Approximate shape of bushing and rod-gap flashover curves (13.8 kv class) compared with *A* and *B*

The probability of surge current of a given magnitude occurring at any particular location on a distribution system decreases rapidly with increasing current. Some potential exists by induction at practically all locations every time there is a lightning discharge in the vicinity. The nearer the discharge to the line, the higher the potential on the line will be. Due to the reduced insulation level at transformer locations and other points along the line, induced currents exceeding 2,000 amperes would not be expected. With the advancement in the art of surge protection, transformer insulation and protective devices, currents of this amplitude are of no serious consequence. The serious problem of protecting distribution systems, as well as high-voltage transmission systems, is to deal with direct and near direct strokes. In distribution systems, this problem is complicated by the fact that most distribution lines are carried on wooden poles having a high insulation value to earth. Also, the resistance of the earth at the poles may be quite high. This combination of factors makes it possible for surge currents of high magnitude to travel long distances along distribution lines and be diverted to earth through the low resistance path of the transformer secondary services. This means that lightning does not have to strike very near transformer locations for them to be subjected to high surge current. With the rapid extension of distribution systems into exposed rural areas, adequate surge protection afforded by protective devices capable of handling severe lightning stroke currents is paramount.

The time duration of surge discharges through lightning protectors has not been as completely measured as the current magnitudes. Available data indicate, however, that a lightning stroke of 50,000 amperes will generally have a time duration of 25 microseconds at least. Consequently, time values of this order of magnitude should be considered in judging the surge current handling ability of protective devices.

The fact that many lightning strokes are repetitive argues that if the surge current capacity of a lightning protector is to be defined in terms of a single stroke, some allowance must be made for the cumulative dissipation of energy associated with multiple strokes. Consequently, there is additional reason for placing the minimum acceptable surge current capacity at a high value.

## III. Voltage Protective Requirements

Adequate protection of distribution transformers and other equipment on distribution lines necessitates that the protective device limit the voltage that can exist on the insulation of the equipment to a value that will not damage any part of it. In considering the voltages existing on a distribution system, one has to take into account the high density of transformer locations and other points of reduced insulation. It is impossible, therefore, for voltages of very high magnitudes to be propagated on distribution lines as traveling waves. In general, impulses of this character are harmlessly drained off to ground by protective devices even under unfavorable grounding conditions. Impulses of a more dangerous or damaging character appear as a rapidly rising voltage suddenly reduced by a flashover of the line or a discharging of the protective device, followed by a building up of current through the circuit so formed to earth. This current produces a voltage drop by virtue of the impedance

of the protective device itself and of the circuit in which it is connected. It is imperative that the impedance of this circuit be sufficiently low so that the voltage impressed on the apparatus under the most severe conditions of surge discharge will not damage the insulation of the apparatus. Both the impedance of the protective device and the surge impedance of leads and connections must be small and, consequently, it is necessary that the connections be made as short as possible. To illustrate this fact, it is possible to build up voltages in excess of 10,000 volts per linear foot in straight conductors in the laboratory. All beneficial effects of the protective device can be nullified by long connections.

Distribution transformers are the major apparatus connected to distribution systems. The quality and characteristics of the insulation is an important factor in the successful operation of the distribution system. The normal frequency voltage strength must be sufficiently high to prevent damage from normal overvoltages, arcing grounds, etc., and to prevent corona and radio interference. This is insured by acceptance tests specified by the AIEE. Knowledge of the insulation strength of transformers to impulse voltages is necessary to intelligently co-ordinate and successfully apply protective devices.

A careful study of the impulse characteristics of distribution transformer insulation has been made. Due to the many factors influencing the ultimate impulse strength of transformer insulation, quantitative data can best be analyzed on the basis of average results or guaranteed values.

There exists a fairly definite ratio of the impulse strength of well balanced transformer insulation to its normal frequency strength. This ratio has been expressed numerically as 2.2, based on the 60-cycle crest value of the insulation breakdown strength. Applying this factor to the acceptance test voltages gives an indication of the minimum impulse strength built into transformers by the manufacturer. These values for low voltage distribution transformers are given in table I. In this class of apparatus the manufacturer maintains a much higher margin of safety to minimize mechanical defects and to insure reliable service than in higher voltage apparatus. While this margin cannot be definitely utilized, it nevertheless aids in preventing damage from lightning.

The volt-time characteristics of the insulation and protective devices is shown in figure 2. Curve *A* shows the characteristics of transformer insulation for a $1^1/_2 \times 40$ microsecond wave. The minimum or full-wave impulse strength is represented as 100 per cent and as a function of time in microseconds from the start of the voltage wave. The shape of this curve was determined by the average of a large number of tests to failure of actual distribution transformers.

Curve *B* of figure 2 shows the probable limits of voltage and time below which deterioration of the insulation is not expected to occur. The shape and values of this curve are established by applying repeated impulses of a given voltage and time duration to a transformer and noting whether or not deterioration begins. In applying this curve to a particular transformer, it is necessary to take into account the natural variation or spread in impulse strength of transformers of the same voltage class and design. It is applicable to the figures in table I, directly without encroaching upon the manufacturer's margin of safety.

On the same figure, curve *C*, showing the volt-time characteristics of deion gaps and lightning arresters, is given. Note that these curves are lower and flatter than curve *B*. Also, the approximate shape of the voltage-time flashover of bushings and standard rod gaps for 6,900-13,800 volt class transformers is shown as curve *D*. While these 2 curves are not exactly of the same shape,

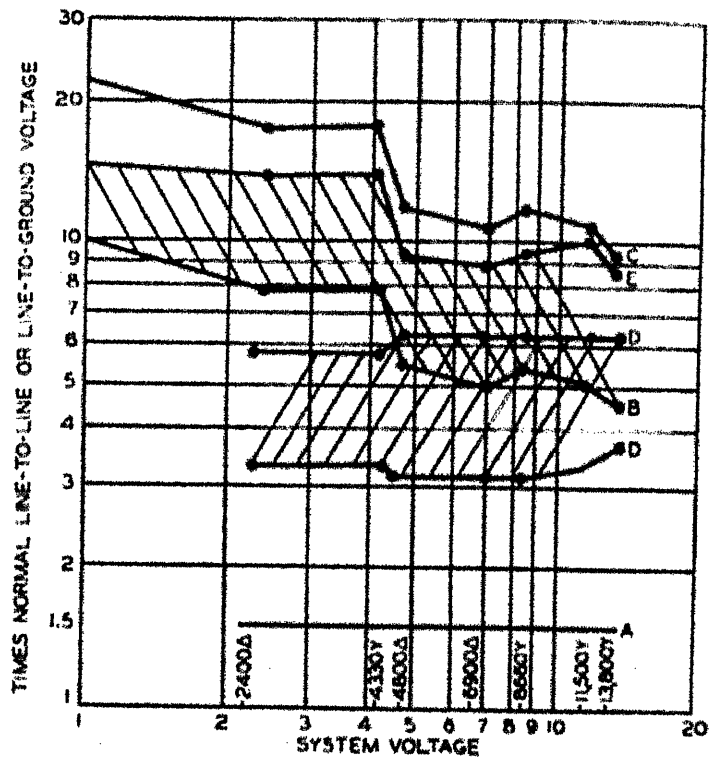



**Figure 3. Comparison between protective devices and transformer test levels**

*A* Minimum 60-cycle voltage requirements of protectors
*B* One minute dielectric acceptance test
*C* Minimum impulse strength based on *B*
*D* Valve type lightning arrester breakdown voltage level
*E* Deion gap arrester breakdown voltage level

they have the same general characteristics. Note that the bushing and rod gap curves are higher than the curve of probable insulation deterioration, as well as the insulation breakdown strength. For lower voltage classes, both the rod gap and bushing flashover characteristics are flatter due to their more uniform dielectric fields. It is necessary, however, to resort to considerably shorter gaps than the recommended co-ordinating gaps before the flashover curves are similar in shape to the insulation breakdown curve.

These curves illustrate the desirability of a surge

protective device having voltage discharge characteristics similar in shape to the insulation characteristics of the transformer, and also the fact that standard bushings and rod gaps do not have this.

The history of past development shows that protective-device engineers have constantly endeavored to design and produce apparatus which would be more reliable and which would have a lower ratio between discharge voltage and normal frequency line voltage. These 2 requirements have not been entirely compatible and have been accentuated by code requirements. With the advancement in the knowledge of the characteristics of natural lightning and with it the theory of surge protection, the codes have been modified to remove these restrictions. Transformer engineers have kept pace by obtaining knowledge of transformer insulation characteristics and limitations. The protective-device engineer should have a free hand to design apparatus suitable for the service required of it and unhampered by past traditions. This means simply proper co-ordination of transformer insulation levels and protective-device discharge voltage. As indicated by table I, it is satisfactory to design distribution surge protective equipment for much higher discharge voltages than would have been considered practical several years ago.

## IV. Normal Frequency Requirements of Lightning Protectors

The desire to reduce the surge level of lightning protectors to a low value results in designing these devices so that their normal voltage cutoff is reasonably close to the applied power voltage. If this procedure is carried too far, the protector itself is endangered and it becomes a hazard to the power system. Consequently, at times there have been failures of these devices which were not associated with the discharge of lightning energy. It is, therefore, necessary to examine the power voltage conditions of the circuit to which the lightning protectors are to be applied, in order properly to design and use this type of equipment.

Generally, protectors are applied to 3-phase power systems. These systems may be operated with the neutral solidly grounded or free from ground. In either case, the normal line to ground voltage will be the line-to-line voltage divided by 1.73. In the event of a fault from one line to ground, however, the performance of the 2 classes of systems is quite different. The solidly grounded neutral system will, under theoretically ideal conditions, prevent the line-to-ground voltage during fault conditions, from rising at all. Actually this voltage will increase to a value of approximately 120 per cent normal line to ground voltage in average cases. If the neutral is not grounded, the full line-to-line voltage will appear from line to ground in the event of a ground fault on one conductor. Consequently, it is essential that the protective device be capable of interrupting the flow of power current after surge discharge with a voltage applied which will be at least 120 per cent of the normal line to ground voltage if the neutral is grounded, and which will be at least 1.73 times line to ground voltage if the neutral is ungrounded.

Grounded neutral systems are subject to considerable variation depending on the magnitude of the ground impedance. While the average overvoltage from line to ground in the event of a fault may be only 120 per cent, lightning protectors must operate satisfactorily on systems of high ground impedance. Furthermore, protectors may be located at a considerable distance from the point of actual grounding and a line to ground fault near the protector location effectively increases the ground impedance so far as voltage across the protector is concerned. It is very difficult to determine the maximum per cent of line-to-line voltage which the protector should withstand, but experience indicates that the value should be 80 per cent for solidly grounded neutral systems. In other words, the line-to-ground voltage will rarely exceed 140 per cent of its normal value.

Systems in the distribution voltage class are generally supplied with power through step-down transformers from higher voltage systems. In case lightning strikes the high-voltage system, surges of considerable magnitude may cause a flashover to ground and power current may flow through ground for several cycles. If the neutral points of the 2 systems are connected together to a common ground of comparatively high resistance, this flow of power current in the high-voltage system may introduce considerable overvoltage of power frequency in the low-voltage system. Direct flashover from the high to the low-voltage system during the surge is also a possible cause of high dynamic voltages on the low-voltage system. Obviously, the greater the difference between the normal voltage of 2 connected systems, the greater is the possibility of excessive power-frequency voltages introduced into the low-voltage network as a result of fault conditions. Consequently, it is good practice to build lightning protective devices at the lower voltages with a greater factor of safety or difference between maximum permissible line-to-ground voltage and normal line-to-ground voltage, than is the case with lightning protectors of the high-voltage class.

Generally low-voltage lightning protectors are applied with less care than high-voltage devices. Often it is not possible to employ a theoretically ideal rating because low manufacturing costs preclude the availability of a wide range of voltage classes. These facts again introduce the requirement that the voltage tolerance of distribution lightning protectors should be comparatively great.

Another factor which at times influences the required voltage cutoff characteristics of lightning protectors, is the presence of harmonics in the supply voltage, particularly during fault conditions. Normally the applied voltage is sufficiently sinusoidal so that the crest value bears the normal relation to the meter readings. During faults, however, saturation of transformer iron may introduce harmonic voltages. The nature of the main power source must also be considered, since waterwheel generators without damper windings are subject to producing high harmonic overvoltages during line-to-line short circuits. It is furthermore possible that in certain

cases various lines and connected apparatus will be resonant to these harmonics, and cases have been experienced where very high harmonic overvoltages were present during fault conditions from line to ground.

Surges resulting from switch operations on the lines may at times prove hazardous to lightning protector devices. Switching surges differ from lightning surges principally in 2 respects. First, the magnitude of overvoltage is much lower in the case of switching surges and major insulation is not endangered. Second, the duration of the switching surge may be much longer than the lightning surge, however, and the energy which must be dissipated in a protective device may be greater for the switching surge than for the lightning surge. Consequently, the lightning protector must be built sturdily enough so that it will handle any currents passing through it as the result of normal switching operations.

As lightning protectors are generally constructed, a certain minimum voltage must be impressed across them before they begin to pass appreciable current. In other words, these devices exhibit definite breakdown characteristics. Generally, the breakdown voltage of protectors is considerably higher than their cutoff voltage. This is fundamental in the design of these devices, because the isolating means is generally a gap of some form and it is impossible to design a gap so that it will interrupt current up to the voltage necessary to cause a breakdown. Furthermore, it is very desirable to set the breakdown voltage of the devices considerably above normally applied voltages, and in many cases higher than the normal switching surges. In this way unnecessary operations of the protective device are prevented.

In the distribution voltage class it has been general practice to have the breakdown voltage at least 1.5 times the maximum permissible voltage or cutoff value of the device. This figure is low for the best obtainable performance. The breakdown voltage at normal power frequency may easily be 2 to several times the cutoff voltage without impairing the surge protective characteristics, and if the designs are made in this way much greater safety of the protective device itself is obtained.

## V. Voltage Levels of Protective Devices

The 2 preceding sections define the upper limits of discharge voltage of protective devices, and the lower limits of power frequency cutoff and breakdown voltage. In figure 3 the minimum insulation impulse strength has been plotted (curve *C*) for the different distribution voltage classes. The basic data for this curve are taken from table I. Also the minimum acceptable power frequency breakdown voltage has been plotted in figure 3 (curve *A*). The difference between these 2 curves is a broad band into which the characteristics of the protective device must be fitted. Since the 60-cycle and surge discharge voltage of protective devices is different, or in other words since their impulse ratio is greater than unity, 2 curves must also be plotted for the protective device. These 2 curves again form a and which is much narrower than the band of required performance. The difference represents the total margin of safety of the protective device over service requirements. This total margin can be divided by design between margin over 60-cycle minimum requirements and margin under surge requirements. On account of the relatively great total margin, there is considerable choice in the design of the lightning protector.

**Table I. Comparison of Guaranteed Normal Frequency and Impulse Strength of Distribution Transformers Based on AIEE Standards and Recommendations**

| | | Expected Minimum Impulse Strength Based on | | | |
|---|---|---|---|---|---|
| | Dielectric | Dielectric | Test Gap | | Bushing |
| Voltage Class (RMS Kv) | Test (RMS Kv) | Test (Crest Kv)* | Inches | (Crest Kv)* | Flashover† (Crest) |
| 1.0 | 10 | 31 | 0.8 | 32 | 37 |
| 2.4– 4.3 | 19 | 59 | 2.2 | 59 | 68 |
| 4.8– 8.7 | 26 | 81 | 3.3 | 81 | 87 |
| 6.9–13.8 | 34 | 106 | 4.5 | 102 | 107 |

* Minimum flashover or full wave for 1½x40-microsecond positive waves.
† Maximum voltage applied in making impulse tests which flashes over bushing or equivalent gap. See recommendations of transformer subcommittee on impulse testing.

In figure 3 curves are also plotted showing the minimum 60-cycle and maximum surge characteristics of valve arresters (curve *D*). Arresters have been widely applied to protect insulation of varying and unknown surge strength, and consequently, their characteristics have been designed to be comparatively low. Deion protectors, on the other hand, have generally been designed as an integral part of distribution transformers of known insulation strength. Furthermore, the transformers are tested on 60 cycles with the deion protector connected, and it is consequently necessary to maintain the 60-cycle breakdown of the protector higher than the test voltage applied to the transformer (curve *B*). For these reasons, the deion protectors have surge characteristics considerably higher (curve *E*) than those of valve arresters. Field service records prove conclusively that both devices provide adequate protection to the transformers.

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# Application of Spill Gaps and Selection of Insulation Levels

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## Synopsis

This paper presents, from the viewpoint of the engineer who plans and operates electric power systems, the application logic or theory and the performance results with various forms of spill gaps, for the protection of circuits and equipment from lightning, and the selection of insulation levels co-ordinated with this type of protection.

The performance results are largely confined to transmission voltages, although the same general principles and logic apply over the entire transmission and distribution operating voltage range.

## Background

AS A BACKGROUND of scientific research, service observation, and engineering experimentation the industry has available the results to date of study in 4 fields, concerned with protection of circuits, equipment, and service against lightning:

1. Field research of natural lightning, also laboratory research, having to do with the nature and occurrence of lightning[1,2,3]

2. The volt-time characteristics of insulators and insulating materials under impulse and normal frequency voltages[4,5]

3. The performance characteristics of gaps and lightning arresters in commercial use[4,6]

4. Analyses of observed operating performance of electric transmission and distribution systems with particular reference to protection from lightning[2,7]

In none of the above 4 fields of investigation and experience can it yet be said that the results or knowledge are so complete that unqualified conclusions can be drawn with respect to each of the pertinent factors in the problem. Nevertheless, enough has been learned that it has been possible to formulate tentative insulation and protection policies and to secure from actual experience a reasonably conclusive check as to their soundness.

## General Aspects of Lightning Protection

As in most transmission and distribution problems the best solution to the protection problem is judged in terms of both performance and cost.

Protection from lightning has 2 primary aspects:

1. Protection of equipment against damage
2. Protection of service against interruptions

Each of these is capable of separate evaluation, and obviously is dependent on such factors as density of load, type of load, and degree of exposure to lightning.

The methods available for accomplishing protection may be broadly divided into the 2 groups of shielding and drainage.

### Shielding

Shielding of circuits and equipment is accomplished either by underground construction, or by the so-called "lightning proof" type of construction. To be effective, the shielding must be capable of withstanding all direct strokes of lightning, except possibly the most severe, without breakover or conduction of the lightning current to the power conductors.

Shielding within the limitations of the specific installation, protects service and equipment. Unfortunately it is economically feasible only in the case of the higher transmission voltages, and on circuits of major importance.

In the lower transmission and distribution range of voltages, overhead circuits are not generally shielded. There are also many situations with the higher transmission voltages, where lightning storms are infrequent or where lines serve large areas having small load densities, where the added investment for shielding disqualifies it from the standpoint of economy.

### Drainage

Drainage is accomplished by providing for relief and limitation of lightning voltages through flashover at preferred locations. This includes the use of:

1. Plain gaps with which no attempt is made to interrupt or seal off power follow current

2. Fused gaps in which the series fuse interrupts the power follow current. These have limitations in application with respect to interrupting ability

3. Lightning arresters which do not permit power follow current. Their effectiveness is limited to their surge current discharge capacities

4. Arc-interrupting gaps, in which the series tube interrupts the power follow current. These tubes have limitations with respect to minimum and maximum interrupting ability, and their application as at present commercially available is confined largely to line insulation protection

## Application of Spill Gaps

The logic underlying the application of spill gaps of any type is:

1. A spill gap provides a definite voltage discharge level with very high capacity for discharging lightning stroke current. The setting may be in terms of inches of air or in terms of voltage and time. The cost of the installation is the very minimum

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The authors acknowledge the use of much information available both from previously published papers and from reports covering the performance of transmission and distribution systems of operating companies with which the authors are associated. These operating data have made possible the most valuable part of this paper.

1. For all numbered references see list at end of paper.

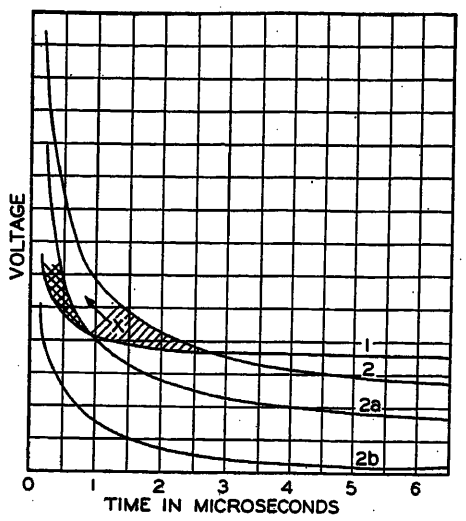



**Figure 1**

2. Except for solid or oil insulated equipment, practically all line and substation insulation can be expressed approximately in terms of equivalent inches of air

3. Co-ordinated with line insulators, bushings, switch and bus insulators, spill gaps provide dependable relief from dangerous surge voltages, at preferred locations for flashover, establishing definite levels in terms of inches of air or in terms of voltage and time

The usual application of the different types of spill gaps is:

1. Spill gaps of the extinguishing types, that is, arc-interrupting gaps or fused gaps, installed along a transmission or distribution circuit, are used for 2 purposes:

*a.* To provide a definite margin under the line insulation so that flashovers along the line will occur at the gaps, with interruption of power-follow current, to prevent line outages

*b.* To limit the voltage impressed on the circuit and transmitted to installed equipment

2. Plain spill gaps are installed at substations:

*a.* At the line entrances, with margins under all other insulation levels within the substation

*b.* Within the substation, on the bus or at equipment, with discharge levels somewhat higher than those established at the line entrances, as final or back-up protection against bus flashover or equipment failure

3. Fused spill gaps are installed at substations either at line entrances or on the bus or at equipment in a manner similar to and supplementing plain spill gaps to protect against service interruptions. Their use depends upon the expected frequency of lightning flashovers and the type and importance of the load served.

## Selection of Insulation Levels

### Basic Insulation Levels

During early discussions on insulation co-ordination it was common practice to think of insulation levels in terms of the amount of porcelain insulation or in inches of air (rod gap), in which case a level would not be a level in terms of voltage but would vary with the volt-time breakdown curve of the rod gap or insulators.

More recently, the accepted measure of a basic insulation level is in terms of volts, and is therefore more truly a level, being a constant value of voltage, regardless of the time to breakdown, except that the time is limited to a range in microseconds usually associated with impulse voltages.

Nevertheless, insulation as used, does not have a fixed voltage breakdown strength, and the volt-time breakdown curve of each unit of insulation or piece of apparatus is its own insulation level.

A "basic" insulation level serves no other purpose than as one of a series of standardized voltage bench-marks to which the insulation levels of line and station insulators, bushings, transformers, protective devices, and other equipment may be referred in the process of selecting a proper or desired level of insulation for a particular installation and working out co-ordination.

The minimum practicable basic insulation level that may be established for a given installation must be high enough so that insulation flashovers or failures will not occur from normal frequency overvoltages or from surge voltages originating within the system, such as switching surges.

The adoption of these minimum insulation levels on a system would result in minimum initial investment in line and station equipment insulation. This practice may not be practicable in specific situations, as for example a basic insulation level above the minimum often will be advisable in order to provide (1) equipment levels that will directly withstand or are capable of being protected against incoming traveling lightning voltages, or (2) equipment levels that can be adequately protected against severe nearby direct strokes of lightning.

### Insulation Levels for Equipment

The selection of the insulation levels for the bus and equipment, such as transformers, co-ordinated with a given basic insulation level, must take into account:

1. The relative volt-time characteristics of the other equipment including the protective device

2. The economic margin of protection, taking into consideration the expected severity and frequency of occurrence of lightning surge voltages

3. Margins to provide for variations in insulation strength due to manufacturing tolerances and from deterioration

Insulation research has demonstrated quite definitely that the breakdown of insulating materials under impulse voltages is a function of voltage and time. For fibrous insulations of most equipment the volt-time breakdown curve has the general shape of curve 1, figure 1. The curve is relatively flat except at the very short time intervals.

The impulse flashover characteristics of gaps are found to have the general shape of curves 2, 2*a*, and 2*b*. As compared to the curve for solid insulation, the gap curves are not as flat, voltage values rising sooner as the short time region is approached.

Assuming gaps and insulation as illustrated, gap 2*b* would prevent flashovers of gap 2*a*, and gap 2*a* would protect gap 2. Gap 2 would protect the insulation represented by curve 1 only against impulse voltages rising to flashover of the gap in a time longer than that point on the time scale where the 2 curves cross. Impulse voltages rising to crest or to flashover of the gap in region *X* would damage the insulation represented by curve 1. A greater time range and margin of protection would be secured to the insulation by gap 2*a*, and over the entire time range il-

lustrated, with margin, by gap 2*b*. These are equivalent to providing protection against more severe lightning impulse voltages.

In spite of the large amount of work which has been done investigating actual strokes of lightning, insufficient knowledge and data are available concerning the voltage magnitudes and rate of rise at the point of stroke incidence and the relative probable frequency of occurrence of direct strokes of the greatest severity. For the present at least, reliance must be placed upon the record of operating experience to tell when a satisfactory degree of protection has been achieved.

## Operating Experience With Spill Gaps

For discussing gap settings generally, without necessarily always referring to the associated system operating voltage, figure 2 has been prepared as a convenient reference chart, wherein the commonly accepted 60-cycle flashover values of rod gaps are plotted in terms of the number of times normal phase to neutral voltage, for the range of rated circuit voltages.

### Minimum Permissible Settings

Perhaps the most outstanding result secured from the observation of operating experience with gaps over the past several years is that, even in areas frequented by severe lightning storms, much lower spill-gap settings can be used than were originally considered possible.

For transmission voltages on grounded neutral systems, it generally has been found that gap settings corresponding to approximately 2 times normal (phase - to - neutral voltage) are the lowest possible. That is, gap settings of these magnitudes may be used without an undue number of flashovers, if any, due to switching surges. However, the more generally applied minimum gap settings in the transmission voltage range correspond to approximately 3 times normal voltage to neutral.

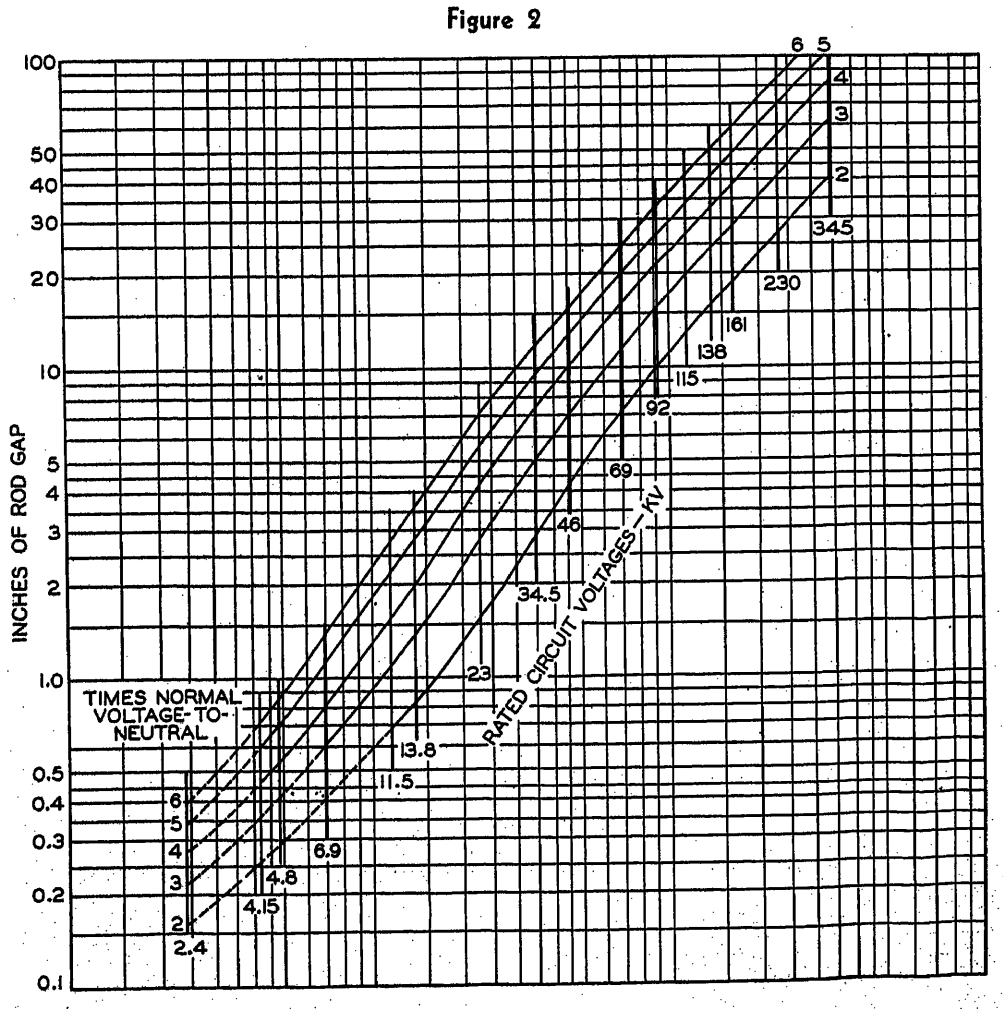
In the distribution voltage range, the minimum gap settings are relatively higher, as they are fixed, not so much by switching surges and overvoltages, as by mechanical and other considerations such as interference from birds, also higher settings are permissible due to the relatively greater prevailing insulation strengths of equipment.

Probably the extreme lower limit of permissible gap settings is typified by operating experience at a substation in Louisiana on the extensive 110-kv grounded-neutral system in the lower Mississippi Valley. This substation is at the end of a 110-mile section of single circuit H-frame line, having very high impulse insulation strength. Following a number of transformer failures, during which time the gap settings were reduced by steps from 31 inches to 18 inches, staged switching tests were made to determine the minimum permissible gap setting. In these tests the gap settings were reduced by steps to 10 inches. With the 10-inch setting during one setup on the system, these gaps flashed over twice during 15 switching operations, although on another system setup 65 switching operations did not cause flashover. The gap settings were increased to 11 inches and did not flash over during 45 switching operations under the same setup which caused flashover with the 10-inch setting.

These tests were made early in 1935 and the gaps have subsequently remained in actual service with the 11-inch setting during 2 lightning seasons. The gaps are of the repeater fused type, mounted directly at the transformer terminals. The setting of 11 inches is equivalent to approximately 1.7 times normal phase-to-neutral voltage.

At another substation on this same 110-kv system, where 11-inch repeater fused gaps were installed in 1936, further tests have definitely indicated that the switching surge caused by the opening of an oil circuit breaker on a

Figure 2



stub line can cause an 11-inch gap to flash over.

Early in 1936, at the first substation, 2 additional sets of repeating fused gaps were installed, with the 11-inch setting. Retaining the original set at the transformers, one new set was installed on the first structure of the incoming 110-kv line, and the other set on a line structure about 2 miles from the substation. During the year 1936, the total number of fused gap operations, on all 3 phases, at the 3 locations, were as follows:

| | Number of Operations of Repeater Fused Gaps |
|---|---|
| At the transformers | 28 |
| At the first line structure | 21 |
| At structure 2 miles away | 20 |

A definite correlation was not determined between fuse-gap operations at the 3 locations or between operations of individual fuse gaps and oil-circuit-breaker openings. There probably were a number of simultaneous operations of gaps. The evidence indicates that if any of the gap flashovers were occasioned by switching surges, they were successfully cleared by operation of the series fuses. During the year the line tripped out a total of 28 times due to lightning flashovers.

### Effect of Gap Settings on Number of Flashovers

Along shielded overhead circuits, the values of voltage induced on the circuit conductors through coupling effects, vary with the severity of the strokes of lightning to the line. The maximum voltage that can appear on the circuit at the point of stroke is limited to the line insulation level.

Along exposed circuits, there is probably less variation in the magnitude of the lightning voltages appearing on the circuits as it seems reasonable to assume that any direct stroke and most side flashes and branch streamers would cause line flashover, regardless of the amount of line insulation. The voltage therefore is determined by and limited to the line insulation flashover level.

In any case the impressed surge voltage at the point of stroke, travels toward the line terminals and appears at substations, after being subjected to the effects of attenuation and reflection, with magnitudes very seldom any greater and usually much less than at the origin.

Experience with both shielded and nonshielded lines in different parts of the country, all exposed to frequent and severe lightning, indicates that with gap settings at substations equivalent to or greater than 3.5 times normal phase-to-neutral voltage, there are relatively few gap operations compared with the number of line tripouts or line flashovers from lightning. There are an increasing number of gap flashovers, as lower and lower settings are used.

The following paragraphs cite typical experience with gap settings ranging from 3.5 down to 1.7 times normal, for transmission voltages. While only limited data are included, experience on these and other situations covers a period of 6 to 10 years.

As an example of experience with gap settings averaging 3.5 times normal for transmission voltages, and somewhat higher for distribution, the following number of stations were protected during 1935 and 1936 by spill gaps in central and eastern Texas. The performance record of these spill gaps during this period is summarized in table I.

| | Number of Substations Protected | |
|---|---|---|
| | 1935 | 1936 |
| 22 kv and above | 50 | 55 |
| 12.5 kv and below | 44 | 65 |
| On both high and low voltages | 20 | 25 |
| Total number of stations protected on either high or low voltage by spill gaps | 74 | 95 |

In Florida, on a 66-kv system, with line-terminal gaps set at 11 inches (approximately 3.0 times normal), and with line-insulation levels equivalent to 14 inches to 45 inches, of air, experience indicates that gap flashovers at the substations occur with about 4 per cent to 16 per cent of the lightning flashovers on the lines. The lower and higher percentage values are associated with lines of low and high insulation levels, respectively.

At a generating station bus in Arkansas, on the same Mississippi Valley 110-kv system previously mentioned 3 14-inch spill gaps per phase with series fuses (approximately 2.2 times normal) were installed in July 1934. In

**Table I. Spill-Gap Performance in Texas—1935–36**

| Operating Voltage (Kv) | Gap Settings | | Number of Individual Phase Gaps in Service | | Number of Individual Gaps Which Did Not Flash Over During the Year | |
|---|---|---|---|---|---|---|
| | Inches | Times Normal* | 1935 | 1936 | 1935 | 1936 |
| 132 | 20–36 | 2.5–4.5 | 69 | 69 | 64 | 68 |
| 66 | 12 | 3.1 | 249 | 249 | 245 | 246 |
| 60 | 10–12 | 2.8–3.2 | 153 | 153 | 148 | 149 |
| 33 | 6–8 | 3.5–4.4 | 12 | 15 | 12 | 15 |
| 22 | 5–6** | 4.6–5.2 | 54 | 69 | 53 | 68 |
| 12.5 | 1¾–3† | 4.0–5.8 | 282 | 402 | 275 | 395 |
| 7.2 | 1¾ | 7.0 | 9 | 15 | 9 | 15 |
| 4.16 | ⅛–3†† | | 27 | 27 | 27 | 26 |
| 2.4 | 1¾ | | 18 | 18 | 18 | 18 |
| | | | 873 | 1017 | 851 | 1000 |

* Gap 60-cycle flashover in terms of number of times the normal phase-to-neutral voltage
** In some cases with 1-inch or 2-inch auxiliary gaps in series with main gaps
† In most cases with 1-inch series gaps
†† In most cases with from ¼-inch to 1-inch series gaps

Table II. Two-Year Performance of Arc-Interrupting Gaps on 66-Kv Lines in Pennsylvania—1935–36

| Miles | Structures | Structures With Gaps | | Gap Operations | | Line Tripouts | Cases of Damage to Structures | | Cases of Damage to Gaps | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | Number | Per Cent | Structures | Gaps | | 1935 | 1936 | 1935 | 1936 |
| 36.4 | 355 | 91 | 25.6 | 95 | 158 | 11 | 1* | 4* | 0 | 7** |
| 13.8 | 160 | 23 | 14.4 | 54 | 100 | 3 | 2* | 5* | 4 | 19** |
| 17.8 | 175 | 175 | 100 | 149 | 203† | 0 | 0 | 0 | 0 | 0 |
| 13.4 | 130 | 130 | 100 | 175 | 306 | 0 | 0 | 0 | 0 | 0 |

* On unprotected structures
** Primarily loss of targets
† Line not put into service until after close of 1935 lightning season; 65 gap operations occurred on dead line
Note: Each of the four lines are single-circuit H-frame wood construction.

each of the years 1934 and 1935 there were 3 operations of the gaps, and in 1936 there were 4 occasions of gap flashover totaling 8 individual gap operations. All operations were associated with lightning and none caused service interruptions, except for one case in 1935 in which the fuse tube exploded.

At another substation in Arkansas similarly equipped in 1935 with 14-inch fused gaps on the bus, there were in 1936 3 occasions of gap flashover totaling 5 individual gap operations, without interruption to service.

At one of the 110-kv substations in Louisiana previously mentioned, the operating experience throughout the year 1935, with one 3-phase set of 11-inch repeater fused gaps (1.7 times normal) at the transformers, included a number of difficulties due to tube failures, also inadequate mechanical design of the fuse holder mechanism, which were not remedied until November 1935. In spite of, or including these difficulties, analysis of the record for the 1935 season shows at least 20 and perhaps 25 occasions of gaps operating, with a total of 37 blown fuses. During the same period the 110-mile connecting line having very high impulse insulation tripped out due to lightning 33 times. There were at least 8 occasions of gap operations totaling 10 blown fuses without line tripout, and there were at least 12 line tripouts without operation of these gaps.

Although at present this substation is connected to only one line, so that every line tripout causes a service interruption, the foregoing operating data indicate the possibility that had the gaps not been fused there would have been about a 30 per cent increase in the interruptions to service.

On extensive transmission and distribution systems in the Pacific Northwest, where lightning is not prevalent, a large number of plain spill gaps have been installed with settings approximating 2.5 to 3.5 times normal. There are practically no gap operations.

### Protection to Line Insulation

The experience with arc-interrupting gaps along transmission lines has shown that in most cases protection to line insulation and against service interruptions is secured. The first applications of this type of protection, made in Arkansas, continue to give fairly good performance. On the Pine Bluff-Dixie line (110-kv, H-frame, single circuit), approximately 46 miles in length, with arc-interrupting gaps at approximately $^1/_2$-mile intervals, the records show an average of 14.6 tripouts per 100 miles per year from lightning during the 4 years after the installation of these gaps, whereas during the 3 years prior there were approximately 38.0 tripouts per 100 miles per year from lightning. If the 2 periods can be considered otherwise comparable, there was a reduction of 60 per cent in the number of outages caused by lightning.

Another line in Arkansas, from Pine Bluff to Carpenter, (also 110-kv, H-frame, single circuit), 59 miles in length, was constructed with arc-interrupting gaps installed on every structure. This line operating in the same territory as the one mentioned above, shows an average number of outages caused by lightning over a 4 year period of 5.5 per 100 miles per year. Detailed descriptions of these installations were reported by Messrs. McEachron, Gross, and Melvin in 1933.[8]

On 4 sections of 66-kv transmission line in Pennsylvania during the 2 years 1935–1936 the results secured from the use of arc-interrupting gaps are set forth in table II. It will be noted in the case of the 2 lines partially equipped, that only partial protection is being obtained, and that all cases of damage occurred on structures which were not protected by gaps.

Plain gaps of various types for porcelain protection on transmission lines are effective, as is well known.

### Protection to Bus Insulators and Bushings

Analysis of the operating experience records shows that spill gaps properly set and connected, effectively protect bus insulators and bushings.

Out of the many thousands of installations, there have been only a few instances of failure to protect bushings, some of which probably were deteriorated internally.

For example, at one substation on a 132-kv system in Texas, 28-inch gaps (3.5 times normal) are installed on the first and second line structures adjacent to the substation. During 1936, the top half of one oil-circuit-breaker bushing was shattered by lightning, and another similar bushing flashed over. On the 66-kv system in this same territory, one oil-circuit-breaker bushing punctured below the flange, which should have been protected by a 12-inch spill gap (3.0 times normal).

In other locations there have been a few instances where insufficient physical separation existed between a gap and the porcelain it was supposed to protect, with resulting thermal damage to the porcelain.

### Protection to Transformers

With respect to the protection of transformer insulation by spill gaps, a few examples of experience data should be of interest.

On the 66-kv and 110-kv systems in the Carolinas, a rather general application was made during the period from 1929 to 1931 of fused gaps and plain gaps at the line terminals. These gap settings ranged from 12 to 15 inches on the 66-kv lines (3.0 to 3.8 times normal), and from 25 to 30 inches on the 110-kv lines (3.8 to 4.5 times normal). The average number of transformer units that failed from lightning during the 5 years up to and including 1928 was approximately 8 per year. For the 5-year period beginning with 1932 the average number of transformer units that have failed has been approximately 3 per year.

An alarming number of transformer failures occurred from lightning at scattered locations throughout the extensive Mississippi Valley 110-kv system during the years immediately following the major expansion and construction program, with as many as 10 failures in a single year. Where protective levels were previously in the range of from 24 inches to 31 inches they were in almost all cases reduced to 20 inches or less, and the record since of transformer failures from lightning is 1934, 4; 1935, none; and 1936, one.

At a 110-kv station in Arkansas, previously mentioned, there were 2 failures of transformers from lightning prior to 1934. This station is at the end of a 59-mile 110-kv line, equipped with arc interrupting gaps at each structure. In 1934, rod gaps set at 18 inches were installed directly shunting the high-voltage bushings of the 110-kv transformers. Within 3 months after installation there were 7 flashovers of these gaps and one more failure of a transformer. Following this experience there were installed on the switchyard bus, 9 14-inch fused gaps—3 per phase. This installation is located at the switchyard approximately 800 feet from the transformers. The lines connecting the transformers to the switchyard are equipped with overhead ground wires. A second transmission line extending from this switchyard has been in service during 1936. During the last 2 years there have been no further flashovers of the 18-inch gaps at the transformers or transformer failures and there were 14 operations of the 14-inch fused gaps on the bus.

Mention has already been made of a series of transformer failures occurring within several years at a 110-kv substation in Louisiana, with gap settings of from 31 inches to 18 inches. All failures occurred in the low-voltage windings from lightning voltages transmitted through the transformer. The low-voltage windings are connected to cable circuits and not exposed to lightning.

The first failure occurred in March 1931 with ring-ring gaps set at $27^1/_2$ inches adjacent to the substation, on the line structure. In June 1932 rod gaps set at $26^1/_2$ inches were installed on the substation structure and 31-inch rod gaps immediately adjacent to the transformers. Also 4-inch gaps were installed on the low-voltage (13.8-kv) bus. In April 1933 another transformer failed from lightning and on August 15, 1933 2 more transformers failed. The substation and transformer gaps were then changed to a 20-inch setting. At the same time overhead ground wires were installed over the substation and on the 110-kv line for a distance of about 3 miles out. Another failure occurred in April of 1934 and still another in August 1934. Thus there were a total of 6 failures in 4 years.

Fused gaps arranged with 3 sets of fuses for repeater closing were installed in November 1934 with the gap set at 14 inches. Between then and June 1935, 5 operations of these gaps occurred, each one successfully clearing the circuit without interruption to service or transformer failure. A series of switching tests (previously described) were then made and the gap setting arbitrarily reduced to the minimum practicable setting of 11 inches. At the same time the gap settings on the 13.8-kv bus were reduced from 4 inches to 2 inches and lightning arresters were installed on the 13.8-kv phase and tap leads. In the 2 year period since these last changes, there have been no failures of transformers.

## Conclusions

1. Spill gaps are effective as a means of establishing and co-ordinating insulation levels on lines and stations, and affording dependable protection to equipment and insulation, against failure from lightning.

2. The minimum permissible spill-gap settings, for transmission voltages, without adverse effects on service, are less than those previously considered possible.

*a.* The lower limit generally applicable is the equivalent of approximately 3.0 times the normal phase-to-neutral voltage, in terms of 60-cycle flashover

*b.* When extremely low protective levels are necessary or desirable, and preferably where fused gaps may be applied, the minimum permissible limit may be approximately 2.0 times normal

*c.* The foregoing spill-gap settings are associated with experience to date with existing lines and equipment. No conclusion or recommendation is attempted with regard to the application of desirable levels to specific situations or for guiding future practice

3. In the range of distribution voltages, spill-gap settings in terms of times normal voltage to neutral are relatively higher. Experience indicates that this practice is logical and practically necessary because of interference with closely set gaps, also the practice is permissible with the relatively greater prevailing insulation strengths of equipment.

## References

Reference is made to only a few of the most recent papers, in some of which will be found more complete bibliographies covering earlier work.


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# System Recovery Voltage Determination by Analytical and A-C Calculating Board Methods

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THE PERFORMANCE of current interrupting devices on systems is dependent not only on the characteristics of the device itself but also on the characteristics of the system. The voltage rating of the system and the connections at the time of fault have considerable influence on the recovery voltage and in turn on the application of the interrupting device. For example, the last oil circuit breaker to open must be capable of interrupting current under extreme system recovery conditions, while a deion protector tube always has at least the line section on which it is applied, connected at the time of clearing. This means that in considering broadly the current interruption problem it is necessary to have a knowledge of voltage recovery characteristics for a large number of system conditions. Tests can be made for particular system conditions, but this is expensive and it is difficult to obtain data for all possible combinations of faults and system connections. A general analysis taking into account all the factors makes calculations practically impossible, and on account of the complexity, the human factor cannot be overlooked.

It is the purpose of this paper to present a method of obtaining system recovery voltages by setting up the 3-phase system in miniature on the a-c calculating board, applying faults of several types under different system conditions at several locations and actually measuring the recovery voltages. This method permits taking into account the effect of loads, ground and arc resistance, point of applying the fault with respect to the voltage wave, point of interrupting the current, effect of leaving the fault on the system for different lengths of time, effect of different fault locations, or practically any condition that could be experienced on an actual system in commercial operation.

It is proposed in this paper to present a method which extends the work previously done to allow a more general study of systems. The results of general analysis will be presented in a subsequent paper.

## General Discussion of the Recovery Voltage Phenomena

The problem of determining the recovery voltage of a system is merely that of finding the voltage-time curve for the transients in the system that follow the interruption of an arc path. The basic elements of the problem may be brought out by a discussion of figure 1. Assume that the system is subjected to a short circuit in an arc path at the point $F$ and that the current which flows is interrupted at a normal zero point of the current wave. The transient that follows the interruption of the current gives rise to an oscillation in the voltage which reappears across the arc path. If the insulation strength of this arc path when expressed in voltage and time is higher than the voltage produced by the system, the arc path will not be re-established and the fault current will be suppressed at the current zero assumed. The recovery voltage of this simple system may be calculated according to conventional methods. As illustrated in figure 2, the recovery voltage may be considered as the sum of 2 components: (1) a steady-state or forced frequency component, which is determined by the circuit constants and the generated voltage of fundamental frequency, and (2) a high or natural frequency component which is determined by the circuit constants of this system for free oscillation. The latter component is subject to an exponential decrement on account of losses which in the course of time reduce this component to zero. The current and the various voltages and their components for the simple system of figure 1 are illustrated in figure 2.

When a system with several meshes is considered, each mesh has its own steady-state and natural frequency components and these react on each other through their mutual couplings. The resultant recovery voltage curve, therefore, consists of the sum of a steady-state component and a number of natural frequency components, each of which may have different decrements. While the calculation of recovery voltage for extensive systems becomes quite complicated, it should not be considered something mysterious, since the basic phenomenon is quite simple as brought out in the discussion of figure 1.

It is desirable to review the character of recovery voltage from the standpoint of its practical application and to establish the meaning of the terms to be used in the subsequent discussion. For complicated systems, the recovery voltage-time curve may have quite an irregular shape, such as illustrated in figure 3. Curve $A$ applies to one hypothetical system where there is no residual charge left on the system and curve $B$ applies to another hypothetical system having a residual charge. The entire voltage-time relation is generally implied when the term recovery voltage is used. Recovery voltage is of importance depending on the closeness with which it approaches the insulation strength of the particular arc

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1. For all numbered references see list at end of paper.

path under consideration. The shape of this insulation recovery curve will vary for the different conditions of the arc path and particularly for the different arc interrupting devices. Some insulation strength curves may be of the shape illustrated by curve *C* of figure 3, which as drawn approaches the system recovery voltage curves near their crest. For such conditions the maximum recovery voltage and the time to crest represent the important part of this system recovery voltage-time curve. Another insulation recovery curve might be of the shape shown in curve *D* which comes closest to the system recovery voltage-time curve *A* at a point close to that of the maximum recovery voltage rate. There is also the possibility that the insulation recovery curve might be of the shape shown by curve *E* which contacts the system recovery voltage curve *A* at an intermediate crest between the point of maximum recovery voltage and the point of maximum slope.

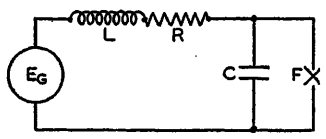
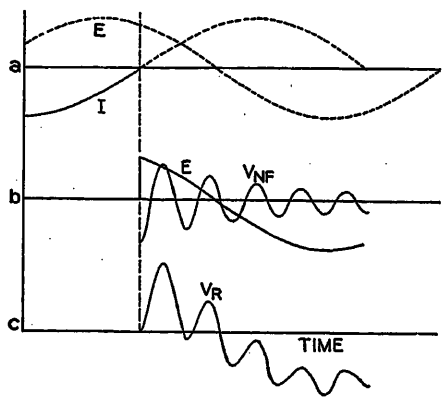



**Figure 1. Simple system for illustrating recovery voltage for a fault F**




*E*—Generated voltage (steady-state value)

*I*—Fault current suppressed at current zero (steady-state value)

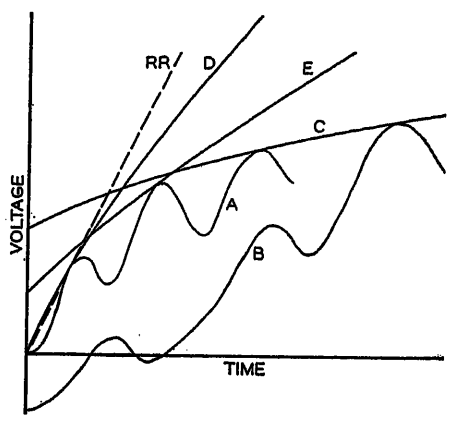
$V_{NF}$—Natural frequency voltage component

$V_R$—Recovery voltage

**Figure 2. Voltage and current relations for clearing the fault on the system shown in figure 1**

## Part I. Analytical Methods for Calculating Recovery Voltage

There is now available considerable literature on the calculation of transients in circuits involving an a-c source and resistive, inductive, and capacitive branches. In general, the approach is to consider a current circulating in each mesh and to make these currents follow Kirchoff's laws for the transient conditions. Differential equations may be set up and the boundary conditions determined in line with the classical theory. The complete solution is complicated by the necessity of providing for (1) all the possible initial conditions of energy storage in each of the various circuit elements as well as for (2) the various natural frequencies of oscillation and for (3) the various rates of decrement. The mechanical labor of solution may be minimized by systematizing the process and an excellent reference is the work by Guillemin.[1]




*A*—Recovery voltage curve for system without residual charge

*B*—Recovery voltage curve for system with residual charge

*RR*—Maximum recovery voltage rate for curve *A*

*C, D, E*—Insulation voltage recovery curves

**Figure 3. Comparison of system recovery voltage curves and insulation strength curves**

The conventional method of approach to a solution may be considered as a single-phase method in contrast to the polyphase method to be described subsequently. In the single-phase method the solution may be obtained by assuming a fictitious source of voltage equal in magnitude but of opposite polarity to the voltage existing in the system at the instant of arc suppression, this source being superposed on the actual system and its energy being dissipated through losses in the system. The circuit involves one phase of the power system with return through the neutral and the other 2 phase wires in parallel, and thus it becomes very complicated if many meshes are considered. Such a method has the disadvantage of employing circuits which are difficult to visualize and which will vary for each type of fault; for example, the circuits will be different for a line-to-line fault than for a single line-to-ground fault. Furthermore, the various steps of the solution are also difficult to visualize and the calculations must be carried through in a mechanical manner. In order to avoid a number of these objections a polyphase method utilizing symmetrical components is proposed.

From the foregoing it is apparent that for any particular application, the significant factor of the system recovery voltage may be defined in terms of a voltage magnitude and the corresponding time. It is, of course, possible to define the point of interest in terms of a voltage recovery rate and either the corresponding time or the corresponding voltage magnitude. The quantity "recovery voltage rate" by itself is obviously insufficient to define the significant points on either the insulation strength curve or the system recovery voltage curve. Since the term recovery rate is applicable to only a limited range of conditions its general use may become confusing and misleading. For these reasons it has seemed preferable to use the terms recovery voltage magnitude or merely "recovery voltage" and "time to crest" for defining the point of interest on the recovery voltage-time curve and this form of expression is adopted in this paper.

## Transient Analysis by the Method of Symmetrical Components

The application of the principle of symmetrical components to the solution of high frequency transients on polyphase systems constitutes an important step in the simplification of this problem. It will be recalled that steady-state solution of unbalanced faults on ordinary 3-phase power systems was found to be generally impracticable as long as "single-phase" methods of solution were employed. The introduction of the method of symmetrical components by the late Doctor C. L. Fortescue radically changed the status of this problem and the method has come into general use for a variety of applications subsequent to the introduction of the sequence networks. Similar simplification in the solution of high frequency transients is obtained through the use of symmetrical components. In this method the natural frequency components are themselves resolved into positive-, negative-, and zero-sequence components in a manner quite analogous to that employed in the analysis of the ordinary steady-state solution of unbalanced circuits at

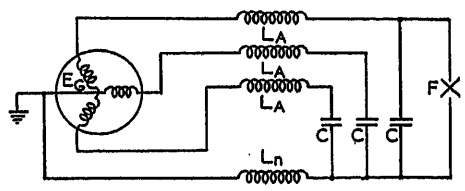



**Figure 4. Simplified 3-phase system subjected to a line-to-ground fault**

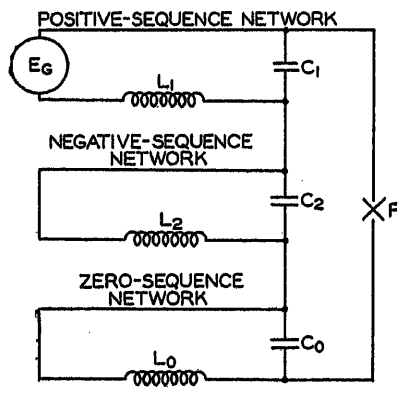
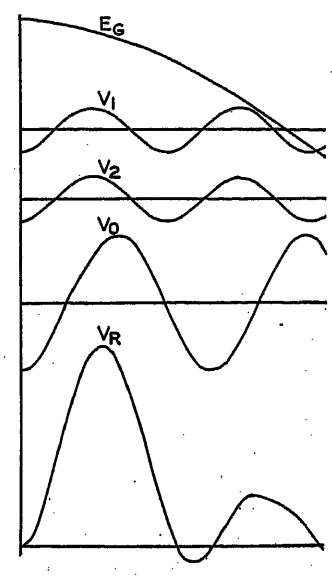



**Figure 5. Connection of sequence networks to simulate single line-to-ground fault. Opening circuit at F simulates clearing of the fault and recovery voltage appears at this point**

fundamental frequency. The advantage of resolving the natural frequency components into their respective sequence components is the same as with fundamental frequency, namely, that the components do not react upon each other in a symmetrical system. The boundary conditions for the natural frequency components are determined, of course, by the dissymmetry of the system occasioned by the fault itself.

In order to illustrate this method a relatively simple system, as shown in figure 4, will be considered. This system is assumed to have a positive-sequence generated voltage $E_G$ in the reference phase with capacitances and inductances in each phase and in the neutral as shown. For this example a fault of the single line-to-ground type is considered. The current is assumed to be interrupted at its normal zero point. The losses in the circuit are ignored and the fault current condition is calculated in the familiar manner making use of the sequence networks.

The manner of setting up the sequence networks for the ordinary circuits containing apparatus and transmission lines, including capacitances and loads is now well established.[2] For a single line-to-ground fault the 3 networks must be connected as shown in figure 5 in order to satisfy the requirements for this particular fault condition. Since by assumption the circuits do not involve loss the resultant current lags 90 degrees behind the voltage of the faulted phase. Consequently, the circuit is interrupted at the zero point of the current wave, the generated voltage on the faulted phase is a maximum, and the various capacitances associated therewith have their maximum charge; the sequence networks are isolated automatically and each oscillates according to its own natural frequency. In the course of time, such oscillations in an actual circuit would be damped out because of the losses. In the case of the negative- and zero-sequence networks, only the natural frequency oscillations are present; in other words, after the fault is removed there are no voltages and currents under steady-state conditions. In the case of the positive-sequence network, however, there is a steady-state solution because of the generated electromotive force and superposed on this is the free oscillation which is determined by the difference in voltage across the capacitances under fault conditions and the value which would be obtained under steady-state conditions. This difference in voltage sets up a free oscillation in the positive-sequence network which in the actual circuit would be dissipated by losses. The total voltage on the faulted conductor consists of several com-



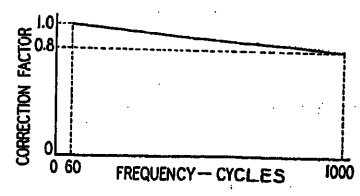




**Figure 7 (above). Frequency correction factor to be applied to the inductance of a synchronous machine. The 60-cycle value corresponds to negative-sequence reactance**

**Figure 6. Components and total recovery voltage-time curve for system of figure 5**

$E_G$—Steady-state voltage
$V_R$—Total recovery voltage
$V_1$—Natural frequency component in positive-sequence network
$V_2$—Natural frequency component in negative-sequence network
$V_0$—Natural frequency component in zero-sequence network

ponents, as shown in figure 6. These include $E_G$, the steady-state voltage due to the fundamental system frequency; $V_1$, the voltage arising from the free oscillation in the positive-sequence network; $V_2$, the voltage arising from the free oscillation in the negative-sequence network; and $V_0$, the voltage arising from the free oscillation in the zero-sequence network. The sum of these voltages must be taken as zero initially in order to fit the fault condition. When the fault is removed these components oscillate according to their respective forced or natural frequencies and the recovery voltage is the sum of the several components and is plotted as $V_R$ in figure 6.

The use of the sequence networks to solve the transient oscillations makes it possible to obtain a better visualization of the phenomena taking place. The various sequence networks may have different natural frequencies of oscillation and different rates of decrement. These considerations make it clear that the shape of the actual recovery voltage curve is in general quite complex. The time to crest and the magnitude of this crest depend on the relation that these oscillating components bear to each other at that instant. Thus, if the several components are in phase the maximum crest is reached. If some of the components of considerable magnitude are in opposition when the remaining components reach their maximum value, the recovery voltage curve is considerably distorted and the crest may be relatively low.

## Representation of System Elements With Lumped Constants

The simple system of figures 4 and 5 can be extended readily to all systems with lumped constants. Question naturally arises as to the necessity for modifying the constants of the circuit elements for representation at high frequencies. Ordinarily these branches, such as machines, transformers, reactors, and capacitors can be represented by inductances or capacitances corresponding to their 60-cycle reactances. In the case of synchronous machines the reactance to be used in the positive- and negative-sequence networks is intermediate between the leakage reactance and the negative-sequence reactance and may be obtained by impressing high-frequency potential on the machine terminals. As the frequency of the impressed voltage is increased the equivalent inductance decreases because of eddy current effects. From the data available the frequency correction to apply to the 60-cycle negative-sequence reactance of the machine is shown in figure 7. The impedance at high frequencies is closely the same for both the positive- and negative-sequence components and, therefore, the same value may be used in both networks.

More accurate representation of the various circuit elements may be required in special cases, as for example, the case in which the recovery voltage is to be obtained on a bus with only the generator connected. For this case it is necessary to determine with some accuracy the capacitance of the bus and the distributed capacitance of the winding. Under such conditions the machine, transformer or reactor representation involves a problem quite similar to that discussed subsequently for circuits having distributed constants. Such refinement in apparatus constants is not required for the usual problem since the effect of these relatively small capacitances is negligible in comparison with the relatively large capacitances of transmission lines, but it is important for the special case of circuit breaker opening, since the analysis is usually made for the case involving opening the last circuit breaker on the bus section.

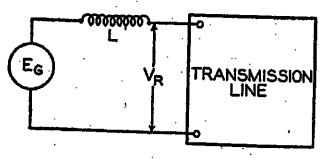



**Figure 8. Transmission line with inductive source**

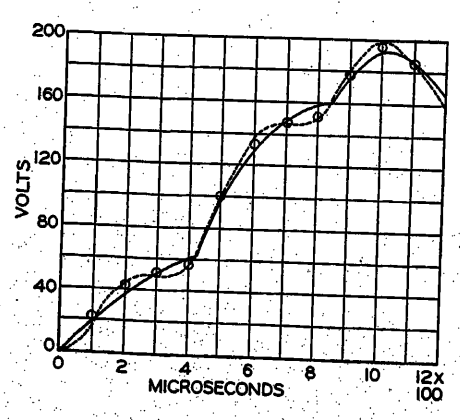



**Figure 9. Calculated recovery voltages for a transmission line with inductive source**

Solid curve—Wave theory

Dashed curve—Equivalent network figure 11*a*

Circles—Equivalent network figure 11*b*

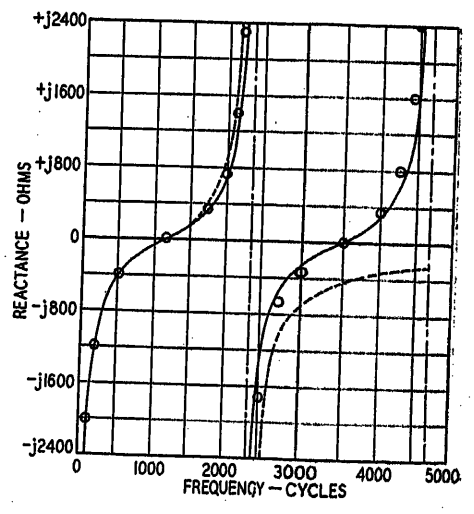



**Figure 10. Frequency - impedance curves**

Solid curve—Transmission line, finite length

Dashed curve—Equivalent network figure 11*a*

Circles—Equivalent network, figure 11*b*

## Representation of System Elements With Distributed Constants

Special consideration is required for the representation of a system element having distributed constants, such as a transmission line. The actual transmission line has 3 phases, which may be considered as composed of an infinite number of sections, each with its own self and mutual series impedances and its own self and mutual shunt capacitances. It is possible to use the sequence representation so that the problem reduces from the 3-phase circuit to

that of 3 single-phase circuits with distributed constants, one for each sequence.

The typical case requiring consideration is shown schematically in figure 8 in which $L$ represents the inductance of the source and the square represents the transmission line. If the line were of unlimited length it might be represented by its surge impedance. However, in power work the transmission lines are usually too short to justify such an approximation for determining the maximum crest, although this representation is useful for obtaining the first crest after current zero. The magnitude of the recovery voltage for a particular case of a finite line charged through an inductive source has been calculated by the conventional wave theory and the results are shown in figure 9.

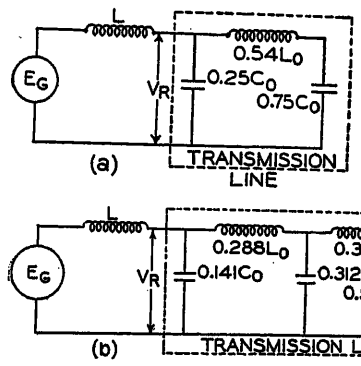



**Figure 11. Equivalent networks for representing transmission line with distributed constants**

(*a*) Single mesh equivalent circuit

(*b*) Two mesh equivalent circuit

$L_0$—Total inductance of line
$C_0$—Total capacitance of line
$L$—Inductance of source (not part of network for transmission line)

Such calculations entail too much labor for general use. Hence, it is desirable to represent the transmission lines by a suitable approximation in the form of an equivalent circuit. The approximation need not hold beyond the maximum overshoot and as a matter of fact it need not be accurate throughout this range if it is accurate in both magnitude and time for the particular point on the recovery voltage-time curve that requires consideration. An extremely simple equivalent circuit for transmission lines of finite length consists of an inductance and a capacitance connected in series across the circuit, the combination having the same natural frequency. The recovery voltage of such a circuit will have a time to crest which will be the same as that required for a wave to travel to the far end of the circuit and return.

A more accurate representation by means of equivalent circuits may be arrived at from a comparison of the frequency-impedance characteristics. A transmission line of finite length will have a frequency impedance curve, such as shown by the solid line curve in figure 10; the other curves show the frequency-impedance characteristics of the 2 equivalent circuits shown in figure 11. It will be noted that these circuits have frequency-impedance characteristics which are closely the same as that of the actual transmission line throughout a limited range of frequencies. The calculated recovery voltage curves for the 2 equivalent networks of figure 11 are plotted in figure 9 for convenience in comparison with the recovery voltage calculated by the wave theory. It will be noted

$L_0$—Total inductance of line
$C_0$—Total capacitance of line

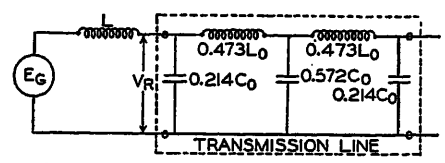



**Figure 12. Double-end equivalent network for representing transmission line with distributed constants**

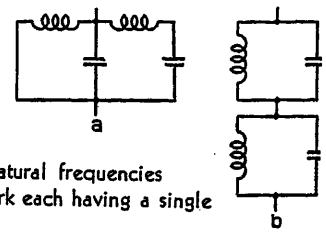



**Figure 13. Network transformations**

(*a*) Two mesh network with 2 natural frequencies
(*b*) Equivalent single mesh network each having a single natural frequency

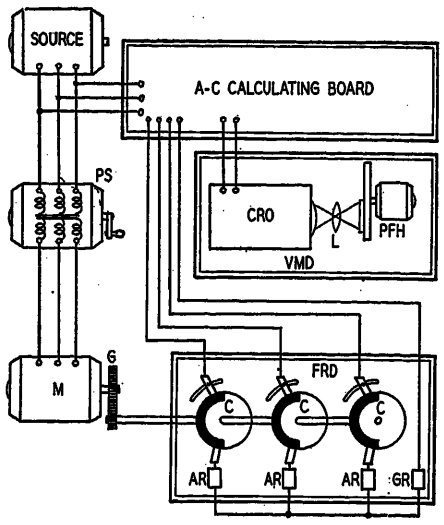
that reasonably good approximation is obtained by these relatively simple equivalent circuits.

For more accurate representation of a transmission line, greater complexity in the equivalent circuit will be required. In general, these networks should be the same for both an open-circuited and a short-circuited receiver. Also, the equivalent circuit should be of the "double-end" type so as to facilitate the introduction as an element in the complete network. One of these double-end networks is illustrated in figure 12.

Another method of studying the equivalence of networks is to compare the simple equivalent circuit with the more elaborate circuit requiring a very large number of series inductance and shunt capacitance elements.

## Solution for Line-to-Ground Fault

The general method of setting up the equivalent circuits for each of the different sequences has already been described. For a line-to-ground fault the 3 sequence networks must be connected in series as shown in figure 5 in order to meet the requirements for the fault condition. When the fault is suppressed, oscillations will take place in each of the sequence networks. The natural frequencies of oscillation for each sequence network and their rates of decrement may readily be computed for the simple circuit shown in figure 5. For more complicated systems it is necessary either to transform the equivalent circuit to a more manageable form or to resort to the conventional solution using differential equations. When the equivalent circuit for each sequence network is not too complicated but is of a form similar to that shown in figure 13*a*, it is usually more convenient to transform it to the form shown in figure 13*b* which facilitates calculation of the natural frequencies of the individual sections. This use of equivalent circuits has been used by E. W. Boehne[3] for calculating recovery voltage by the single-phase method. The transformation depends upon the use of equivalent circuits having the same impedances at all frequencies and a number of such equivalent networks has been worked out by K. S. Johnson.[4]




*PS*—Phase shifter
*M*—Synchronous motor
*G*—Gear
*FRD*—Fault representation device
*C*—Commutator
*AR*—Arc resistance
*GR*—Ground resistance
*VMD*—Voltage measuring device
*CRO*—Cathode-ray oscilloscope
*L*—Lens system
*PFH* — Polar film holder

**Figure 14. Schematic diagram for a-c calculating board method of determining system recovery voltage**

## Solution for Other Types of Faults

For other types of faults the same sequence networks may be used in various combinations. The method of connecting these networks varies with the type of fault and is the same as for the steady-state solution, for example, for the line-to-line fault the positive- and negative-sequence networks are connected in series with the normal direction of fault current flow reversed in the negative-sequence network. For the double line-to-ground fault the connection is the same as for the line-to-line fault except that the zero-sequence network is placed in parallel with the negative-sequence network. From this it is apparent that even the sequence method becomes involved for the more complicated types of faults. It has its greatest advantage in the solution of the line-to-line or line-to-ground faults.

## Limitations of Analytical Methods

Before taking up the ultimate method of solution proposed in the paper it is desirable to consider the further limitations of analytical methods. For example, the initiating transients arising from the application of the fault at voltage crest may not be dissipated before the fault current is suppressed and the resulting subsidence transients begin. In addition, the fault itself may not be single phase in character but may involve several transients, such as those that are incident to the simultaneous opening of each of the 3 poles of a circuit breaker. Further complication arises from the fact that the circuit opening is made through an arc which is not of linear resistance characteristic.

From the foregoing considerations it is apparent that the analytical method of solution is of restricted use. While the method of symmetrical components has simplified the problem for certain types of calculations, many limitations still remain. For this reason a more general method of solution is suggested using the a-c calculating board with connections corresponding to the analytical methods described.

## Part II. Determination of Recovery Voltage by A-C Calculating Board Method

In view of the limitations of the analytical solution of system recovery voltage transients, the method of setting up the system in miniature on the a-c calculating board is proposed. This method has opened the way for the first time to a general investigation of system recovery voltages, practically eliminating the mechanical labor and the human errors unavoidable in analytical solutions of such an involved and complicated nature. The arrangement of apparatus used in this method is shown schematically in figure 14 which includes:

1. The source
2. A-c calculating board
3. The fault representation device
4. The recovery voltage measuring device

The fault representation device includes means for controlling the point of application of the fault, its duration, and its resistance. To obtain a simple recording device, the transients are made repetitive in character with an

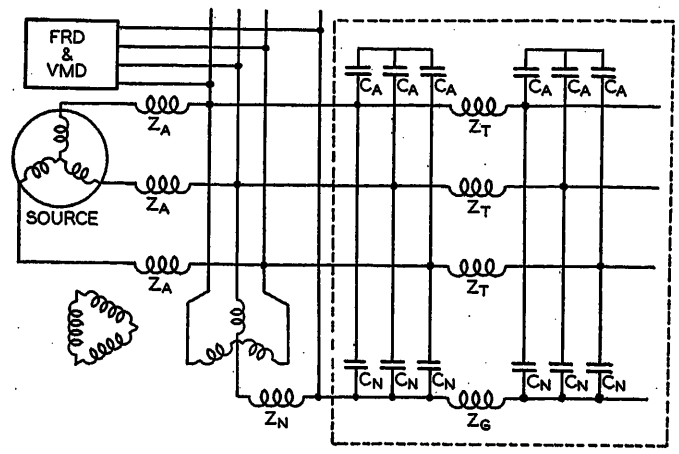



**Figure 15. Schematic diagram for the polyphase method of system representation on the a-c calculating board**

*FRD*—Fault representation device
*VMD*—Voltage measuring device

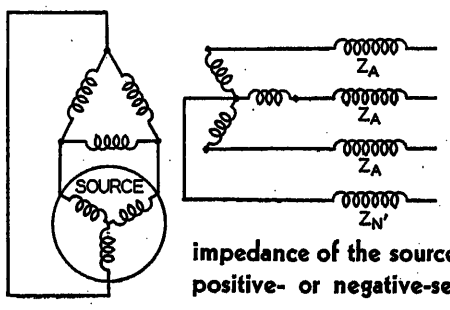



**Figure 16. Schematic diagram of simplified methods for representing power source applicable when zero - sequence impedance of the source is greater than the positive- or negative-sequence impedance**

intervening period of sufficient length that one transient does not interfere with the next.

## Connection of A-C Calculating Board

The a-c calculating board used in this investigation has been described in the literature.[5] Two methods of setting up the system on the calculating board are available, namely, (1) the sequence method and (2) the polyphase method. In the sequence method the system is set up in the form of the 3 sequence networks corresponding to the analytical solution of part I. This use of the a-c calculating board merely provides a means for minimizing the mechanical labor that would be required in the analytical method. In the polyphase method the system is set up with a 3-phase source and a 3-phase miniature system. The polyphase method has the advantage of corresponding more closely in form to the original system and it is more convenient since all the phase quantities are included directly in the setup and are available for various fault investigations without manipulation. However, in setting up either method the steps involve the same requirements in the miniature system, namely, that it shall have the same positive-, negative-, and zero-sequence constants for all of the circuit elements requiring consideration.

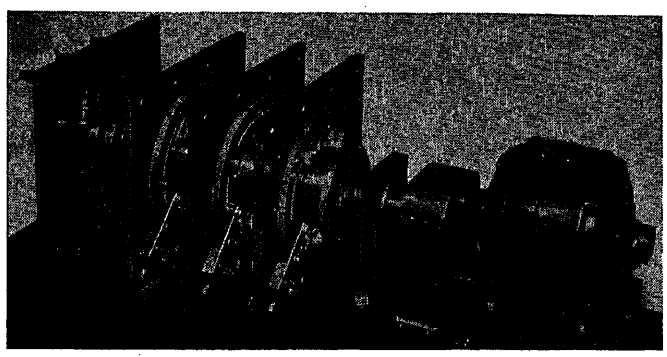


**Figure 17. Fault application device, shown schematically in figure 14**

In order to illustrate the polyphase method of setting up the system on the a-c calculating board, a more complicated system, such as shown in figure 15, is used. Incidentally, this system is sufficiently representative as to give a reasonably good solution for a large number of problems. Figure 15 applies to a system with a source of power consisting of a generator and step-up transformer, and a transmission line subjected to a fault as indicated. The branches $Z_A$ and $Z_N$ correspond to the generator and step-up transformer constants and the remaining branches correspond to the transmission line when represented by the equivalent $\pi$. The branches $Z_A$ represent the positive- or negative-sequence impedance per phase of the generator and transformer, and the branch $Z_N$ represents one-third of $Z_0$, the zero-sequence impedance of the transformer. If the zero-sequence impedance is higher than the positive-sequence impedance, the source may be represented by a grounded-star transformer with a neutral impedance as shown in figure 16. For this case, as in the previous case, the impedances $Z_A$ represent the positive- or negative-sequence impedance of the generator and transformer. For the neutral branch, however, the impedance $Z_N$ is equal to (1/3) $(Z_0 - Z_A)$. In the transmission line similar relations hold for the 3 sequence constants. The positive- or negative-sequence series impedance branch is equal to the impedance $Z_T$ in each phase, and the neutral impedance branch $Z_G$ is equal to (1/3) $(Z_0 - Z_T)$. The equivalent capacitance for each end of the $\pi$ representation consists of $C_N$ which is equal to the zero-sequence capacitance for each phase and $C_A$ which is equal to the difference between the positive- or negative-sequence capacitance and the zero-sequence capacitance for each phase.

## Fault Representation Device

The representation of the fault involves 2 elements.

1. The applicator by which the fault is applied and removed.
2. The representation of fault resistance characteristic.

The fault representation device is shown schematically in figure 14 and includes the commutator arrangement $C$ which consists of 3 separate elements, one for each phase. Each element has 2 brushes, one of which is adjustable. The commutator is driven by a synchronous motor connected to a phase shifter supplied from the same source as the a-c calculating board. The fault is established when 2 brushes make contact with the conducting section which spans half of the commutator periphery. The fault is removed when either of the brushes leaves the conducting section. Such a commutator may be built to permit individual control of the instant of application of the fault, but ordinarily it is sufficient to consider the fault applied simultaneously to the 3 phases and this may be done by a set of fixed brushes and a phase shifter. The duration of the fault is controlled by separate adjustment of the brushes which can be set to maintain the fault for different periods from a half cycle to several cycles of the fundamental. The gear, connected between the driving motor and the commutator, makes it possible to apply the fault alternately on a point on a positive wave and on the corresponding point on the

Solid curve—Characteristics of Rectox resistor for fault representation

Circles—Characteristics of deion flashover protector

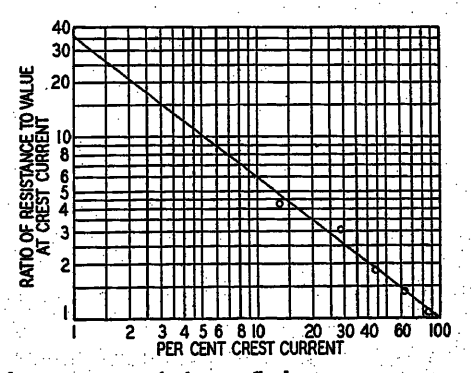



**Figure 18. Arc characteristic of deion flashover protector compared with fault representation device**

negative wave. The object of the gear is to avoid cumulative magnetizing action in the source. The fault applicator used in this investigation is shown in figure 17.

Consideration will now be given to the means for representing the fault and arc resistances. The first approximation of a fault is a resistance, which is of zero value while the current is flowing, and suddenly changes to infinite value when the current zero is reached. A second approximation of fault characteristics takes into account the tower footing resistance and the arc resistance. This

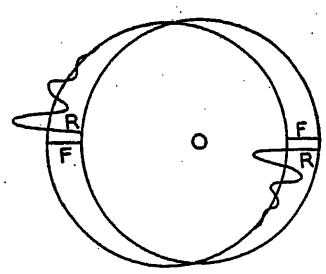



**Figure 19. Polar oscillogram of heavily damped oscillations**

*F*—Point of fault application
*R*—Point of fault suppression

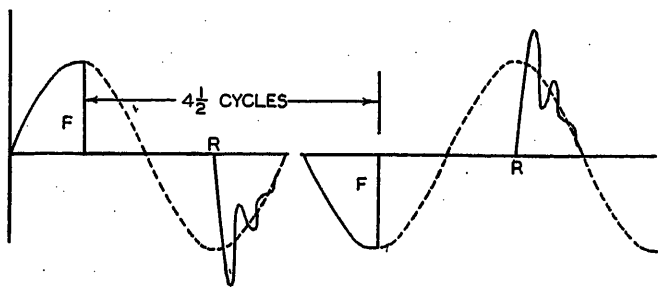



**Figure 20. Cartesian plot corresponding to figure 19**

*F*—Point of fault application *R*—Point of fault suppression

is, of course, readily represented by introducing an appropriate resistance in the fault path through the commutators and in the neutral as shown by the branches *AR* and *GR* of figure 14. A more accurate representation may be accomplished by the use of a resistor whose resistance-time curve would correspond to that obtained from the actual voltage across the arc and the current through it. Such a resistance curve could, of course, be obtained by a synchronously driven commutator which would vary the resistance throughout the cycle. A more convenient and practical device is the Rectox resistor which has approximately the desired characteristic. Two sets of Rectox units oppositely poled are connected in parallel to give the same resistance for either direction of current flow. This combination forms a resistor whose value is relatively low for high currents and relatively high for low currents. It is possible to choose the number of units to give a good approximation of certain arc characteristics throughout the principal part of the arcing period. The arc characteristics and Rectox approximation for a deion flashover protector are shown in figure 18. However, the representation at the end of the interval may not be accurate as the apparent resistance of the arc increases very rapidly at the instant at which the arc is suppressed. For this reason the Rectox resistor has been used in combination with the opening of the fault slightly ahead of normal current zero in order to leave a charge on the system.

## Recovery Voltage Measuring Device

The transient measuring device for viewing and recording the recovery voltages constituted a major problem. The requirements for the device included accurate response to the various high frequency oscillations, the imposing of small burden on the network always a factor in the use of miniature systems, and means for obtaining a visual trace and a permanent record. The magnetic oscillograph failed to meet all these requirements because an element designed for high frequency response, required a special hookup to avoid placing undue burden on the network. This pointed the way to the use of a cathode-ray oscilloscope which met all the requirements but that of recording. To overcome this difficulty the transient was made repetitive in character by the means just described. On this basis it was readily feasible to photograph the record appearing on the cathode ray screen. The arrangement of apparatus used in most of this work is illustrated in figure 14. The cathode-ray oscilloscope recorded the recovery voltage on its screen and this image was placed on a film through a suitable lens system. While it is possible to photograph the image using the cathode ray sweep circuit to provide the time scale, it was more practical to rotate the film by means of a synchronous motor thus obtaining a uniform time scale on an oscillogram of the polar form.

The type of record obtained for a highly damped transient is shown in figure 19 and the corresponding Cartesian plot in figure 20. The entire oscillogram repeats every 9 cycles and includes 2 applications of the fault indicated at the points *F* which are $4^1/_2$ cycles apart. The faults are impressed for $^1/_2$ cycle and the arcs are suppressed at the points *R* at which the recovery voltages begin to appear. The high frequency oscillations are superposed on the steady-state voltage as shown in the figures, and in this case are damped out in less than $^1/_2$ cycle. If the transient is not highly damped it may persist for many cycles. In general, however, the high frequency oscilla-

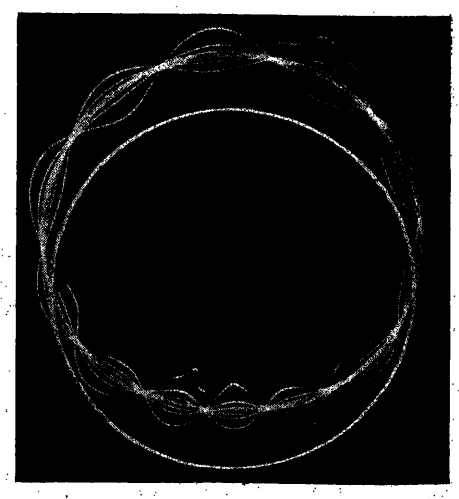


**Figure 21. Typical oscillogram of recovery voltage on a system with lightly damped oscillations**

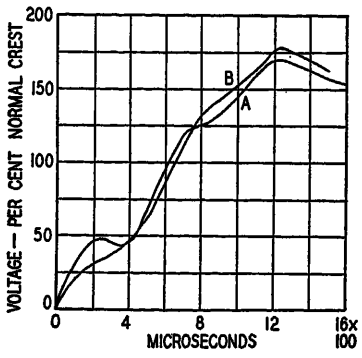



**Figure 26. Effect on recovery voltage of varying the duration of fault**

*A*—Fault duration, 1/2 cycle
*B*—Fault duration, 1 cycle

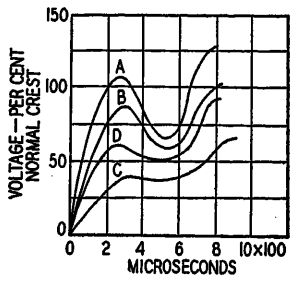



**Figure 27. Effect on recovery voltage of fault and arc resistance. Single line-to-ground fault**

*A*—Zero fault resistance
*B*—8-ohm fault resistance
*C*—33-ohm fault resistance
*D*—Rectox resistor, 5 ohm minimum (see figure 19)

138-kv system included measurements of recovery voltages with a cathode-ray oscillograph. For two of these tests involving a single line-to-ground fault, the system consisted of a generator and step-up transformers connected in star on the high voltage side and grounded through a 50-ohm reactor, and 39 miles of 138-kv line. Figure 22 compares the recovery voltages of these 2 field tests with results of calculations made for identical circuit conditions with the transmission line represented in one case by an equivalent "T" network and the other case by the equivalent network of figure 11*a*. The closeness of these checks made early in the investigation were very encouraging and greatly stimulated the work that followed.

Following the proposal of the a-c calculating board method and the development of the equipment previously described, it was of particular interest to compare results obtained with this method and results obtained by calculation. Figure 23 compares one of the calculated

**Figure 28. Effect on recovery voltage of arc interruption with residual charge. Fault simulated by Rectox resistor and circuit opened before normal current zero**




**Figure 29. Effect on recovery voltage of the addition of load**

*A*—Without load
*B*—With load




**Figure 30. Transient voltages of 3-phase system upon clearing of single line-to-ground fault on phase B**

$V_{AN}$, $V_{BN}$, $V_{CN}$—Voltages to neutral

$V_{AC}$, $V_{BC}$, $V_{CA}$—Voltages, phase-to-phase




ing of the first phase at its normal current zero and this is followed by a similar adjustment for the second phase.

## Part III. Application of A-C Calculating Board Method and Comparisons With Analytical Solutions and Field Tests

It is now of interest to compare the recovery voltages as obtained by the analytical method and the a-c calculating board method directly with cathode ray oscillograms of tests made on actual systems. It is beyond the scope of this paper to give results of general investigations of system recovery voltage. A few illustrations will be given to show the range of use of the a-c calculating board in analyzing some of the factors.

It was recognized throughout this work that the results would only be of academic interest unless the solutions by the proposed methods provided a satisfactory check with the results of actual field tests. Some tests[6,7,8] made on the Indianapolis Power & Light Companys' curves of figure 22 with the recovery voltage measurements from the a-c calculating board using the alternative forms of connection. It will be observed that close checks are obtained between field tests, analytical solutions, and the a-c calculating board solutions.

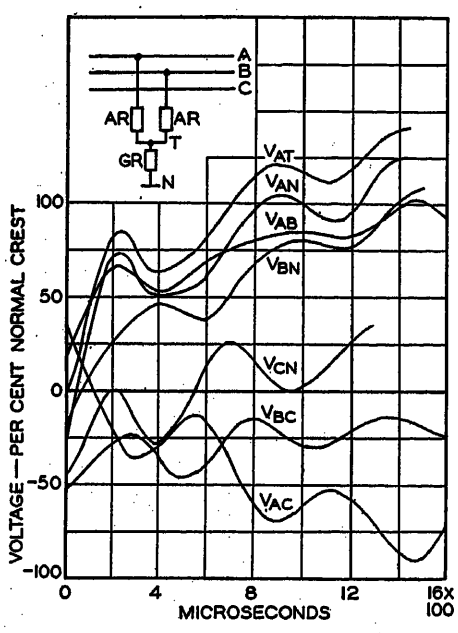
The a-c calculating board method provides an ideal means for carrying out general studies of system recovery voltage. It is, however, beyond the scope of this paper to present results of work along that line. It is pertinent, nevertheless, to discuss the range of application of the a-c calculating board method in this study of the various factors entering into the recovery voltage problem. For this purpose a few illustrations are given to show the ways in which these factors may be studied.

It is of general interest to study the effect of applying the fault at different points on the voltage wave. With the a-c calculating board set up by the 3-phase method to represent the Indianapolis Power & Light Company system, a single line-to-ground fault was applied before voltage crest, at voltage crest, and after voltage crest and was interrupted at normal current zero. The results

of this study are shown in figure 24. Similar studies were made for the fault applied at the voltage crest and the current interrupted before, at, and after the normal current zero. The results of such an investigation are shown in figure 25. These results provide an explanation of the familiar fact that interrupting devices tend to operate at normal current zero. They illustrate further the difficulties of attempting to interrupt a circuit in less than one-half cycle.

The effect on the recovery voltage of varying the duration of the fault is shown in figure 26. This comparison brings out the fact that the shorter the duration of the fault the more important will be the results of the initiating transients on the recovery voltage.

The effects that arc resistance has on the interruption problem have always been of interest. Figure 27 shows the effects of adding different tower footing resistances of fixed resistance values as well as the effect of adding a resistance of varying value, such as shown in figure 18, to simulate the arc. This study was made for a 138-kv




$V_{AN}$, $V_{BN}$, $V_{CN}$—Voltages to neutral

$V_{AB}$, $V_{BC}$, $V_{CA}$—Voltages, phase-to-phase

$V_{AT}$—Voltageacross arc representation device

$A_R$—Arc representation device

$G_R$—Ground resistance

**Figure 31. Transient voltage of 3-phase system upon clearing of double line-to-ground fault on phases A and B. Fault applied at crest of B phase voltage. Phase B and then phase A opened at first normal current zero points. Curves include the highest transient voltages for the opening of phase A or B. (Curves start at an arbitrary zero time)**

impedance-grounded system with 90 miles of line, the system being capable of supplying short circuit current of 4,000 amperes at the sending end.

In order to simulate arc and fault characteristics in a more accurate manner for the condition in which a residual charge is left on the system, tests were made with the Rectox resistor in the circuit to simulate the arc throughout most of the cycle and the circuit was opened slightly ahead of current zero to simulate the very abrupt change of resistance at current zero. Figure 28 shows the results of a test which simulate a deion flashover protector when interrupting its full current rating.

The effect of load on the recovery voltage can readily be studied on the a-c calculating board and figure 29 shows a comparison of recovery voltage for zero load and for full load on the 90-mile 138-kv system.

It is of interest to have a knowledge not only of the voltage on the faulted conductor but also on the other conductors to neutral as well as between conductors. Figure 30 shows transient voltages for the 90-mile 138-kv system when clearing a line-to-ground fault on phase *B*.

On account of the complexity of the problem it has been practically impossible to get a co-ordinated picture of the transient voltages on the various conductors to ground and from conductor to conductor for a double line-to-ground fault condition. The a-c calculating board method has given a relatively simple approach to this problem and results of such a study for the 90-mile 138-kv system are shown in figure 31. Only the sections of the various transient voltage curves which are of an abnormal nature are shown, the plot starting at an arbitrary zero time in order to simplify the figure.

## Conclusions

1. The symmetrical components method proposed constitutes a simplification of the analytical solutions.

2. The a-c calculating board method is a practical means of determining the electrical transients of systems.

3. The combination of these methods has for the first time opened the way to a systematic general investigation of recovery voltage transients and related problems.

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# Vibration-Measuring Instruments

## Fundamental Considerations in Their Design

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ASSOCIATE AIEE

## Synopsis

A general-purpose wide-range high-precision vibration-measuring instrument must embody several fundamental design requirements which determine the useful frequency range, the accuracy of measurement, the intensity of vibration to which it can be applied, and the effect of the instrument on the vibrating body.

In this paper the advantages and disadvantages of certain mechanical and electrical detecting and amplifying systems for the measurement of vibration amplitude, velocity, and acceleration, are discussed in the light of their design requirements.

A vibration generator capable of producing sinusoidal vibrations over a wide frequency and amplitude range, and a set of vibration standards with which the vibrations produced can be accurately determined, are also described.

In conclusion, criteria for evaluating the performance of vibration measuring instruments of different types are suggested.

AN ever-growing demand for smaller and more accurate vibration measuring instruments has intensified design and development activities in this direction. This increased interest is due in part to the destructive possibilities of vibration on modern high-precision machinery and in part to an awakened recognition of the tremendous nuisance effect of unconfined vibrations.

The interest thus aroused has lead directly to more exacting specifications on the part of those who purchase vibrating or rotating equipment. To meet such specifications has required vibration instruments having increased sensitivity, greater portability, and broader operating ranges, which can be applied to ever-widening fields of investigation.

The general term "vibration instruments" is capable of considerable division and subdivision. The first broad classification can be labeled "precision measuring" as distinct from "vibration detecting." By vibration detecting is meant a device that will simply show that vibration is present or is not present. The mechanical or electrical output from such an instrument may be proportional to the relative amount of vibration over a limited frequency range and still be far from the precision concept.

Precision measuring vibration instruments can in themselves be roughly separated into 2 broad application classes. In one group can be placed all those highly technical and very special instruments built and designed to emphasize or surmount unusual vibration requirements. Practically every extensive vibration investigation program will require one or more of these special instruments, and in general a skilled vibration engineer is necessary to use them successfully. In the other broad division can be included all the general purpose devices. These are characterized by broad operating range, relatively low cost, and a susceptibility to particular adaptations, such as, permanent mounting, recording, and telemetering.

## Types of Instruments

Subsequent discussion will be confined to these general purpose precision measuring vibration instruments. Another subdivision into the 3 main aspects of vibration is required. Three different types of instruments are required for measuring amplitude, velocity, and acceleration. Frequency may be considered more of a condition than an aspect. The first type measures the double amplitude of vibration, or the amount of physical displacement of the vibrating body independent of the frequency or rate of moving.

A velocity type of instrument measures the product of vibration frequency and amplitude, or the rate of vibratory motion. This type of measurement is often convenient, since the vibration energy of the moving body is proportional to its velocity squared. Acceleration depends, of course, on the change in the rate of movement and an acceleration measuring device has an output proportional to the product of amplitude times frequency squared.

These 3 types of instruments are all subject to certain limiting mechanical factors. Some of the most important of these factors are:

(*a*) Establishment of a point stationary in space against which to measure
(*b*) Low natural frequency
(*c*) High structural resonance
(*d*) Ability to follow large accelerations
(*e*) Small effect on vibrating body
(*f*) Measurement in any direction
(*g*) Light weight and portable

## Mechanical System

Perhaps the most fundamental requirement of a general purpose vibration instrument is the creation of a

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1. For all numbered references see list at end of paper.

point or body stationary in space relative to which the vibratory motion can be measured. A vibrationless object, which can be used as a reference base, is seldom found ready to hand on the job, and usually is too costly to warrant construction. The establishment of such a stationary mass can be obtained in instruments, by the compliance coupling of a mass to the vibratory motion. The fundamentals of such a scheme are shown in figure 1*a*. The stationary mass $M$ is supported from the moving mechanism $R$ which is in contact with the vibrating body $B$, by the coupling spring $S$. The direction of vibration is shown by the double-headed arrow marker. At the point $A$, between the end of the moving mechanism and the stationary mass, any one of several mechanical or electrical methods for obtaining a measure of the relative motion between the 2 parts can be interposed.

Figure 1*b* shows the electrical equivalent of this mechanical system. The current $i_1$ represents the vibratory motion applied to the instrument. Neglecting $L_1$ and $C_1$ for the moment, the current $i_1$ will divide between $C_2$, representing the compliance of the coupled system, and $L_2$ representing the mass $M$. When the frequency of the applied current is more than 5 times the resonant frequency of the network including $L_2$ and $C_2$, the impedance of $C_2$ has become very small compared to the impedance of $L_2$, and substantially all the current flows through $C_2$.

The coupling spring represents the heart of the mechanical system. Under the action of gravity or inertia, a given mass will oscillate on a given spring at a certain natural frequency. Conversely, if the end of the spring is driven by a vibration having a frequency equal to or nearly equal to the natural frequency just determined, a condition of resonance is set up and the mass, instead of remaining stationary in space, will tend to vibrate at tremendous amplitudes limited only by the friction of the spring and the inertia and friction of the supporting hand and arm in which the mass may be held. Mechanical system resonances are, in general, sharply peaked, and experience has shown that the mass will remain substantially stationary when the end of the spring is driven at a frequency from 4 to 5 times the natural frequency of the system. In a great deal of vibration work, it is desirable to be able to measure down to 10 vibrations

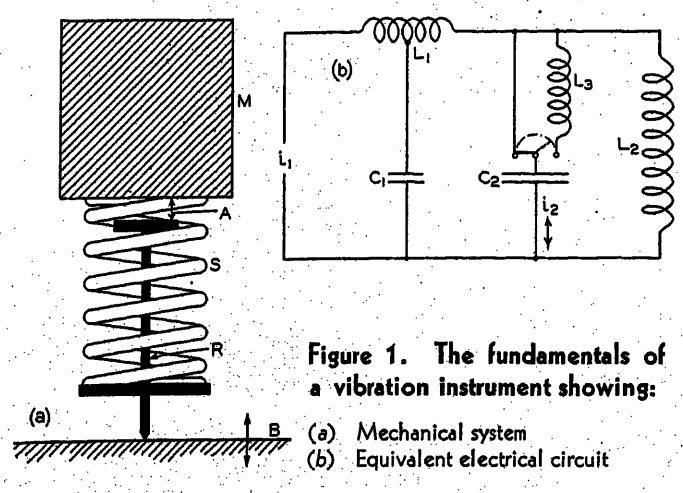



**Figure 1. The fundamentals of a vibration instrument showing:**

(*a*) Mechanical system
(*b*) Equivalent electrical circuit

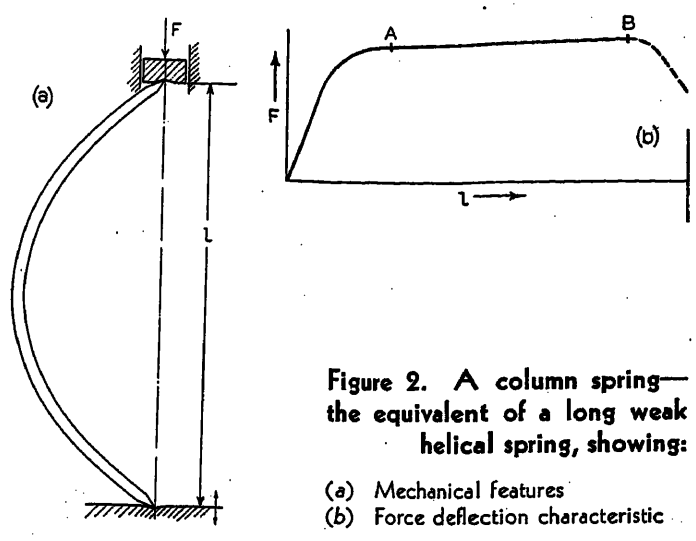



**Figure 2. A column spring—the equivalent of a long weak helical spring, showing:**

(*a*) Mechanical features
(*b*) Force deflection characteristic

per second, equivalent to 600 rpm. This means that the natural period of the mass on its coupling spring should be from 2 to $2^1/_2$ vibrations per second.

The formula[1] for the natural frequency of such a mechanical system is given by:

$$f = \frac{1}{2\pi}\sqrt{\frac{Kg}{W}} \text{ or } K = \frac{W}{g}\omega^2$$

where

$f$ = vibrations per second
$W$ = weight
$g$ = gravity acceleration
$K$ = spring constant of coupling spring

If $f$ is to be small, 2 to $2^1/_2$ vibrations per second, and $W$ must also be small, for lightness and portability, it is apparent that $K$ will be small, representing a weak spring. To avoid fatigue and failure due to excessive stress in the outer fibers of the spring, it will be necessary to make this spring relatively long. A long, weak spring is difficult to contain in a small space.

Thus, one of the most active lines of endeavor in the design of vibration instruments has been to produce the equivalent of a long weak spring, which can be contained in a small space and which will not permit too great relative movements between the mass and the driving mechanism.

One such equivalent is shown in figure 2*a*. When a force, continually applied along the original major axis of the column, has compressed the spring beyond a certain point, further compression increases the spring resisting moment arm[2] and the external eccentric loading moment arm by approximately the same amount. This means that a very small change in pressure will cause a relatively enormous change in effective length of the column. The force versus effective length characteristic of such a spring is shown in figure 2*b*. The spring constant of the column, as shown by the slope of this curve between the points $A$ and $B$, is very small.

Another method[3] for supporting a mass on springs at a low natural frequency is shown in the negative compliance system of figure 3*a*. Movement of the mass toward the left causes a compression of the spring $A$ and

**Table I. Vibration Amplitudes and Velocities Corresponding to an Acceleration of 25 Times Gravity**

| f = Vibrations per Second | D = Double Amplitude (Displacement) in Inches | V = Maximum Velocity (Inches per Second) |
|---|---|---|
| 10 | 4.89 | 154 |
| 60 | 0.136 | 25.6 |
| 200 | 0.0122 | 7.65 |
| 1,000 | 0.000489 | 1.54 |
| 4,000 | 0.0000805 | 0.385 |

a lengthening of the spring $B$, thus producing resisting forces vectorially represented by $A$ and $B$ in figure 3*b*. At the same time, the ends of the knife-edge links bearing on the mass are displaced toward the left. The pressure of the springs $F$-$F$ tends to continue the movement of the mass toward the left. By the proper adjustment of the relative compression forces exerted by all the springs, the component of the knife-edge linkage forces $F$, which opposes the resultant of forces $A$ and $B$, can be made to balance or very nearly balance the resisting force of spring $A$ and spring $B$. This will hold, of course, only so long as the angle $\theta$ is small so that this opposing component is substantially equal to $2F\theta$. The force deflection characteristic of this system is shown in figure 3*c*.

## High Structural Resonance

The measurement of vibrations of high frequency, requires a mechanical transmission path from the point at which the vibration is contacted to the point within the instrument at which the measuring takes place, which will be free from structural resonances at any frequency lower than the highest frequency to which it is desired to measure. Structural resonance will occur at that frequency at which the distributed mass of the moving system, as represented in the equivalent electrical circuit, figure 1*b* by $L_1$, resonates with the distributed compliance, as represented by the lumped value $C_1$. When this occurs, the current through capacitor $C_2$ is no longer a true indication of the current $i_1$.

The surmounting of this difficulty requires a stiff yet light transmission system which can be obtained by keeping the transmitting member as short and small as possible and utilizing an inherently high resonance shape, like a rod or tube driven longitudinally.

## Ability to Follow Large Accelerations

In order to meet the prerequisites for a wide range general purpose instrument, it must be possible to hold the spring-coupled contact rod in contact with the vibrating object during accelerations many times that of gravity. Experience has shown that an ability to follow up to an acceleration of 25 times gravity would be generally acceptable for most types of work. In certain cases, such as the vibrations of an unbalanced high-speed spinning motor shaft, which sometimes exceeds 70 times gravity, much higher accelerations may be encountered. Table I shows an acceleration of 25 times gravity expressed in terms of double amplitude of vibration at several different frequencies.

Applying the known equation,

$F = MA$, or $A = F/M$

where

$A$ = acceleration
$F$ = force
$M$ = mass

to figure 1*a*, it is evident that for $A$ to be large, $F$, the pressure exerted by the coupling spring, must also be large, and the mass of the moving mechanism, $R$, must be small. In the equivalent electrical circuit of figure 1*b*, $L_1$, which represents the mass of the moving mechanism, must be small.

## Small Effect on Vibrating Body

Since a general purpose instrument should be applicable to any vibrating body from a massive turbine shell down to a $^1/_{100}$ fractional-horsepower motor frame, it is desirable to have the moving mechanism of the instrument produce as little effect as possible on the vibrating body. This is particularly true when dealing with light bodies which are vibrating at, or near, resonance. When the contact rod is pressed against a vibration, the mass of the moving mechanism, and part of the mass of the spring, are effectively coupled to the vibrating body. Thus, the smaller the mass of the moving system the smaller will be the effect on the vibrating body.

In addition to this mass loading condition, the pressure of the coupling spring, acting through the contact rod, may set up stresses in the vibrating body which will materially affect its vibratory motion. This is especially true in the case of resonant vibration of thin bodies such as the walls of an air duct.

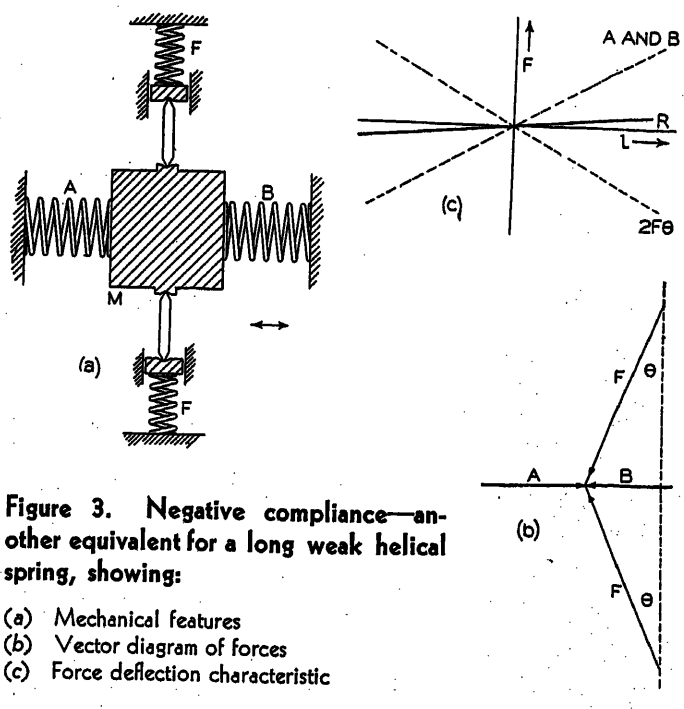



**Figure 3. Negative compliance—another equivalent for a long weak helical spring, showing:**

(*a*) Mechanical features
(*b*) Vector diagram of forces
(*c*) Force deflection characteristic

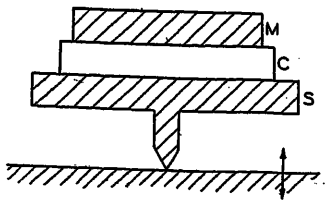



**Figure 4 (above). A piezoelectric crystal used for the measurement of vibration acceleration**

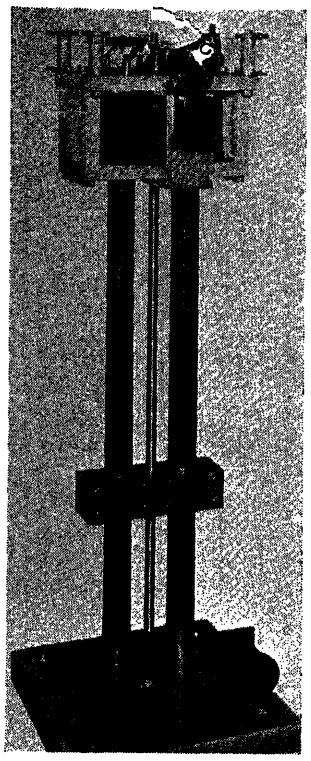


**Figure 5 (right). Vibration generator**

Both the ability to follow a large acceleration and the attainment of a small effect on the vibrating body call for a moving mechanism of small mass, but in the former a strong spring is needed while the latter requires a weak one. One way to obviate this difficulty is to provide an adjustable spring or springs, the pressure of which can be increased when it is desired to measure large accelerations. In general the acceleration of small bodies under resonance conditions will be small, thus permitting the use of a relatively weak adjustment of the spring. On somewhat larger bodies which are capable of handling much greater vibration energies, and hence producing larger accelerations, it is permissible to increase the spring pressure.

## Sensitivity

Modern requirements as written into rotating machinery specifications sometimes call for the limitation of vibration amplitudes to values less than 0.0001 inch. In addition to these mechanical requirements, it must be remembered that the awakened interest in noise calls for vibration measuring instruments of even greater sensitivity. A vibration amplitude of one millionth of an inch at 1,000 vibrations per second will produce an appreciable noise. The attainment of such sensitivity depends upon the electrical or mechanical measuring means which are interposed between the stationary mass and the moving mechanism of figure 1*a*.

## Mechanical Measuring Systems

A load, small in comparison with the inertia of the stationary mass of figure 1*a*, can be connected between the moving mechanism and the mass. This load, for example, may be an amplifying mechanical lever, gear train, or light-beam system adapted to greatly magnify the vibratory motion.

This load, in effect, is simply a continuation of the mechanical system already outlined, and its parts are subject to similar requirements of light weight, structural stiffness, etc. Referring to figure 1*b* the moving mass added by this load will increase $L_1$, while the lack of stiffness in its parts will increase $C_1$, thus increasing the effect on the vibrating body and reducing the ability of the instrument to follow large accelerations.

The reaction of the moving parts on the stationary mass $M$, to which they are connected, can be represented by the addition of an inductance $L_3$ in series with $C_2$. When $L_3$ is an appreciable fraction of $L_2$, which it may be when the lever amplification is large, some part of the current $i_2$ will shunt through $L_2$ and be lost for measurement purposes. Under these conditions $L_2$ is no longer stationary in space, but has some movement.

It is almost impossible to construct a mechanical system of large amplification which will at the same time be rigid and have small inertia. In addition the friction and lost motion at the joints will seriously limit the accuracy of the instrument.

Until ways are found to circumvent this practical difficulty, purely mechanical systems will continue to be restricted to vibrations of relatively low frequency, of the order of 50 vibrations per second or less, and amplitude measurements of the order of one mil or larger.

## Electrical Measuring Systems

By making the stationary mass $M$, figure 1*a*, a magnet which surrounds a coil rigidly attached to the moving mechanism, it is possible to generate a voltage proportional to the velocity of the vibrating body and at the same time add very little mass to the moving mechanism and introduce but a very small amount of reaction on the stationary mass. The inherent sensitivity of this electrical method depends, like all a-c generators, on the establishment of a high flux density and a high coil space factor. Furthermore, the enormous amplification obtainable from vacuum-tube amplifiers has no deleterious effect on the fundamental mechanical system, nor are serious frequency limitations introduced by the amplifying means.

This system is admirably adapted to the measurement of vibration velocity. It can, by the use of a frequency analyzer, be used to measure amplitude, but the process is apt to be laborious, especially when dealing with non-sinusoidal vibrations.

An electromechanical method for the direct measurement of acceleration is shown in figure 4. The mechanics of this system differ from those shown in figure 1*a*. A piezoelectric crystal $C$ is cemented to a stiff member $S$ which can be held in contact with the moving body, and a heavy metal block $M$ is cemented to the back of the crystal. Under conditions of vibration the block $M$, due to inertia, will produce alternating pressure and tension on the crystal. The amount of pressure and tension depends directly on the mass of the block $N$ and the acceleration of the vibration.

The voltage, proportional to pressure, generated by the piezoelectric crystal, can be amplified in the same

manner as the output of the velocity type of instrument.

In contrast to the amplitude and velocity instruments the whole mass of this acceleration device, including the hand which holds it in contact, will appear as a load on the moving body, thus reducing the maximum acceleration to which it can be applied. This difficulty can be surmounted in part by making the crystal and the mass $M$ very small.

The measurement of velocity or amplitude by this crystal method requires, respectively, a single or a double integration of the output.

## Vibration Testing Equipment

For the design and development of vibration instruments, it is vitally necessary to have a known controllable source of sinusoidal vibration. A great deal of time and effort have gone into the production of the vibration generator shown in figure 5. The output from a beat-frequency oscillator is stepped up by means of a 250-watt power amplifier and fed to a specially constructed moving coil which operates in an electromagnet field in the same manner as a loudspeaker. This edgewise-wound aluminum driving coil is capable of dissipating the full 250 watts of power at elevated temperatures. The motion of the coil is transmitted through a steel cone to the driving rod which projects from the top of the generator. The whole moving system is suspended in the air gap by means of steel piano wires under tension. Objects to be tested rest on, or are bolted to, this driving rod.

Such a generator is capable of producing amplitudes up to $^1/_4$ inch at vibration frequencies from 10 to 200 per second. At higher frequencies, up to 3,000 vibrations per second, proportionately smaller amplitudes are obtainable. Above 1,000 cycles the driving rod is locked to the resonance rod which extends downward between the supporting pillars. This resonance rod can be solidly clamped to the supports at any point throughout its length. When it is desired to vibrate the driving rod at say 2,000 vibrations per second the resonance rod is clamped at that length at which the natural longitudinal resonant frequency of the rod and driving mechanism equals 2,000. Two-thousand-cycle power applied to the driving coil will now produce relatively large movements of the driving rod. The amplitudes attainable are limited mainly by the internal friction of the resonance rod and its associated structure. Accelerations exceeding 70 times gravity have been measured and these when using only a small part of the total available power.

## Vibration Standards

Accurate determinations of the vibrations produced by this generator are obtained by means of primary and secondary standards. The secondary standard of frequency, the beat-frequency oscillator, can be checked when desired against primary frequency sources.

Amplitudes greater than 0.0005 inch are measured with a microscope equipped with a filar micrometer eyepiece. A spot of light reflected from a point on the moving generator drive rod produces a bright line in the microscope field. The length of this line, which is the amplitude of vibration, can be measured with great accuracy.

The determination of amplitudes below the microscope range is accomplished in 2 ways. A coil rigidly attached to the upper end of the drive rod, and partaking of its motion, generates a voltage by interaction with the surrounding field from a permanent magnet. This voltage is proportional to the velocity of vibration. By means of a high-gain amplifier, very small velocities of the driving rod can be measured. The calibration of this tertiary working standard coil and amplifier can be checked at one end of the amplitude range with the microscope, and at the other end by means of an acceleration device dependent on the constant of gravity.

A single point check can be made in a more fundamental manner. A hardened steel ball set on a hardened steel plate attached to the driving rod, will maintain contact with the plate when the acceleration of the driving rod is less than gravity. By passing a small current between them it is possible to accurately determine the exact point at which the driving rod reaches gravity acceleration, and the ball loses contact with the plate. At 2,000 vibrations per second this will occur at an amplitude of $1 \times 10^{-5}$ inches, approximately $^1/_{50}$ of the amplitude which can be measured accurately with the microscope.

## Conclusions

1. The growing need for general-purpose wide-range high-precision vibration measuring instruments makes it desirable to establish a systematic method of evaluating the performance obtainable from different types of instruments.

2. Three separate instruments or an instrument with 3 adjustments are required to measure the 3 different aspects of vibration; i.e., amplitude, velocity, and acceleration.

3. The natural frequency of the mechanical coupling system should not be greater than $^1/_4$ of the lowest frequency it is desired to measure.

4. The frequency of moving structure resonances should be considerably higher than the highest frequency to be measured.

5. The instruments should be capable of measuring vibration accelerations as high as 25 times gravity and should not have any large loading effect on the vibrating body.

6. Existing mechanical vibration amplitude measuring systems have undesirable frequency and sensitivity limitations.

7. Electrical generating and amplifying systems are well suited to the measurement of vibration velocity.

8. Wide range vibration generating equipment and accurate calibration standards are necessary for the development of high-precision vibration-measuring instruments.

## References


1. Vibration Prevention in Engineering (a book), Arthur L. Kimball. John Wiley & Sons, Inc., 1932, page 7.

2. Strength of Materials (a book), James E. Boyd. McGraw-Hill Book Company, third edition, 1924, page 250.

3. Dynamic Balancing of Rotating Machinery in the Field, E. L. Thearle. ASME *Transactions*, volume 56, October 1934, pages 745–53.

4. A New Portable Meter for Noise Measurement and Analysis, W. O. Osbon and K. A. Oplinger. *Journal* of the Acoustical Society of America, volume 5, July 1933, pages 39–45.

# Basic Impulse Insulation Levels

A Report* of EEI-NEMA Joint Committee
on System Insulation Co-ordination**

AS A RESULT of a great deal of operating experience and from a survey of the then current practice as regards insulation of high-tension equipment, it began to be evident some 9 years ago that too little, if any, attention had been paid to co-ordination of insulation in power systems. Apparatus was being built to specifications which were primarily formulated on a 60-cycle basis, with consideration given mainly to the ability of the apparatus to withstand 60-cycle voltages and almost no consideration to impulse strength. Further, very little consideration was given to insulation margins between the different types of apparatus used on the same system voltage. This was first brought to the attention of the membership of the AIEE in 2 papers presented some 9 years ago.

The subject of insulation co-ordination thus brought into the open, was discussed rather extensively in committees by users and manufacturers and before the Institute for the next 2 or 3 years. Very little progress was made, however, owing to the complexity of the problem and the fact that several different industry interests were involved. Eventually this was recognized, and this led to the formation in 1931 of a joint NELA-NEMA committee to act upon the entire broad subject. The work of the NELA group was transferred to the Edison Electric Institute group when it was formed in 1933.

## Purpose and Scope of the Committee

When active work was started on this subject in 1931, the following statement of principles was made by the NELA (now EEI) group.

"The co-ordination of insulation involves 3 steps:

1. Establishment of insulation levels.

2. Specification of insulation strengths of all classes of equipment in establishing insulation levels.

3. Allocation of the insulation levels to the nominal system voltages taking into account all operating and environmental conditions."

## Activities of Committees

Without going into the details of the various meetings held and the subjects discussed, progress in the work took the following form.

1. It was generally agreed that the 60-cycle basis was not adequate alone for establishing insulation levels.

2. On account of the lack of a suitable agreed-upon yardstick with which to measure voltage levels, an air gap was at first considered, it being the best means available at that time. This gap initially took the form of a so-called edge gap, and later became the rather well-known rod gap, having definite limitations of spacing and physical arrangement.

3. Recognized testing laboratories of manufacturers and others were not in agreement on voltage flashover values of standard every-day types of equipment such as suspension insulators, bus supports, bushings, insulators, etc. This disagreement covered not only the field of 60-cycle voltage measurements but also that of impulse voltages. A so-called interlaboratory group was, therefore, formed to work on this problem and reach an agreement on proper values for similar apparatus. The work of this committee has been carried on carefully and persistently until at the present time the hoped-for agreement has been reached, within reasonable tolerances of measurement, on a great deal of electric equipment and on gaps. One paper has previously been published[1] giving results of this work. Also, a paper is now being presented[2] by the interlaboratory group giving agreed-upon flashover values of insulators and gaps.

A subcommittee was also appointed to investigate the existing practice of insulation of lines and equipment in the operating companies with the idea that such data would serve as a basis for setting up practical, workable, and effective levels of insulation in carrying out the first statement of principles given above.

This subcommittee spent a great deal of time and effort

**Table I. Basic Impulse Insulation Levels**

| (1) Maximum Rated Voltage Classification (Kilovolts)§ | (2) Basic Impulse Insulation Level (Crest Kilovolts)# | (3) Rod Gap† Having Flashover in Column 2 (Inches) |
|---|---|---|
| 1.2 | 32 | 0.8 |
| 2.5 | 53 | 1.6 |
| 5.0 | 63 | 2.2 |
| 8.66 | 80 | 3.3 |
| 15 | 100‡ | 4.5‡ |
| 25 | 150 | 7.1 |
| 34.5 | 190 | 10.2 |
| 46 | 250 | 13.5 |
| 69 | 360 | 20.6 |
| 92 | 470 | 27.5 |
| 115 | 570 | 34.5 |
| 138 | 680 | 42.1 |
| 161 | 790 | 49.0 |
| 196 | 950 | 60.0 |
| 230 | 1,100 | 70.4 |
| 287 | 1,360 | 88 |
| 345 | 1,620 | 106 |

§ Based on "NEMA-NELA Preferred Voltage Ratings for A-C Systems and Equipment," NELA Publication Number 043, page 12, and on transformer subcommittee AIEE paper, ELECTRICAL ENGINEERING, January 1937, page 32.

# Crest kilovolts of 1½x40 impulse wave.

† Given for reference only. Gap spacings are those giving 50 per cent flashover and 50 per cent full wave when subjected to 1½x40 positive impulses with crest values given in column 2 under standard conditions of air density and humidity.

‡ Consideration should be given to increasing these values approximately 10 per cent.

A paper recommended for publication by the AIEE committees on electrical machinery, protective devices, and power transmission and distribution. Manuscript submitted March 18, 1937; released for publication April 12, 1937.

* Sponsored by the lightning and insulator subcommittee of the AIEE committee on power transmission and distribution.

** Prepared by the group chairmen: Edison Electric Institute group, Philip Sporn; National Electrical Manufacturers Association group, C. A. Powel.

1. For all numbered references see list at end of paper.

in collecting and correlating these data, keeping in mind that the final levels selected must be based on practical as well as theoretical considerations. Within the last few months it finally agreed upon a set of basic impulse insulation levels utilizing as steps the preferred voltage classification adopted by NELA.[3] This series of basis impulse insulation levels adopted by the joint committee in January 1937 is presented in table I.

It will be noticed that the table gives the basic impulse levels for each "maximum rated voltage classification." In the lower range of voltages, this classification differs slightly from the preferred voltage ratings previously adopted by NEMA in the publication referred to above, but the steps given in table I are considered advisable in the light of the fact that present-day transformers in that range are specified in terms of those voltages.

It will be further noted that a fundamental and very important change has been made in this table, in that basic impulse insulation level is definitely expressed in terms of voltage. This voltage is the crest voltage of a $1^1/_2 \times 40$ positive wave which will just cause flashover on the tail of the wave when impressed on the so-called standard rod gap having $^1/_2$-inch square-cut electrodes. The gap spacings corresponding to these voltage values are given in the third column. These rod gap spacings are given for reference only, the basic level being crest kilovolts in column 2.

## Future Work

The first step in the co-ordination of insulation has therefore been finished and the second step, *viz.*, "Specification of insulation strengths of all classes of equipment in the established insulation levels," is now ready to be undertaken. This work has actually been begun since a subcommittee of the joint committee has been appointed and is working on this part of the program.

Now that the above insulation levels have been agreed upon, it is expected that more rapid progress will be made in carrying on the work still to be done. As the work progresses, it is planned to officially release periodically to the engineering field the findings and recommendations of the joint EEI-NEMA committee on system insulation co-ordination.

## References


1. FLASHOVER VOLTAGES OF INSULATORS AND GAPS, committee report, AIEE TRANSACTIONS, 1934, page 882.

2. REPORT ON FLASHOVER CHARACTERISTICS OF ROD GAPS AND INSULATORS, interlaboratory group of EEI-NEMA. ELECTRICAL ENGINEERING, volume 56, June 1937, pages 712–14.

3. NEMA-NELA PREFERRED VOLTAGE RATINGS FOR A-C SYSTEMS AND EQUIPMENT, NELA Publication No. 043, page 12.


# Flashover Characteristics of Rod Gaps and Insulators


**A Report by the Subcommittee* on Correlation of Laboratory Data of EEI-NEMA Joint Committee on Insulation Co-ordination****


THIS REPORT has been written to present the agreed upon impulse and 60-cycle flashover values for rod gaps and suspension line insulators, together with a method of making correction for variation in humidity. The laboratory work and correlation upon which these data are based was done by the subcommittee on correlation of laboratory data* of the joint EEI-NEMA committee on insulation co-ordination. The joint committee authorized the publication in ELECTRICAL ENGINEERING of this work through a paper sponsored by the AIEE subcommittee on lightning and insulators. This makes the information more generally available to the the industry for use in connection with the general problem of insulation co-ordination.

## General

With the advent of impulse testing, it was immediately apparent that the flashover values given out by various laboratories for the same test piece were different. In an effort to learn the cause of this, 2 things were done; a string of suspension insulators was circulated to the Locke, Ohio Brass, and General Electric laboratories; and identical bushings were tested in the Westinghouse and General Electric laboratories. These moves, while of some benefit, did not lead to any lasting results. Then the laboratories of Westinghouse and General Electric, between whom the widest divergence in results existed, began to interchange information on testing procedure. Soon Ohio Brass joined the group, then Locke, and finally Allis-Chalmers. For a while the group was known as the "laboratory group" and later as the "EEI-NEMA subcommittee on correlation of laboratory data."

No effort will be made in reporting the work of this committee to include any supporting data—only the final results will be given and with a minimum of explanatory remarks.


A paper recommended for publication by the AIEE committees on power transmission and distribution, electrical machinery, and protective devices. Manuscript submitted February 26, 1937; released for publication April 20, 1937.



* Personnel of Edison Electric Institute-National Electrical Manufacturers Association subcommittee on correlation of laboratory data: C. A. Powel, *chairman;* J. B. Clem, *secretary;* P. H. McAuley; H. A. Frey; J. T. Lusignan; L. H. Hill; C. M. Foust; and K. B. McEachron.

** Prepared by J. E. Clem.

## Test Conditions and Method of Analysis

FLASHOVER TESTS

Before any effort was made to agree upon flashover values for common use, the committee laid down the requirement that the test points from which the curves were obtained in any of the participating laboratories should be within plus or minus 5 per cent of the average curve of that particular laboratory. The requirement was also made that the curves of all the laboratories be within a spread of less than 5 per cent. These requirements covered both impulse and 60-cycle flashover tests.

On this basis it is reasonable to expect that the individual points in any laboratory may have an extreme variation from the average curve of plus or minus 8 per cent. Consequently, when the curves based upon the average results of all the laboratories are used for determining flashover values the tolerance of points detained in any specific laboratory from the general average curves should be plus or minus 8 per cent.

During the course of the work of the subcommittee, each laboratory developed its own type of equipment and methods for producing and measuring impulse voltages. The study of the technique of impulse testing was taken up a few years ago by a subcommittee of the AIEE instruments and measurements committee and the technique has since then become more and more standardized. The laboratory group had for its major problem the study of the factors which cause divergence in results among the various laboratories rather than a study of the details which would lead to extreme accuracy. This latter topic is more properly the work of the AIEE instruments and measurements committee.

Flashover values were obtained on both the 1x5- and 1.5x40-microsecond waves. These 2 waves are among those proposed as standard by the AIEE subcommittee on lightning and insulators. For the work on this subcommittee the first number in the wave designation was taken as indicating the time in microseconds from the virtual time zero to actual crest voltage, and the second number as indicating the time from the virtual time zero to the point on the tail of the wave where the voltage is half of the crest value. The flashover data recorded is the crest value of the minimum impulse flashover voltage (full wave) and is given for both negative and positive polarity waves.

The virtual time zero is the point of intersection with the zero voltage deflection line of a line drawn through

### Table I. Impulse Voltage Flashover—Suspension Insulators, 10-Inch Diameter, $5^3/_4$-Inch Spacing

Barometer, 30 Inches; Temperature 77 Degrees Fahrenheit; Humidity 0.6085-Inch Vapor Pressure
Data From Allis-Chalmers, General Electric, Locke, Ohio Brass, and Westinghouse Laboratories Averaged

| Number of Units | Minimum Impulse Flashover Voltage (Kilovolts) | | | |
|---|---|---|---|---|
| | 1x5 Microsecond Wave | | 1.5x40 Microsecond Wave | |
| | Positive | Negative | Positive | Negative |
| 1 | 155 | 155 | 150 | 150 |
| 2 | 285 | 295 | 255 | 255 |
| 3 | 395 | 410 | 355 | 345 |
| 4 | 500 | 520 | 440 | 415 |
| 5 | 610 | 630 | 525 | 495 |
| 6 | 715 | 750 | 610 | 585 |
| 7 | 820 | 860 | 695 | 670 |
| 8 | 930 | 975 | 780 | 760 |
| 9 | 1,040 | 1,090 | 860 | 845 |
| 10 | 1,145 | 1,205 | 945 | 930 |
| 11 | 1,250 | 1,320 | 1,025 | 1,015 |
| 12 | 1,355 | 1,430 | 1,105 | 1,105 |
| 13 | 1,460 | | 1,185 | 1,190 |
| 14 | 1,565 | | 1,265 | 1,275 |
| 15 | 1,670 | | 1,345 | 1,360 |
| 16 | 1,775 | | 1,425 | 1,445 |
| 17 | 1,880 | | 1,505 | 1,530 |
| 18 | 1,985 | | 1,585 | 1,615 |
| 19 | 2,090 | | 1,665 | 1,700 |
| 20 | 2,200 | | 1,745 | 1,785 |

**Tolerances**

These values represent average results of tests on suspension line insulators of different design and manufacture made in different laboratories. When tests are made in any particular laboratory upon an insulator unit or assembly of specific design and manufacture, the flashover should be within plus or minus 8 per cent of the value given in the tabulation.

In accordance with AIEE Standards No. 41, the comparison should be made on the basis of the average flashover obtained from tests on 3 separate insulator units or assemblies.

NOTE: Negative wave flashovers are inherently more erratic than positive wave flashovers resulting in a greater chance of the tolerances being exceeded occasionally.

### Table II. Impulse Voltage Flashover—Rod Gap

Barometer, 30 Inches; Temperature, 77 Degrees Fahrenheit; Humidity, 0.6085-Inch Vapor Pressure
Data From Allis-Chalmers, General Electric, Locke, Ohio Brass, and Westinghouse Laboratories Averaged

| Gap Spacing (Inches) | Minimum Impulse Flashover Voltage in Kilovolts | | | |
|---|---|---|---|---|
| | 1x5 Microsecond Wave | | 1.5x40 Microsecond Wave | |
| | Positive | Negative | Positive | Negative |
| 0.5 | 22 | 23 | 22 | 23 |
| 0.75 | 30 | | 30 | |
| 1.0 | 38 | 38 | 38 | 38 |
| 1.5 | 51 | 51 | 51 | 51 |
| 2 | 60 | 62 | 60 | 62 |
| 3 | 76 | 83 | 75 | 82 |
| 4 | 97 | 103 | 91–95* | 102 |
| 5 | 120 | 124 | 106–114 | 123 |
| 6 | 143 | 146 | 128–141 | 143 |
| 7 | | 167 | 141–155 | 163 |
| 8 | 187 | 188 | 159–166 | 183 |
| 9 | | 209 | 175–178 | 203 |
| 10 | 233 | 231 | 190 | 224 |
| 12 | | 273 | | 259–271 |
| 14 | | 315 | | 293–318 |
| 15 | 340 | 335 | 275 | 309–342 |
| 16 | | 360 | | 323–359 |
| 18 | | 400 | | 360–386 |
| 20 | 440 | 445 | 350 | 395–415 |
| 25 | | 550 | | 490 |
| 30 | 640 | 660 | 505 | 575 |
| 40 | 835 | 875 | 650 | 740 |
| 50 | 1,035 | 1,085 | 800 | 910 |
| 60 | 1,230 | 1,300 | 945 | 1,070 |
| 70 | 1,425 | 1,515 | 1,095 | 1,235 |
| 80 | 1,620 | | 1,240 | 1,405 |
| 90 | 1,815 | | 1,385 | 1,570 |
| 100 | 2,010 | | 1,530 | |

* Dual values are due to unstable conditions the cause not being known.

**Tolerances**

These values represent average results of tests made in different laboratories. When tests are made in any particular laboratory using the rod gap as a basis of comparison the flashover voltage shall be taken from the above tabulation and shall be considered as correct within plus or minus 8 per cent.

NOTE: Negative wave flashovers are inherently more erratic than positive wave flashovers resulting in a greater chance of the tolerances being exceeded occasionally.

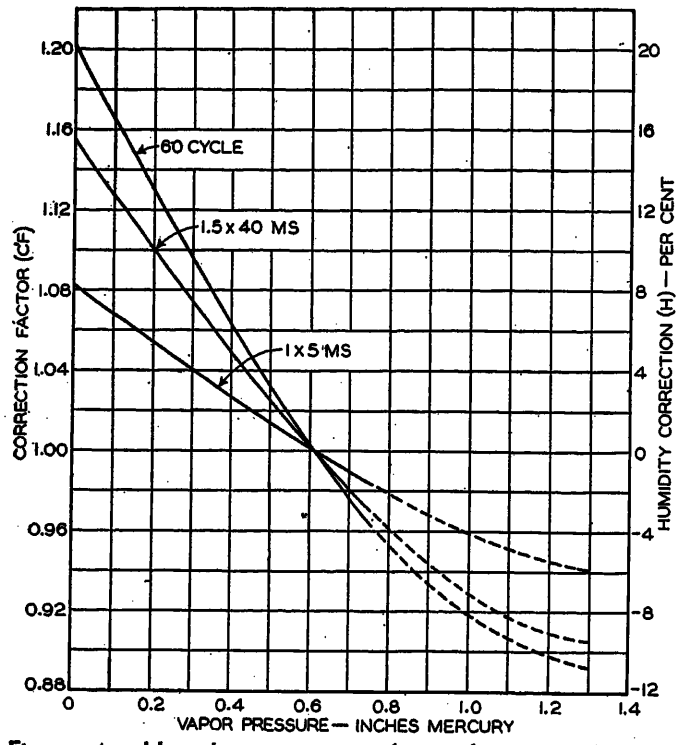



**Figure 1. Humidity correction factor for 60-cycle and positive-wave impulse flashover of rod gap and suspension line insulators**

For humidities 0.75 inch and above the correction is less reliable on account of the erratic data from which the correction was determined

Curve values apply to flashover voltages above 141-kv crest. For lower flashover voltages reduce H in proportion H′ = H kv/140

points on the front of the wave at 10 per cent and 90 per cent of the crest voltage deflection.

All 60-cycle tests were made in accordance with the rules of the AIEE.

Voltage measurements were made in some cases by means of sphere gaps and in other cases by means of the cathode-ray oscillograph. The flashover values given are all based on the revised sphere gap calibrations given in the report of the AIEE subcommittee of the instruments and measurements committee, and published on page 783 of the July 1936 issue of ELECTRICAL ENGINEERING.

## Humidity Effects

Data on the effect of variations of humidity on the flashover have been analyzed and correction factors developed. The flashover data for each insulator assembly and gap spacing were plotted against the recorded humidity and the flashover voltage determined for the standard vapor pressure. This reference value was then used as the base for determining individual correction factors for the test points. The curves of correction factors thus obtained for various insulator assemblies and gap spacings were combined and the most probable average curve determined. The accuracy of the data did not support any differentiation between the correction factor for rod gaps and insulators at the present time.

It should be noted that there is a wide variation of the points in some cases, especially for the higher values of humidity. Accordingly, it is highly possible that some inconsistencies may be encountered when flashover tests are made at high humidities.

## Results

### FLASHOVER DATA

The average flashover voltages agreed upon for insulators and rod gaps are given in tables I, II, and III. In the opinion of the committee these values are sufficiently accurate to warrant their use for co-ordination purpose and are recommended for use until such time as sufficient additional data are obtained to confirm or modify them.

### HUMIDITY CORRECTION

The curves showing the correction factors to be used for variation in humidity are shown in figure 1. The correction is given in 2 forms: As a "correction factor" by which the observed flashover is to be multiplied; and as a "humidity correction" which is the percentage to be added to or subtracted from the observed flashover.

**Table III. 60-Cycle Voltage Flashover—Suspension Insulators, 10-Inch Diameter, $5^3/_4$-Inch Spacing, and Rod Gaps**

Barometer, 30 Inches; Temperature, 77 Degrees Fahrenheit; Humidity, 0.6085-Inch Vapor Pressure

Data From Allis-Chalmers, General Electric, Locke, Ohio Brass, and Westinghouse Laboratories Averaged

| Suspension Insulators | | Rod Gaps | |
|---|---|---|---|
| Number of Units | Flashover Voltage (Effective Kilovolts) | Gap Spacing (Inches) | Flashover Voltage (Effective Kilovolts) |
| 1 | 80 | 0.5 | 11.5 |
| 2 | 155 | 0.75 | 17.5 |
| 3 | 215 | 1 | 22.5 |
| 4 | 270 | 1.5 | 32 |
| 5 | 325 | 2 | 40 |
| 6 | 380 | 3 | 50 |
| 7 | 435 | 4 | 58 |
| 8 | 485 | 5 | 66 |
| 9 | 540 | 6 | 74 |
| 10 | 590 | 8 | 89 |
| 11 | 640 | 10 | 105 |
| 12 | 690 | 15 | 150 |
| 13 | 735 | 20 | 200 |
| 14 | 785 | 30 | 295 |
| 15 | 830 | 40 | 385 |
| 16 | 875 | 50 | 480 |
| 17 | 920 | 60 | 575 |
| 18 | 965 | 70 | 665 |
| | | 80 | 755 |
| | | 90 | 835 |

**Tolerances**

SUSPENSION INSULATORS

These values represent average results of tests on suspension line insulators of different design and manufacture made in different laboratories. When tests are made in any particular laboratory upon an insulator unit or assembly of specific design or manufacture, the flashover should be within plus or minus 8 per cent of the value given in the tabulation. In accordance with AIEE Standards No. 41, the comparison should be made on the basis of the average flashover obtained from tests on 3 separate insulator units or assemblies.

ROD GAPS

These values represent the result of tests on rod gaps made in different laboratories. When tests are made in any particular laboratory using the rod gap as a basis of comparison, the flashover voltage shall be taken from the above tabulation and shall be considered as correct within plus or minus 8 per cent.

It should be noted that the sphere gap is the standard for voltage measurements and that the rod gap is to be used only when approximate results will be satisfactory.

# Insulation Co-ordination

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## I. Introduction

THIS SUBJECT of insulation co-ordination has been an active one for the past 10 years or so. It was initially presented and discussed in 1928.[1] Since then, the subject was taken up by practically all groups interested in the transmission problem including designers and operators of electric systems. As the study of the problem gathered headway, the need for further investigation work became quickly apparent. A great number of individual researches were thus started. All of them although closely related were not entirely co-ordinated. Each of them, however, in its own way, arrived at a solution of all, or of a part of the problem of co-ordinating the insulation strength of the electric system.

Such investigation and research work included[2–15] field investigation of lightning on transmission lines, determination of system overvoltages, experience in actual practice, collection and analysis of operating records of apparatus and system performance. In the laboratory, a great deal of work was also done in determining the insulation strength of various pieces of apparatus and equipment. Included in this work was a determination of transformer safe impulse strength, flashover characteristics of insulators, gaps, and some work, still incomplete, on impulse strength of switch insulators and bushings.

## II. Objective of Insulation Co-ordination

All of this work, the scope and inter-relationship of which is daily becoming closer, has as its goal, insulation co-ordination.

Insulation co-ordination has 2 main objectives: (1) protection of service and equipment, and (2) economy. Strictly speaking, however, these 2 objectives merge into one—economy. This is true of every problem in protection. In the case of insulation co-ordination, what is aimed at is an electric system so insulated in its various parts and such an arrangement in the insulation strengths of the various parts as regards one another that under all conditions the grade of service aimed at is obtained at a minimum cost. In the item of cost, there must be included, of necessity, fixed charges on first cost of equipment, cost of damages, cost of outages, cost of spare equipment, and cost or value of decrement or increment in good will.

## III. More Detailed Statement of the Co-ordination Problem

As stated above, insulation co-ordination from a very broad standpoint becomes an economic problem. That, however, is not adequate for a thorough analysis of the problem. For in any such analysis it must be recognized that what one is generally confronted with in a physical plane is insulation strength or insulation failure, both in the right and in the wrong places.

Now insulation strength raises the question of overvoltages. These overvoltages may be divided into 3 groups:

First: Those due to 60-cycle or normal frequency
Second: Those due to switching surges
Third: Those due to lightning

In the past, 60-cycle overvoltages have, in general, not been the subject of any grave concern and we can view the standard overvoltage test of equipment as a safe criterion to use in selecting insulation on a normal frequency basis alone. However, the fact that apparatus designed, tested, and used on the standard double-voltage test has given satisfactory service should not blind us to the possibility that a less severe 60-cycle test would have given equally satisfactory results. If this should prove to be true, it is obvious that insulation can be reduced from the past standards even on a 60-cycle basis with considerable economic gain and without any loss of reliability of service.

The second type of voltage to be protected against is the switching surge. Here, our basic knowledge on switching surges, both as regards the characteristics of such surges and the ability of insulation to withstand them,[15,16] needs enlargement. However, troubles from this source have not been frequent. But switching surges can by no means be overlooked in setting up insulation levels and carrying through any plan of co-ordination.

The third type of overvoltage is the one which has been given most consideration during the past decade, namely, lightning voltages, and it is around this phase that insulation co-ordination problem now largely centers.

The insulation used to furnish protection against these overvoltages must of necessity be of the same material as that used to supply the insulation against the *normal* 60-cycle voltages, that is, it must consist of additional oil, fiber, air, or porcelain. The only problem is how far to go if that method of avoiding trouble is chosen. The general principle of overinsulation, that is, adding insulation above past accepted standards has not proved very successful. Where it has been resorted to in the past and has not resulted in the mere transferring of the

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1. For all numbered references see list at end of paper.

trouble to some other point in the system, it has invariably been at heavy economic expense. The alternative to additional insulation is a group of protective devices such as gaps, lightning arresters, etc. It is unfortunate that, although a great deal of practice has concentrated in that line, altogether too little has been known about most such devices as lightning arresters and gaps. Some of the more recent work on insulation co-ordination has clearly brought this out.

In any event, regardless of whether adequate insulation alone or overinsulation alone is used, or protective devices alone, or a combination of these is employed, it is apparent, as was initially[1] clearly shown that insulation levels must be set up for all the different groups of apparatus, with proper grading between all the links in every insulation chain at any particular level, and satisfactory margin of safety supplied at each of the levels.

## IV. Information Needed

In setting up such insulation levels, there are several essential requirements: First, the expected magnitude and characteristics of overvoltages must be known with some degree of certainty; this applies not only to lightning voltages but also to 60-cycle and switching surge voltages. Coupled with this, information on the safe insulation strength of apparatus must be available. Finally, the voltage protective characteristics of the protective devices used under operating conditions must be known with a reasonable degree of certainty.

In this connection an important factor which has received very little attention is the question of margins at the various insulation levels which are finally adopted between equipment and protective device. For example, if a transformer will withstand, safely, an impulse voltage of, say, 600 kv, the question must be asked as to how much margin should be allowed between the transformer and the protective device to insure that the protective device will prevent excessive voltage on the transformer. The same consideration must obviously be given to other pieces of equipment on a system, such as bushings, bus insulators, instrument transformers, etc. The correctness of such margins as adopted will eventually have to be tried out and proved under operating conditions.

As information of this kind is obtained and correlated, it will eventually make possible a scientifically sound coordinated system of insulation levels for the various operating voltages with proper margins or steps for every insulation level between the different component parts of the transmission system, such, for example, as between the transformer and the switch insulators, between the switch insulators and the bus, and between other similar links in the insulation chain.

## V. Progress to Date

In reviewing some of the work which has been done to date, the following points are of interest as indicative of the progress made in insulation co-ordination: First, 60-cycle strengths are pretty well known for transformers, bushings, suspension insulators, pedestal insulators, gaps, etc. Second, some work has been done in obtaining magnitude of switching surges and data on the ability of insulation to withstand them. Third, and this is probably the most important, impulse strength of many of the most important items of high-voltage equipment has been determined with some degree of certainty. Thus transformers are now being commercially impulse-tested; information is available on impulse strength of transformer bushings; the characteristics of the lightning arrester which, in the past, was a semi-mysterious protecting device, are much better understood and the protective ability of the arrester fairly well known under an ever-increasing number of operating conditions. Also, a great deal of work has been done in determining the impulse characteristics of gaps under surge conditions. In this connection, it is pertinent to point out that the recognized impulse laboratories today have so improved and perfected their technique that they are now almost universally operating on a basis where comparable data can be obtained.

While much data have been obtained, and are being obtained, on impulse characteristics of insulation, the main problem of utilizing these data effectively in insulation co-ordination has not progressed as rapidly. This however, is natural in view of the fact that a practical and workable system of co-ordination must await the time when information is available on the insulation strengths of all the apparatus concerned and accurate knowledge of the impulse characteristics of the protective devices employed. Fortunately, however, a great deal of the fundamental data are now available and insulation co-ordination is beginning to take form. Only recently, as reported in the companion paper, basic insulation levels for the preferred voltage ratings have been adopted. This will undoubtedly serve as a stimulus to the more active pursuit of the work needed to bring about co-ordination. But it must not be forgotten that the entire problem of correlating the laboratory test data, the field data, and various ideas and theories of electrical system design into a practical, workable system of insulation and protective levels still remains to be done.

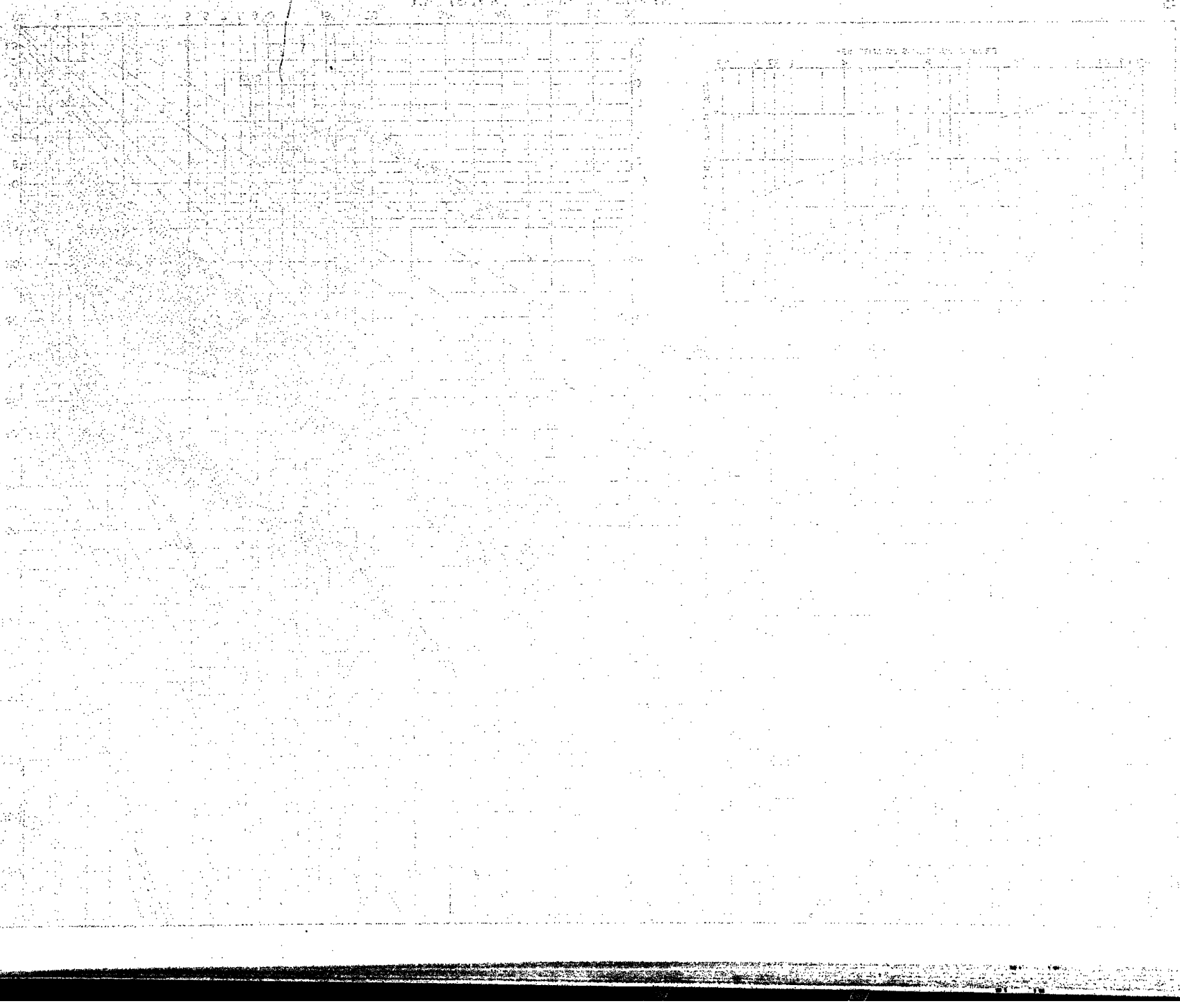
### Insulation Co-ordination Chart

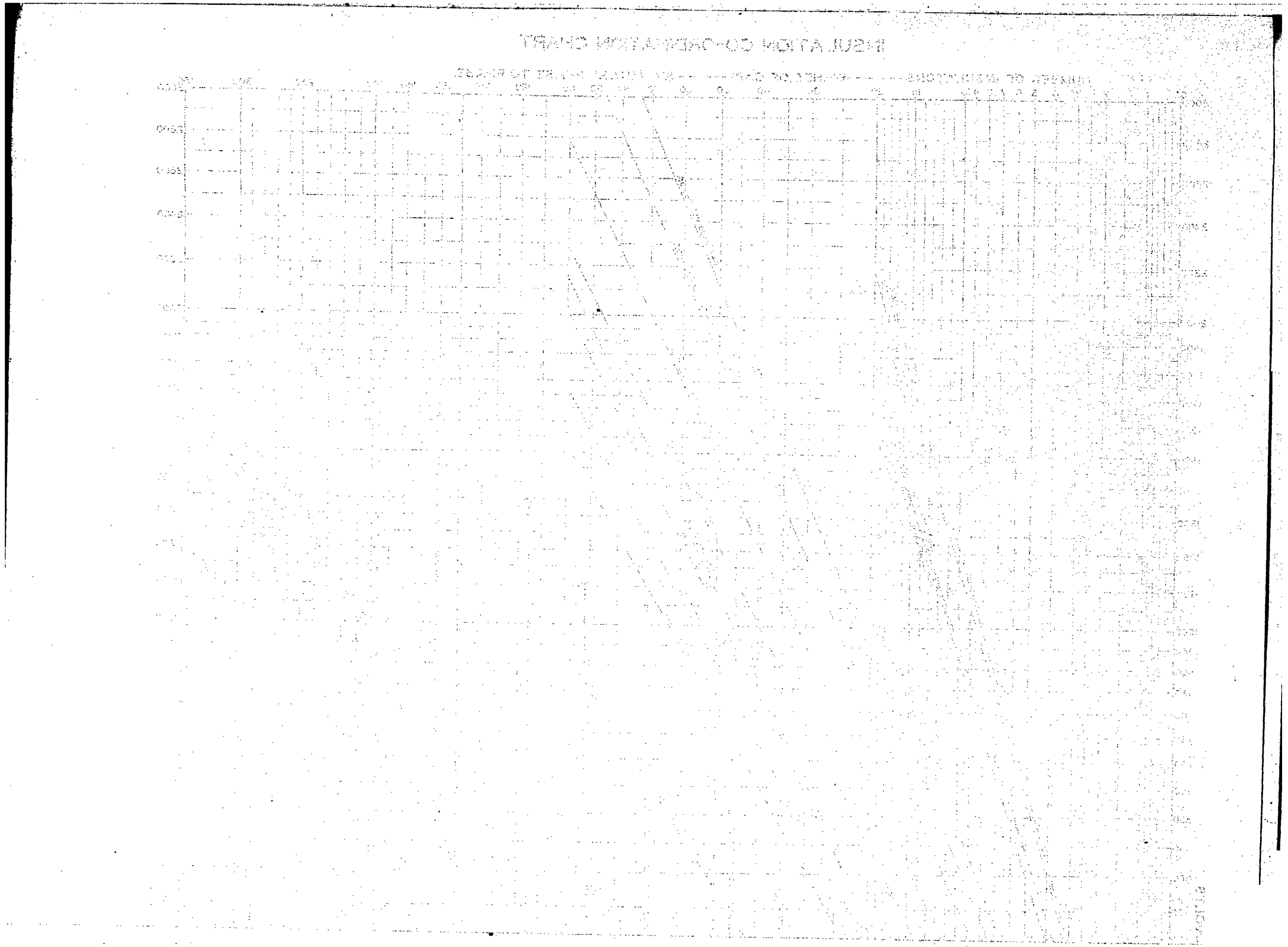
So many different groups have been working on this subject each within its own field that it is believed that it will be helpful to present a rather complete picture of the insulation strength of major equipment and protection available. With this thought in mind, the authors have collected and correlated a great deal of the available data on the subject and have prepared it in graph form. This is shown in the insulation co-ordination chart, figure 1. It is presented as an accumulation of data bearing on the insulation problem which in their own work the authors have found useful time and again to get and keep an over-all picture of the insulation problem in all voltage classes from 1 kv to one step beyond the present range of operating voltages, namely, 347 kv.

On this chart there have been plotted, in the upper left-

# INSULATION CO-ORDINATION CHART

NUMBER OF INSULATORS--------INCHES OF GAP-------- KV. (R.M.S.) PHASE TO PHASE.





hand corner, the impulse characteristics, both positive and negative, and 60-cycle flashover values of suspension insulators from 1 to 20. Flashover characteristics of the rod gap, which has been extensively used during the past number of years as a measuring and test device for co-ordinating the work of the laboratories, are shown immediately below the insulator data. In the lower right-hand corner is a graphic presentation of the magnitude of switching surges as actually observed from field studies under operating conditions. The major group of lines running diagonally through the center of the chart represents the insulation characteristics of various pieces of equipment, and lightning arresters and also multiples of system line to neutral voltages. For easy identification, the preferred voltage class of insulation is shown by vertical lines located at the proper spacing as determined by the phase-to-phase system voltage scale at the bottom of the chart.

By the use of the chart it is possible to get a rather complete over-all picture of the insulation situation in any voltage class by merely following a vertical line marked with the preferred voltage class: For example, reading values from the chart, on a 138-kv system the impulse test on transformers would be 680 kv, the impulse flashover of the bushing 720 kv. A 100 per cent arrester would have an *IR* drop, at 5,000 amperes through the arrester of approximately 600 kv, leaving a margin between the arrester and the transformer of approximately 90 kv. To determine the test gap which would be used in testing the 138-kv transformer according to AIEE transformer standards, merely trace horizontally from the intersection of the 138-kv vertical line with the transformer test (diagonal line) to the gap curve which shows a $42^1/_2$-inch gap. Such a gap, however (tracing vertically upward) would have a flashover of approximately 770 kv with a negative $1^1/_2$x40 wave, 925 kv with a 1x5 negative wave, 1,290 kv if the impulse rose at the rate of 500 kv per microsecond positive, and 1,600 kv if the impulse rose at the rate of 1,000 kv per microsecond. It is obvious that such a gap furnishes little protection to the transformer under impulse if it is assumed that the test value of the transformer is approximately its safe strength.

Another interesting point can be determined from this chart. Again start at the intersection of the 138-kv preferred voltage class line with the transformer test curve and go horizontally to the gap curve for 1,000 kv per microsecond. It is observed that a gap set at $16^1/_2$ inches would flash over at 690 kv, that is, at the same value at which the transformer would be tested. Following down to the 60-cycle gap flashover curve, it is seen that such a $16^1/_2$-inch gap would flash over at 165 kv and again going horizontally from this point to the 138-kv preferred voltage class line it appears that such a voltage would be approximately 2.1 times normal line to neutral voltage. Thus a gap which will limit a steep wave front positive surge in order of 1,000 kv per microsecond to the tested transformer strength would have such a low 60-cycle flashover that it would undoubtedly result in increased service outages under overswitching surge conditions.*

In applying lightning arresters for protection there should, of course, be some margin between the terminal voltage of the arrester under impulse conditions and the safe strength of the apparatus which it is to protect. This margin has been shown near the bottom of the chart for the 100 per cent arrester, as a full line curve. It will be noted that this margin varies from approximately 35 kv in the 2,500-volt class to 120 kv at an operating voltage of 230 kv. This gives an idea of the general range of margins which have been possible in recent years. A curve slightly higher up is also drawn showing the impulse characteristics of an 80 per cent lightning arrester. The so-called 80 per cent arrester is taken as one having 80 per cent of the active material of a 100 per cent arrester and in general is considered suitable for use only on a grounded neutral system of normal rating or on an isolated neutral system rated 80 per cent of the conventional 100 per cent arrester voltage.

Reverting to the example of the 138-kv insulation cited above, it will be noted that a 100 per cent arrester would not supply any protection for a transformer in the 115-kv class. However, if an 80 per cent arrester were used there is a margin between the arrester and 115-kv class of transformer insulation of approximately 110 kv. This 80 per cent arrester, however, has little margin for a standard 92-kv transformer, the transformer test and lightning arrester *IR* drop being about equal. Thus, it is apparent that if it is deemed safe to use an 80 per cent arrester on a 132-kv system (and this is entirely feasible where the 60-cycle voltage is limited by system grounding, etc.) it is possible, from the impulse protection point of view, to use insulation in the 115-kv class. If it is possible to cut the arrester to below 80 per cent it may be possible to use a transformer even in the 92-kv class without decreasing the margin of safety appreciably below that used in the past with standard 100 per cent arresters. Cases of this kind where reduced insulation has been used on our own system with a substantial economic saving will be cited below. In every case careful analysis shows that ample margins of insulation remained between the transformer and arrester levels.

It is believed that this chart will be found useful in analyzing in a general way with considerable accuracy many problems of the above character.

It should be pointed out that some of the data in the above chart are subject to further check and confirmation, such, for example, as impulse flashover of switch insulators and the *IR* drop characteristics of modern lightning arresters under present-day conditions. All data, however, have been collected from sources believed to be reliable and are the best available at the present time.

## VI. Present Insulation Practice of American Gas and Electric Company

In the work on their own system the authors have been using the principles of co-ordination over the past 10 years. Initially the basic idea sought was to have the various

* This, however, does not take into account the possibilities of ultrahigh-speed breaker reclosure.

component parts of the transmission system properly insulated with regard to each other and all properly insulated for the operating voltage and conditions encountered. But as they progressed in their work and in thinking out the problem, the ideas of co-ordination began to offer more and more means of reducing intelligently the cost of transmission equipment. Some 5 years ago, therefore, the authors first went thoroughly into the insulation problem presented by a 132-kv transformer installation and, as a result, placed in service a reduced insulation transformer, that is, one with insulation lower than normal for the system rating. As a matter of fact, they actually used 115-kv insulation on a grounded-neutral 132-kv system. Several very similar installations involving large 132-kv transformer banks have been placed in service on their system during the past year and others are being added. A comparison of the insulation co-

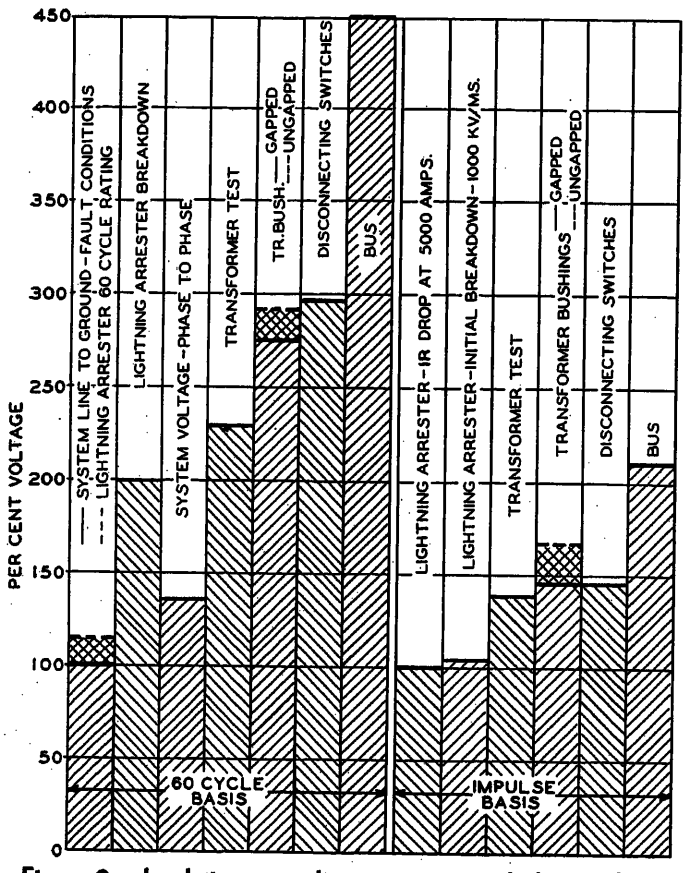



**Figure 2. Insulation co-ordination on grounded-neutral 132-kv system of American Gas & Electric Company (installation in 1936)**

ordination of such a transformer with some of the other links in the insulation chain in the station is shown in figure 2. It will be noted that on an impulse basis, the transformer tested strength is approximately 40 per cent above the lightning arrester *IR* drop. It will also be noted that the switch insulators have an impulse strength some 5 per cent above the transformer strength and the bus some 50 per cent above the switches. The transformer bushings were gapped, according to present transformer practice, at 5 per cent above the transformer test. In this connection, however, it may be well to point out that the practice of gapping transformer bushings in service to the 5 per cent margin above the transformer test recommended by the transformer subcommittee has been recently discontinued by the authors.

There are 3 reasons for doing this: First, the impulse characteristics of the transformer bushing, with gap spacings recommended, does not indicate that protection will be afforded the transformer on steep wave fronts; second, if the gap on the bushing flashes over there is almost sure to be sufficient damage to the bushing so that extensive repairs have to be made, in many cases, not only to the bushing itself but to other bushings. Two cases of this kind have been experienced in the last year on gapped bushings. Third, transformer bushings in the lower voltage class, if gapped, have such small mechanical clearance that these gapped bushings become hazards in a major substation instead of safety devices.

It will be noted also in figure 2 that the bus insulators, both impulse and 60-cycle, are placed well above any other equipment in the station. This policy the authors have consistently followed on the basis that any damage to the bus structure may involve service interruptions sometimes that will affect a larger area of service than damage to any other piece of equipment of embarrassing durations.

## Selecting Transformer Insulation

In selecting reduced insulation for large-size high-voltage transformers, the procedure followed by the authors within the past year has been as follows:

1. The overvoltages on a system, due to faults or other effects, such as hydro, are calculated and on this basis a suitable arrester is selected adequate to stand up in service under the worst 60-cycle voltage conditions.
2. The impulse characteristics of this arrester are determined.
3. The transformer impulse strength is placed at a margin considered safe above the lightning arrester voltage and the class of insulation into which that transformer falls is then selected.

In other words, the start is with the lightning arrester as a protective level; the necessary margin between the arrester and the transformer is then set, and then the transformer insulation level is picked. As mentioned above, this has resulted on the authors' system in the selection during the past year of several large-sized transformers with 115-kv class insulation for 138-kv class of service. There has even been considered in one case, so far, and it is believed feasible, to use so-called 92-kv class insulation for 138-kv service where 60-cycle voltage conditions are favorable.

This plan of so-called reduced insulation not only results in economic savings in the initial cost of the transformer, but also gives added protection to other equipment in the station by holding the impulse level low with a low-rated arrester. In view of the fact that the authors of late have gone extensively into the practice of locating lightning arresters directly on the transformer and are

gradually removing them from the lines at the line entrance, greater protection will be supplied the entire station by the reduced-rated arrester than would be possible with the so-called 100 per cent arrester. Thus, the initial reduction of transformer insulation to a lower voltage class has resulted not only in a more economical transformer but greater protection for the entire station concerned.

## Bus and Switching Insulation Practice

In tables I and II are given 60-cycle and impulse voltage characteristics of the present standards which are being used for switches and insulators in station design on the authors' system. A comparison is made in these tables with values recommended by National Electrical Manufacturers Association. It will be noted that the authors' practice calls for flashover values, both 60-cycle and impulse, except for post-type insulators in the 132-kv class, which are higher than NEMA recommendations. While it may be possible to use insulation with lower flashover than the authors' indicated practice, it should be kept in mind that bus insulators are only a small portion of the cost of the total station equipment, and the steps in insulation from one insulator to another are so large that it is not usually feasible to hew closely to a given minimum insulation value. Further, the bus is one part of the system that it is well to protect against flashover under any condition, leaving the more finely graded steps of insulation to be worked out for the other links of equipment and apparatus in the station.

It will be noted that there is one outstanding case where the authors' insulation practice is below a NEMA recommendation, and that is for post-type insulators in the 132-kv class where the impulse strength is about 15 per cent below NEMA recommendation. It should be pointed out, however, that in practically all of the cases where these are used there exists lightning arrester protection designed to hold impulse voltages down below the bus insulator level. It is interesting to note, in this connection, that this lower insulation which has been used in some 35 stations on their 132-kv system, has according to their records, some of which go back 20 years, never resulted in a major case of trouble.

## VII. Work Still to Be Done

As pointed out in the early part of the paper, a great deal of work has been done in obtaining fundamental data on the characteristics of insulated equipment and protective devices. The work of correlating these data and setting up workable insulation systems has been in progress for the past few years. Further and fairly rapid progress may be expected in the next 2 years. But it needs to be stressed that whatever co-ordination system may be set up, it is bound to be, in part at least, based on theory, and to that extent it must receive its final test in field experience.

The authors have outlined above in a rather general way, some of the practices which they have adopted as a result of their work on the problem and on which we are now getting their field trials. There have also been outlined some of the methods which they have employed in arriving at the various insulation steps which they have employed in their more recent design work, and it is hoped that some of the work described above, the basis on which it was arrived, and the data used, may be useful to others who are now working on this problem. The authors look forward with confidence to the not too distant future when a group of insulation levels will have been set up, with all links of the insulation chain specified in magnitude, and with workable margins between links properly applied.

There is one final point which needs to be stressed in connection with this work of insulation co-ordination and that relates to equipment now in service which was designed and built with very little, if any, consideration given to its impulse strength. A great deal of such equipment is now in service and will of necessity have to remain so for many years to come. The problem of co-ordinating and protecting this insulation is one which will assume considerable importance in the future, particularly when the equipment becomes older. It is believed, however, that as progress is made in the simpler problem of insulation co-ordination on new equipment, the prin-

**Table I. Bus and Switch Insulation Practice—Post Type Insulators**

| Nominal Operating Kilovolts | 60-Cycle Flashover (Kilovolts) A. G. & E. Co. Dry | A. G. & E. Co. Wet | NEMA Dry | NEMA Wet | Impulse 1½x40 Positive* (Kilovolts) A.G. & E. Co. | NEMA |
|---|---|---|---|---|---|---|
| 4 | 85 | 50 | 55 | 35 | 105 | 74 |
| 6.9 | 100 | 70 | 75 | 50 | 145 | 105 |
| 12 | 100 | 70 | 75 | 50 | 145 | 250 |
| 15 | 100 | 70 | 75 | 50 | 145 | 250 |
| 22 | 140 | 100 | 95 | 70 | 210 | 145 |
| 27 | 150 | 115 | 125 | 100 | 240 | 210 |
| 33 | 150 | 115 | 125 | 100 | 240 | 210 |
| 44 | 195 | 145 | 155 | 125 | 300 | 260 |
| 66 | 300 | 235 | 220 | 180 | 500 | 380 |
| 88 | 390 | 290 | 295 | 240† | 610 | 500 |
| 132 | 385 | 285 | 400 | 350 | 620 | 735 |

* Based on some available data and ratio of impulse to 60-cycle values.
† No NEMA rating—value calculated.

**Table II. Bus Insulation Practice—Suspension Insulators**

| Nominal Operating Kilovolts | 60-Cycle Flashover (Kilovolts) A. G. & E. Co. Dry | A. G. & E. Co. Wet | Impulse 1½x40 Positive (Kilovolts) |
|---|---|---|---|
| 4 | 80 | 50 | 125 |
| 6.9 | 135 | 90 | 210 |
| 12 | 135 | 90 | 210 |
| 15 | 135 | 90 | 210 |
| 22 | 195 | 135 | 295 |
| 27 | 235 | 175 | 365 |
| 33 | 235 | 175 | 365 |
| 44 | 280 | 215 | 435 |
| 66 | 330 | 255 | 505 |
| 88 | 420 | 330 | 650 |
| 132 | 550 | 437 | 910 |

ciples and practices arrived at will be helpful in setting up protective measures for older equipment as well.

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## Fire Precautions in Electrical Stations

THE PAPER "Fire Precautions in Major Electrical Stations" by F. C. Winfield (A'22) chief electrical engineer, Merz & McClellan, Newcastle-on-Tyne, England, was presented recently in London before The Institution of Electrical Engineers. In this 10-page paper, which has 5 illustrations, the fact is observed that while electrical duplication or multiplication of equipment is recognized as essential, its complement—true physical segregation of duplicates to secure against the fire or explosion risk—has not received as much attention. However, it is emphasized that the rare occurrence of serious fires, a condition secured by the use of sound plant and good protective gear, justifies a different treatment. It is stated that "the eggs shall not be carried in one basket"; however, the conditions do not require that each "egg" be carried in a separate basket. A single clear division of plant into 2 parts is frequently sufficient. The "unit principle" of electrical arrangements, which means that each major item of equipment is provided with its own separate and distinct control and auxiliary equipment, is favored by the author.

The governing principles in fire considerations may be enumerated in 3 classes:

1. *Provisions which always ought to be made:* (*a*) the use of switchgear and plant of adequate capacity, soundly designed and constructed and provided with suitable automatic protective arrangements; (*b*) the complete electrical and fire sectioning into at least 2 duplicate parts of the switchgear, transformers, cables, etc., supplying an electric system or independent portion of a system; (*c*) minimum arrangements for fire fighting; (*d*) heating of buildings to reduce risks of insulation failures.

2. *Provisions that are easy and inexpensive to make and that reduce the spread of fire or consequential damage within a fire section:* (*a*) sealing of holes in floors or internal parts of any single fire section that has natural structural barriers; (*b*) the elimination of combustible matter not inherent to plant.

3. *Provisions that while not essential are desirable and should be applied where the importance or special conditions of the station justify the expenditure:* (*a*) floor drainage to remove oil quickly; (*b*) permanent and local fire-extinguishing plant either automatic or remote-controlled if the station is permanently attended.

An important factor in any oil-fire fighting arrangement is the dense black smoke which impedes or prohibits access to the seat of the fire. This is a most serious consideration in dealing with fires which occur in the inner regions of large power stations, for example, and for this reason it is strongly recommended that where possible, and except where small-size plant only is in question, all large transformers or switchgear should be mounted in separate buildings or in chambers opening to the outer air and sealed off from the inner side. Where this is not possible, automatic or remote-controlled forms of fire attack should always be employed, to make immediate attack on the fire without actual access being necessary.

A second important matter in all electrical failures is to eliminate the electrical contribution to the fire as rapidly as possible by tripping the switches connected to the affected bus bars and the corresponding remote feeder switches. If a sound basis can be found for doing this automatically so much to the good, but in any case operating instructions ought to provide for immediate action of this type, starting with the section switches, whenever a fire or explosion occurs.

Since prevention is better than cure, routine testing of insulation to find possible sources of failure that might cause fire is desirable. Unfortunately, no form of routine insulation testing has yet been devised which has not important objections. The so-called Doble method of testing, which makes routine field tests of watts loss and power factor with a specially portable apparatus and compares these one against another and all against continuous records of past testing, has shown promising results although there are at present certain physical limitations in its application to metalclad switch equipments.

Despite all precautions, fire cannot be absolutely precluded and the only ultimate safeguard must be a reasonable fire-sectioning of the plant, so that a fire or explosion is limited in its worst effect to a section or group of plant items which can in emergency be done without. Distinct buildings are to be preferred to barrier walls to reduce the possibility of damage by explosions, and it is suggested that one wall of structures have adequate windows or doors secured lightly so that a relief vent will be provided to reduce the force of explosions. Because of the rarity of serious fires, the actual loss sustained in damaged equipment or buildings is not of importance.

# A New High-Speed Cathode-Ray Oscillograph

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## Synopsis

A historical review of advances in the design of high-speed cathode-ray oscillographs and in particular a description of the development, performance, and application of a new type oscillograph is presented in this paper. The new instrument embodies a sealed-glass, high-vacuum, hot-cathode, cathode-ray tube for operation at 15,000 volts.

SINCE its birth in 1897[2] the cathode-ray oscillograph has maintained a position of unchallenged and ever-increasing importance in the realm of problems relating to high-speed electrical phenomena. It owes this distinction to its inherent capability of faithfully recording electrical transients of extremely short duration. Among many other accomplishments the cathode-ray oscillograph has contributed enormously to the progress in the perfection of electrical insulation and to a better understanding of insulation problems in general. For example, the knowledge of the characteristics of electrical stresses produced by lightning disturbances on power transmission and distribution systems has been greatly expanded. As a result of these studies, standardized high-voltage impulse tests are now widely made in the industry's laboratories on electrical equipment and apparatus using artificial lightning of prescribed wave shapes. The modern exact impulse-testing technique of today is quite unthinkable without the cathode-ray oscillograph. Likewise the cathode-ray oscillograph has been indispensable in the studies of recovery voltages during circuit interruption and thus in a large measure responsible for the present state of perfection of the modern circuit breaker.

The evolution of the cathode-ray oscillograph, from its early beginning to the various practical forms which are in use today, has occupied a period of 40 years. It would be impossible here to give a full and detailed account of all the valuable developmental work that has been done. However, a brief survey of the principal steps in the development is made below to serve as a background for the new cathode-ray oscillograph which is described in this paper.

## Historical Review

The earliest cathode-ray oscillograph tube which Braun[2] invented in 1897 consisted of a sealed evacuated glass tube, a "cold" cathode, an anode, a diaphragm with a small hole at its center and a fluorescent screen. The electrons, originating at the cathode, traversed the aperture in the diaphragm and impinged on the fluorescent screen to produce there a luminous spot. Shortly after, a magnetic concentration coil[3] was added by means of which the luminous spot could be focused. At first the electrons forming the cathode-ray beams were deflected magnetically; later, electrostatic deflection plates were added. With early tubes of this kind, at excitation voltages of 30 kv, Zenneck photographed fluorescent screen traces of electrical events of one millisecond duration.[7] During the course of the years the original Braun tube was gradually improved[13] by adding a hot cathode, gas, or electrostatic focusing means, and beam intensity grid controls. Today this type of tube is widely available commercially and is commonly used in low-voltage cathode-ray oscillographs of the repeating-time-axis type for the study of recurring phenomena. In slightly modified form it now also is finding an important place in the field of television.

Because of its recording speed limitations the early Braun tube was found inadequate to satisfy a growing demand for higher and higher recording speeds. This led to a radically new avenue of attack and Dufour in 1914 introduced the photographic plate inside the vacuum to let the electrons impinge directly on the photographic emulsion.[8] He used vacuum pumps to obtain and hold the necessary operating vacuum after insertion of the photographic film. At cathode excitation voltages of 50 or 60 kv Dufour obtained a recording speed of 1,000 kilometers per second. The early Braun tube had a recording speed of perhaps one kilometer per second. Based on his earlier experiments Dufour constructed the first practical cathode-ray oscillograph of the so-called internal-photography type, a description of which he published in 1920.[10] For an excellent history of the cathode-ray oscillograph with a complete bibliography up to 1925 reference is made here to a paper by MacGregor-Morris and Mines.[13]

The successful production of a practical high-speed cathode-ray oscillograph by Dufour[10] stimulated many others to follow his lead. Numerous investigators, among them Dufour himself, Rogowski[19] and Flegler, Gabor,[20] Norrinder,[22] Wood,[12] and Knoll,[29] developed new artifices such as improved methods of focusing by the addition of a second concentrating coil, division of the vacuum chamber into 2 sections having different degrees of vacuum, new shapes of cathodes and anodes, beam traps and improvements in the vacuum system. Modified forms of the Dufour-type high-voltage internal recording instruments for practical use in laboratory and field work

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2. For all numbered references, see list at end of paper.

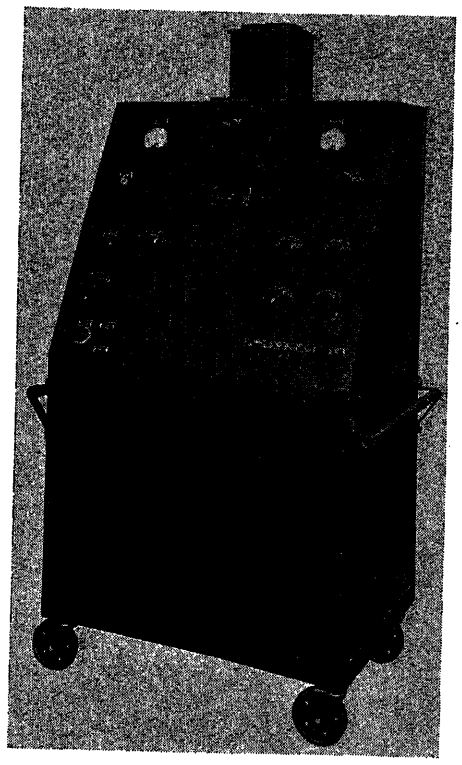


**Figure 1. General Electric cathode-ray oscillograph, type HC-15, front view**

were built in this country by the General Electric Company,[26] by Professor R. H. George,[26] and the Westinghouse Electric & Manufacturing Company.[38] Professor George used a hot cathode and electrostatic beam focusing. As a culmination in the quest for high recording speeds, Rogowski[32] in 1930 succeeded in obtaining the enormous speed of about 60,000 kilometers per second, which is $^1/_5$ the speed of light. Because of the finite velocity of the electrons this writing speed is considered to be the practical limit for the cathode-ray oscillograph. The literature from 1930 to date includes descriptions of several practical high-voltage, internal recording type instruments, some equipped with high-speed rotating film drums especially adapted to switchgear testing work (see bibliography). As a result of highly interesting development work Rogowski and his associates recently have obtained surprisingly high writing speeds with a cold-cathode type instrument at voltages as low as a few thousand volts.[64] This result was due to extremely high beam currents made possible by the use of very narrow discharge tubes having relatively high gas pressures.

During the last few years an increasing number of investigators have been studying the possibilities of obtaining high-speed oscillographic records with the film outside of the vacuum. This came about quite naturally with the growth of the commercial impulse-testing practice and the increased applications of the cathode-ray oscillograph to engineering problems. One of the principal difficulties encountered with inside recording results from the necessity for breaking the vacuum to renew a film. Despite great refinements in vacuum technique[59] the time for obtaining the proper operating vacuum after renewal of a film is not always reliably predictable. Numerous factors contribute to this behaviour. Probably the more prominent ones are unavoidable air leaks which are difficult to locate, the removal of moisture and other impurities from the oscillograph vacuum chamber, and the maintenance of the correct vacuum for best oscillograph performance at a given writing speed.

The earliest method used to obtain oscillograph records outside of the vacuum was to photograph with a camera the luminous trace on the oscillograph fluorescent tube screen. However, because of the recording speed limitations existing at that time, this method was abandoned. The solution for high-speed external recording was sought first with the aid of the Lenard[1] window. This is a very thin vacuum-tight membrane supported internally by a reinforcing grid against the external atmospheric air pressure. By using extremely high tube excitation volt-

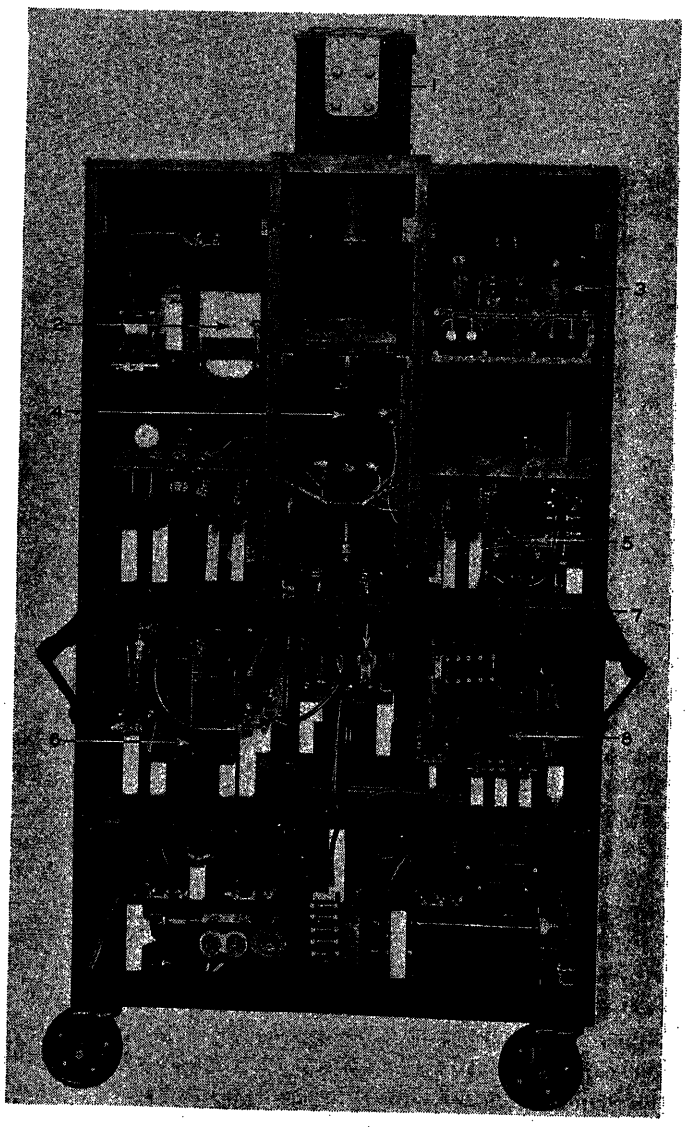



**Figure 2. General Electric cathode-ray oscillograph, type HC-15, rear view**

1. Recording camera
2. Time-axis-calibration oscillator
3. D-c calibration unit
4. Cathode-ray tube
5. Sweep-circuit unit
6. Cathode-excitation-circuit unit
7. Thyratron beam-initiating unit
8. Sweep-initiating unit

ages it was shown by Coolidge[18] that large amounts of electrons can be made to traverse a window of the Lenard type. Knoll[34] first built a practical cathode-ray oscillograph equipped with Lenard windows and obtained recording speeds of 5,000 kilometers per second with a photographic film held against the window (contact exposure) and a cathode excitation voltage of 75 kv. Miller and Robinson[61] have provided a Lenard window attachment for their conventional type of internal photography instrument.

Another line of attack in obtaining oscillographic records by contact exposure has been the use of a glass window coated with fluorescent material on the inside.[14] In this case the light radiation from the fluorescent screen is used to blacken the film. Investigations have been made along this line by a number of workers, Freisewinkel[68] and others, and high recording speeds were obtained in some cases. However, it also was found that unless a very thin glass window is used, the light dispersion will result in a blurred record.[73] Of course, it was known that sharply focused records can be obtained with a camera—which method places no restrictions on the thickness of the glass window—but here only a very much smaller part of the available light is used.

With the availability of commercial high-speed photographic lenses and with the attainment of sharply focused beams and exceedingly high fluorescent spot intensities one of the most interesting trends of recent years is the return to the simple external camera method of recording as used in connection with Braun's tubes. Following earlier experiments by Rogowski[41] and his associates, Dodds[56] in 1933 reported the recording by external camera of speeds of 30,000 kilometers per second at 90 kv cathode excitation with a cold-cathode tube. A year later Gondet and Beaudouin[66] described a new Dufour hot-cathode vacuum-pump type oscillograph with external-camera photography.

It having been demonstrated that very high recording speeds can be obtained by photographing the fluorescent screen from the outside, consideration was given again to a complete sealing off of the tube and the resulting elimination of vacuum pumps. Rogowski and Szeghö[62] developed a permanently sealed glass oscillograph tube with cold cathode and zinc sulfide fluorescent tube screen for 40 or 50 kv excitation voltage. The tube was hydrogen filled for protection of the cathode and to obtain a high spot intensity. Provision is made to diffuse hydrogen into the tube to replenish the loss of hydrogen through clean-up action. As cold cathodes are subject to crater formation, a loosely mounted spherical cathode was used which can be turned to expose a fresh surface by lightly tapping the tube. A complete oscillograph embodying a tube of this type was described by Parker-Smith, Szeghö, and Bradshaw[78] in 1935.

In the above brief historical review it was obviously impossible to mention all of the numerous and valuable contributions that were made toward the gradual perfection of the high-speed cathode-ray oscillograph. However, an extensive bibliography covering the cathode-ray oscillograph development, with particular emphasis on the high-speed type for transient recording, is given at the end of this paper.

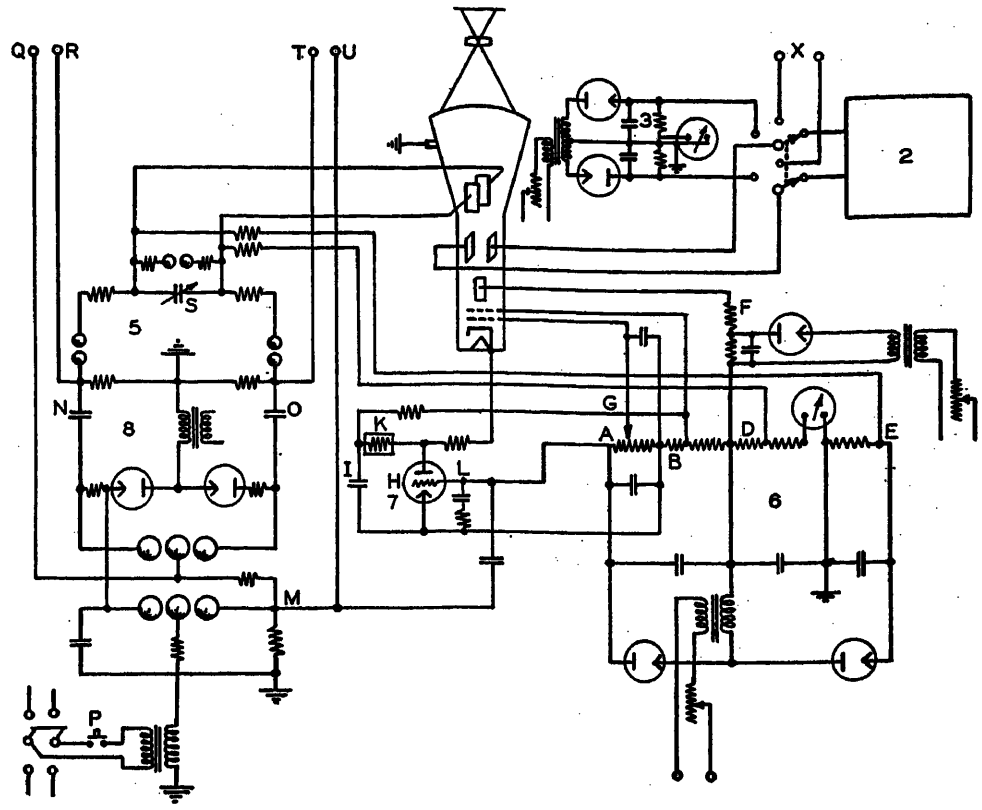



**Figure 3. Simplified schematic oscillograph circuit diagram**

2—Time-axis-calibration oscillator
3—D-c calibration unit
5—Sweep-circuit unit
6—Cathode-excitation-circuit unit
7—Thyratron beam-initiating unit
8—Sweep-initiating unit

## The New Cathode-Ray Oscillograph

It has been shown that the cathode-ray oscillograph is capable of enormous recording speeds. However, when we examine the recording-speed requirements from a practical engineering point of view we find that in most of the fields of application of the oscillograph ultrahigh speeds are not required. This applies particularly to impulse-testing work, to the study of lightning and lightning protection, and to investigation of switchgear problems. Because of the large dimensions of the circuits involved

the transients in these circuits inherently can be but moderately fast. Experience has shown that in this important field a recording speed of 10 inches per microsecond (250 kilometers per second) is sufficient for most practical purposes.

Having recognized this fact, the development of a new cathode-ray oscillograph was undertaken with the object of producing an instrument with sufficient recording speed to meet the practical requirements stated above. It was believed that by omitting the ultrahigh-speed feature and by employing a sealed cathode-ray tube requiring no vacuum pumps, and external camera photography, the apparatus would become simpler and less costly.

## The New Cathode-Ray Tube

The development of a cathode-ray tube to meet the above specifications had its origin in the high-vacuum hot-cathode glass type of cathode-ray tubes described by Zworykin[44] and Metcalf.[54] In recording-speed tests made with the General Electric type *FP*-53 cathode-ray tube, single sweep traces of 100,000-cycle oscillator waves were successfully photographed at an anode voltage of 10,000 volts, the maximum tube rating. The more than linear growth of the recording speed, with increasing

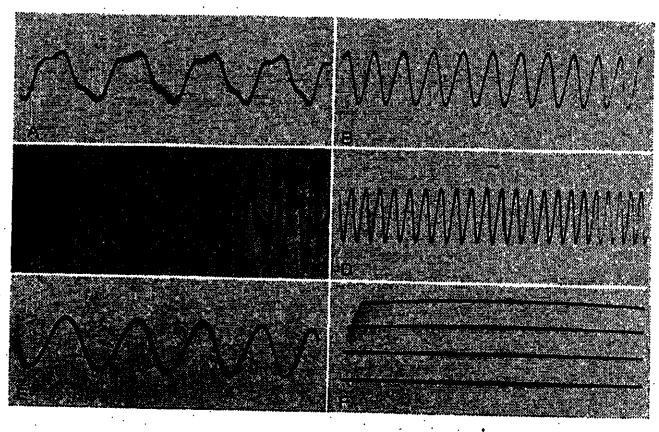


**Figure 4. Oscillator oscillograph records**

*A*—100,000 cycles per second
*B*—500,000 cycles per second
*C*—500,000 cycles per second
*D*—2,000,000 cycles per second
*E*—2,000,000 cycles per second
*F*—D-c calibration record showing 250-volt steps

anode voltage, observed in the tests, suggested further tests at anode voltages higher than 10,000 volts. Therefore, additional tests at higher voltages were made and the boosted to as high as 18,000 volts. that beginning at around 15,000 waves like the 1 x 5- and the 1½ x could satisfactorily be recorded. itely established that a tube of this the field intended for it.

the cathode-ray tube used stood up quite successfully under the added voltage stresses in these early tests, considerable difficulties were first encountered in attempting to reproduce this tube commercially for continuous operation at 15,000 volts. The most annoying and stubborn obstacles were internal discharges, flashovers, and field currents. These tended to render the tubes sometimes completely inoperative. Most often, however, the local field currents distorted the electrostatic focusing field, so that a sharp focus was not obtainable, and other times they caused a flickering, disturbing screen glow. After many disappointments

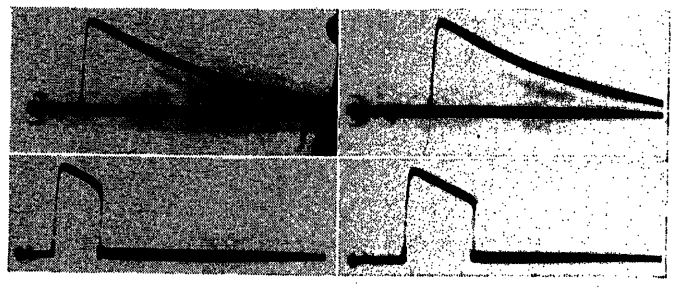


**Figure 5. Impulse oscillograph records**

1½x40-microsecond impulse waves and rod gap flashovers

these difficulties were finally traced to residual gases liberated by the high-speed electrons from the internal tube parts. This discovery led to the adoption of added refinements of the manufacturing processes, mainly during the evacuation stages, and in conjunction with the R. C. A. Manufacturing Company, Radiotron Division, a completely reliable practical 15,000-volt tube known as type RCA-912 was ultimately produced.

## Description of the Oscillograph

The new oscillograph, described in the following, was built around the cathode-ray tube, the successful development of which was discussed above. On account of the relatively low cathode-tube operating voltage used, a very compact arrangement of the complete oscillograph equipment was made possible. Thus there were installed in a single cabinet shown in figure 1 the following component parts: the cathode-ray tube and recording camera; auxiliary circuit units for the cathode excitation and focus of the tube, for the automatic initiation of the cathode-ray beam, for producing the sweep and for the proper time co-ordination of the oscillograph with impulse generator or other external circuits; an oscillator for the time axis calibration; and a d-c supply unit for the oscillograph deflection calibration.

The physical arrangement of the various circuits shown in figure 2 presented many interesting problems. Inasmuch as sharp voltage impulses are used in the oscillograph to perform certain precise timing functions with fairly large currents involved the circuits had to be critically arranged for minimum mutual interference. Also undesirable magnetic fields resulting in a disturbed cathode-

ray beam deflection were carefully eliminated by partial field compensation and shielding. A considerable study was also devoted to the proper arrangement of the deflection-plate-circuit leads and all other leads to prevent pickup through magnetically or electrostatically induced voltages from auxiliary timing circuits operating at as high as 7,500 volts. The cathode-ray tube at 15,000 volts tube voltage was measured to have a deflection sensitivity of approximately 500 volts per inch.

In order to obtain a clear understanding of the purpose and function of each oscillograph circuit, these circuits will now briefly be described.

### The Oscillograph Circuits

In figure 3 is shown a simplified schematic diagram of the oscillograph circuits. For the production of the cathode-ray beam, the tube requires proper d-c potentials for the several elements. These voltages are derived from the cathode-excitation circuit shown at the right of figure 3. For this purpose a simple voltage-doubling circuit was used with bleeder resistance *A*—*E*. The control-grid rheostat was proportioned so that the potential *G* may be varied from complete shut-off of the beam to full intensity. It was also found desirable to provide a separate rectifier circuit for independently adjusting the focusing potential *F*. For the prevention of d-c voltage fluctuations all essential d-c potentials were carefully stabilized with capacitors.

When the oscillograph tube is to be operated at maximum intensity as required for high-speed recording, the time during which the cathode-ray beam is on must be limited. This is necessary because a prolonged high-intensity beam may not only damage the tube screen, but may even soften the glass locally. For the proper time duration of the cathode-ray beam the automatic beam-initiating circuit unit shown in the center of figure 3 was developed. It is seen to consist essentially of a thyratron capacitor resistance discharge circuit *HIK*. For the discharge resistor *K*, thyrite was used which transmits approximately one ampere at 1,000 volts and 0.001 ampere at 100 volts. The circuit operates as follows: By applying a positive voltage impulse to the thyratron grid *L* the capacitor discharge is precipitated. When the discharge current has dropped to a critical value of approximately one milliampere the negative thyratron grid bias shuts off the current and the capacitor charges again slowly through the high charging resistor shown. During the discharge period the voltage drop across the thyratron tube *H* remains approximately constant at around 20 volts. By the use of the thyrite resistor mentioned, instead of an ordinary resistor, it was intended never to let the capacitor voltage drop to less than approximately 100 volts. This special circuit feature was developed to give a sharp cathode-ray beam shut-off as discussed below. After the application of the positive initiating impulse on the thyratron grid *L* the tube voltage quickly drops to a low value and remains essentially at that value until the tube current has reached the critical shut-off point. When the tube shuts off, the voltage instantly rises to about 100 volts and then increases slowly again to the initial value as the capacitor recharges. Referring to the diagram the thyratron anode is connected to the cathode-ray tube cathode through a resistor and the thyratron cathode is connected to *B*. Before the initiation of the thyratron discharge circuit the cathode of the cathode-ray tube is seen to have a positive potential bias with respect to the beam intensity control grid. This is, of course, equivalent to a negative control-grid bias. During the transmission of current through the thyratron, this bias is removed and the cathode-ray beam is on. Owing to the use of the thyrite resistor described above the beam shuts off instantly when the current through the thyratron tube ceases to flow because of the quick rise of the thyratron anode voltage. The resistor shown between the thyratron anode and the oscillograph tube cathode was added to prevent local oscillations. The initiation and timing of the cathode-ray beam could, of course, have been accomplished by swinging the cathode tube control grid rather than the cathode. However, the solution described was found to be more convenient.

The positive initiating impulse for the thyratron grid *L* is obtained from a group of circuits which were designed to provide suitable voltages for the sweep deflection, and the proper time correlation of the oscillograph with the impulse generator or other external circuits. These circuit units are shown schematically in the diagram of figure 3 on the left.

By pressing pushbutton *P* the 3-electrode gap of the primary initiating circuit breaks down near the negative crest of the initiating transformer voltage. The capacitor discharges into the resistor shown and a very steep positive polarity voltage impulse of 7,500 volts appears at *M*. This impulse is transmitted to the thyratron grid *L* through the coupling capacitor shown and the cathode-ray beam comes on and stays on for a predetermined short time. The voltage impulse at *M* is also transmitted through a delay resistance to the midsphere of the 3-electrode gap of the sweep-initiating unit, causing these gaps to break down. The time delay of the gap breakdown was designed to be approximately 20 microseconds. The 2 capacitors of this circuit discharge through the resistors *NO*. A negative polarity voltage of 7,500 volts instantly appears at *N* and a voltage of equal magnitude but of positive polarity appears at *O*. The time constant of this circuit was designed to be 50,000 microseconds so as to give essentially a square voltage wave (d-c voltage) for

Wave-front sphere-gap spark-overs and 2,000,000-cycle oscillator waves with harmonics



**Figure 6. High-speed impulse records**

the excitation of the sweep circuit whose time constant is very much less.

The square voltage wave at *NO* is applied to the sweep capacitor *S* through charging resistors by breaking down a pair of small gaps. This causes the sweep voltage on capacitor *S* gradually to rise, moving the cathode-ray beam sideways along the time axis. When the voltage on *S* has reached approximately 3,000 volts the small protective gap across *S* breaks down. The resistors in series with this gap were so designed in proportion to the charging resistors of *S* that the voltage on *S* remains essentially constant after the protective gap breakdown. The sweep voltage of 3,000 volts is sufficient to deflect the cathode-ray beam off the tube screen where it will remain until the thyratron tube of the beam initiating unit shuts it off.

As may be recognized in the circuit diagram, the sweep initiating unit and the sweep itself are balanced with respect to ground. A carefully balanced design was developed to eliminate pattern distortions on the oscillograph-tube screen. When an unbalanced sweep was used, the deflection amplitude obtained with a given voltage was found to be larger at one end of the time axis than at the other end.

In order that the cathode-ray spot may start from the edge of the tube screen instead of from the center, the sweep capacitor *S* and the sweep deflection plates connected to it must have an initial bias voltage of polarity opposite to that of the sweep voltage. This bias voltage was conveniently tapped off at *D* and *E* of the cathode excitation circuit as shown. This necessitated the use of the small gaps in the sweep circuit to isolate the sweep deflection plate circuit until the initiation of the sweep.

A selector switch was installed to connect to the vertical oscillograph deflection plates either the oscillograph terminals *X*, the d-c calibrating unit, or the time axis calibrating oscillator. The selector switch, the d-c calibrating unit and the oscillator are shown on the right of the cathode-ray tube in the diagram of figure 3.

## The Recording Camera

Considerable developmental work was done to produce a fast lens system giving a one-to-one magnification ratio. Such a lens was produced by the Bausch and Lomb Optical Company and it is used in the photographic camera shown in figures 1 and 2. It gives a full-size reproduction of the cathode-tube screen image. This feature was obtained by the use of 2 lens systems of equal focal lengths connected in series and mounted in one lens barrel. The cathode tube screen was placed at the focal point of one lens and the image appeared at the focal point of the other. Two separate corrective negative lenses were added to compensate for some field curvature and also to partly compensate for the spherical curvature of the cathode tube screen. The lens assembly was designed to have a nominal lens speed of *f*3.

## Oscillograph Records

In designing the oscillograph, consideration was given to a practical photographic equipment which can be operated by anybody with average experience; thus the handling of the films does not require special refinements inasmuch as commercial films and developers may be used. Supersensitive panchromatic film was found to give the best practical results, but for moderately fast work excellent results were also obtained with Kodak Verichrome film.

In. figure 4 are shown reproductions of oscillator oscillograms obtained with the camera described above. Attention is called to the uniform deflection along the entire sweep. This result is due to the use of the balanced sweep circuit described above. Typical records of $1^1/_2$x40 microsecond impulse waves are shown in figure 5.

A set of interesting high-speed records obtained with a sweep of 2 microseconds and a small commercial *f*2 camera are shown in figure 6.

This type of oscillograph may also readily be adapted to rotating film drum recording. In this case only one pair of deflection plates is used and the luminous spot on the tube screen is projected on the moving film by means of a photographic lens. For this application the cathode-ray tube used contains a fluorescent substance having a very short persistence of fluorescence. With film speeds of 500 feet per second oscillatory waves of as high as 100,000 cycles per second were successfully recorded.

By the use of more than one cathode-ray tube multi-

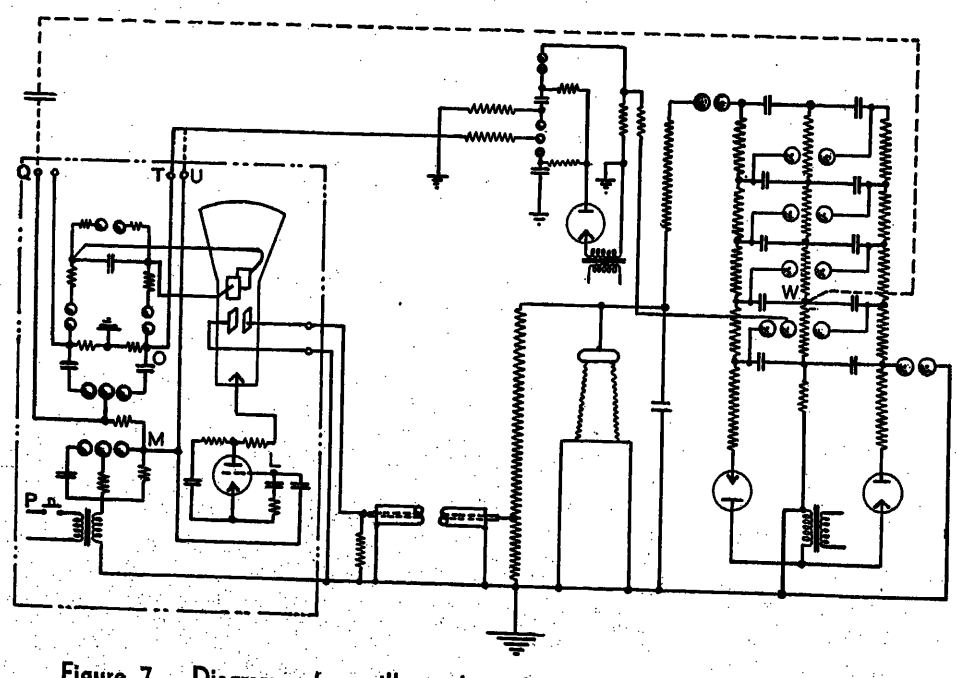



Figure 7. Diagram of oscillograph and impulse-generator co-ordination

circuit recording instruments may be built. Several 3-tube cathode-ray oscillographs are now in use in the General Electric Company.

In one of these instruments the persistence of fluorescence is made use of. The cathode-ray beam is made to sweep across the tube screens recurrently by means of a saw-tooth wave time axis oscillator. Upon occurrence of the fault to be recorded, a relay quickly operates the triggered camera shutter and a snapshot of the tube screens is thus taken. In spite of the time delay introduced by the relay and shutter, the camera successfully photographs the "memory" (persistence of fluorescence) of the fault on the tube screens.

In the development and design of this oscillograph the adoption of 15,000 volts for the cathode tube was quite arbitrary and does, therefore, not represent a final limit for this type of tube. It is believed to be entirely feasible to produce still higher voltage tubes if the range of this type of instrument is to be extended into fields requiring higher recording speeds.

## Application of the Oscillograph to Impulse Testing

There are many ways of co-ordinating a cathode-ray oscillograph with impulse generator equipment and it would be impossible here to describe them all. The engineers concerned with this work have always liked to resort to their own ingenuity for accomplishing desired results and the competition between the various groups has made for remarkable refinements in the art. In order to illustrate the performance of the new oscillograph a method is given of co-ordinating the oscillograph with a Marx-type impulse generator. This method was successfully used in the Schenectady high-voltage laboratory of the General Electric Company.

The simplified circuits are shown schematically in figure 7. As shown, a small 2-stage Marx circuit is used to act as an intermediate initiating circuit between the oscillograph and the impulse generator. The intermediate circuit receives its initiating impulse from the cathode-ray oscillograph and its output in turn is used to trip the impulse generator 3-electrode gap.

In taking an impulse wave record the sequence of events is briefly as follows: With the face held against the viewing window on the front panel of the oscillograph and with the eyes focused on the cathode-tube screen, the camera shutter is first opened. Shortly after pushbutton $P$ is pressed. This causes the 3-electrode gap of the primary oscillograph initiating unit to break down and the impulse from $M$ fires the thyratron tube of the beam-initiating unit. The cathode-ray beam appears on the left edge of the tube screen where it remains stationary. However, within about 20 microseconds the impulse from $M$ also trips the 3-electrode gap of the sweep-initiating circuit and the sweep begins. Simultaneously a voltage impulse of 7,500 volts from $O$ through terminal $T$ travels out through some delay resistance to the trip gap of the intermediate initiating circuit whose output in turn precipitates the impulse generator discharge. The voltage divider leads from the impulse-generator discharge circuit bring the desired voltage impulse to the oscillograph deflection plates. The luminous cathode-ray spot now traces the wave shape which can be seen at the same time the photographic record is taken and the spot finally disappears at the right edge of the cathode tube screen where it is automatically shut off. The camera shutter is now closed and the record is taken.

When very fast sweeps are employed requiring ultra-precision timing, the sequence of the various circuit initiating events is slightly altered. The first impulse from $M$ which establishes the cathode-ray beam is now used to initiate through terminal $U$ the intermediate circuit and impulse generator before the sweep begins. As shown in dotted lines in figure 7 a portion of the impulse generator voltage from $W$ is used to trip the gaps of the sweep-initiating unit through the oscillograph terminal $Q$. This takes place before the arrival of the impulse from $M$ on the same sphere. This modification was found to provide very sharp timing between the start of the sweep and the precipitation of the impulse generator discharge as illustrated by the fast records shown in figure 6.

In conclusion a practical high-speed cathode-ray oscillograph was successfully constructed with external camera photography, incorporating a sealed glass cathode-ray tube, capable of recording transients at a recording speed of 250 kilometers per second (10 inches per microsecond). It was shown that higher recording speeds are not needed in most practical fields of application.

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# Dynamic Balancing of Small Gyroscope Rotors

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A DIRECT METHOD[1] of balancing is generally possible for any type of rotor provided it can be run in a special fixture for the measurements. However, some rotors due to large size or other restrictions can be run only on their permanent mountings and balancing usually requires more or less "trial and error" testing. On the other hand, certain rotors of the first group that are small in size and may be run in special fixtures, impose unusual obstacles which make it difficult to apply the well-known principles to produce a rational method of dynamic balancing. This paper is devoted to a description of the solution of such a balancing problem.

The present method was originally developed to balance a wheel capable of spinning 30,000 to 40,000 rpm. At that time the production method of balancing small gyro rotors in the Sperry Company consisted of placing small amounts of putty or Vulcatex on the rotor periphery and shifting the position and amount until the rotor felt smooth. The rotor was then drilled in accordance with the position and the amount of putty present. This required skilled operators but at the time seemed to be the only method which produced a satisfactory balance. However, this method broke down when applied to very high-speed rotors, since the operators no longer have a proper sense of "feel" at high frequencies. After the application had been made to the high-speed wheel, it was decided that the method would be very useful for production balancing of air-driven gyroscope rotors such as are shown in figure 4. These rotors are used in the standard airplane flight instruments shown in figure 5. Several factors in this balancing problem are unique. The most important of these is the unusually high degree of balance required. This requirement is peculiar to gyroscopic instruments since very sensitive antifriction bearings must be used for rotor and gimbal bearings. Also it is frequently found that dynamic unbalance, even in small amounts, will excite destructive gyroscopic nutations. This is particularly true of gyros with very free gimbal bearings. Quantitatively, the maximum allowable vibration is of the order of $10^{-5}$ inch at the bearing housing. This is not remote from the threshold of "feeling" on these instruments at 200 revolutions per second. It is understood, of course, that very high-grade, smooth running bearings must be used, otherwise one may mistake the "feel" of bearing "noise" for rotor unbalance. This requires an excellence of running balance that is far beyond the range tolerated in any other type of rotating apparatus.

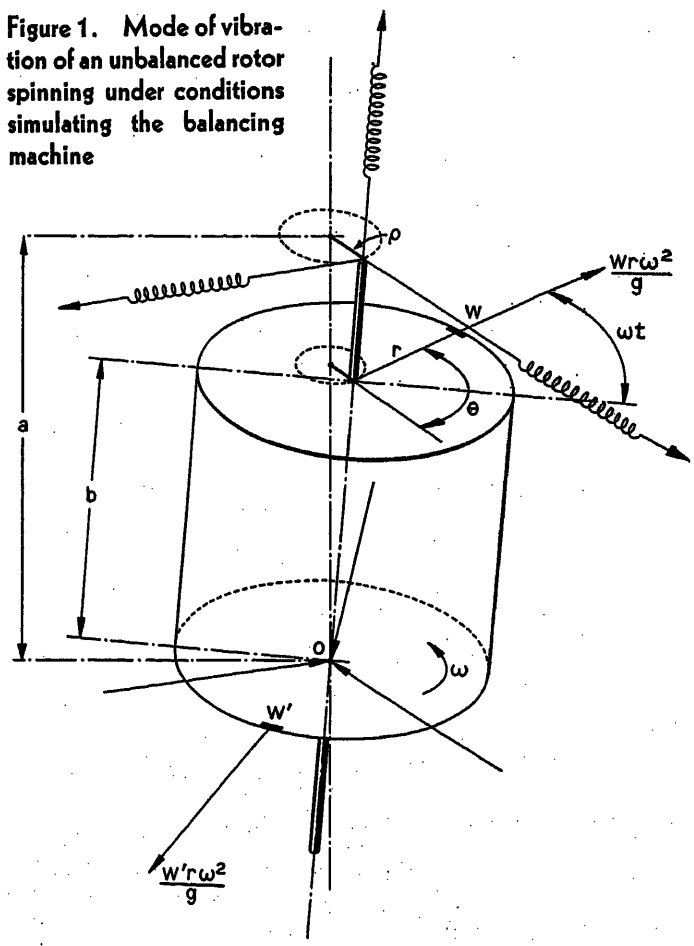
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1. A list of references relating to many of the most important rotor balancing methods is given at the end of this paper.

Pivot-type cone bearings are used on these rotors. These are shown on the central shafts in figure 4. The pivots run on ball bearings in the case of the instrument. Due to this type of construction, it is impracticable to connect mechanically to any type of speed indicator, voltage generator, commutator, or interruptor. Furthermore, any mechanical connections would, when removed after balancing, in all probability cause an unbalance. Therefore, any signal which is to be generated for indication of rotor speed and position must be derived by other than mechanical means.

**Figure 1. Mode of vibration of an unbalanced rotor spinning under conditions simulating the balancing machine**




Due to the nature of the product, extreme care must be exercised in handling the rotors to prevent damage. The sensitive bearings used are affected very badly by any foreign material. The slightest abrasion of the pivot means scrapping. There is also another hazard, namely, the danger of striking the unprotected rotor pivot against some object while it is being removed or assembled in the balancing fixture. Therefore, the machine must be constructed in such a manner that unskilled operators

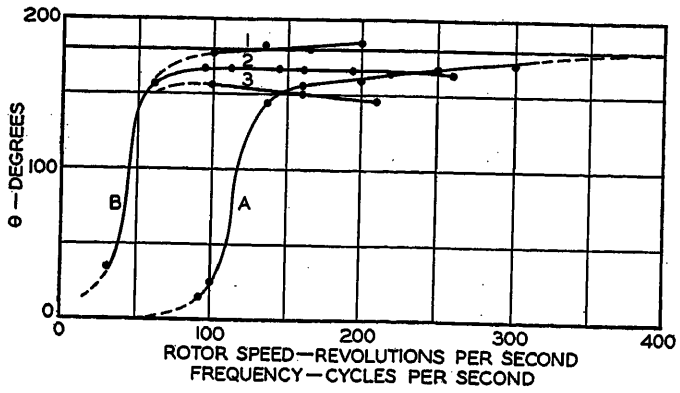



**Figure 2. Phase shift curves**

*A*—Phonograph pickup *B*—Ring pickup

can manipulate it rapidly with the minimum hazard to the finished rotor.

Another condition to contend with is high speed. It must be possible to measure rotor unbalance at a comparatively high speed. This speed may be anywhere from 5,000 to 40,000 rpm. Thus, to obtain high sensitivity, the rotor casing and vibration pickup must be as light as possible and the critical frequency of the mount should be very low with respect to the lowest speed at which we wish to balance.

## Choice of Method

In choosing a method of balancing these gyroscope rotors, we were forewarned that our problem was so different that an unusual machine was necessary. Attempts by various companies interested in up-to-date balancing methods to balance these rotors failed to produce results. The reason, obviously, was that their standard apparatus while excellent for their own product, was not adapted to the small gyro rotors.

## Rotor Mounting

The first attempt at a balancing machine is shown in figure 6. The rotor is mounted in a rigid 3-legged frame. At each end of the frame, in the correction planes, (planes normal to the spin axis which include the balancing weights) are mountings for flat leaf springs 120 degrees apart as shown at the bottom of the frame. The springs can be attached at either end of the frame and their outside ends are secured to a heavy base. The frame is then virtually pivoted at the rotor axis in the plane of the springs. The springs maintain equal rigidity in all planes which include the axis. Therefore, the rotor axis will oscillate in a conical path (this will be found demonstrated in figure 1), the apex of which lies in the plane of the springs. For small vibrations, the damping of such a spring mount is exceedingly low. It is easy to adjust the resonant speed by varying length and thickness of springs and maintain at the same time sufficient rigidity in the plane of the springs to substantially block out the vibration of the end not being measured.

## Reference Signal

Since it is impossible to attach any kind of a signa generator mechanically to the rotor, the obvious way o of obtaining a signal which depends for its phase on a reference mark on the rotor, is the application of the photoelectric cell. A beam of light is reflected from the surface of the rotor to a photocell. A certain part of the rotor surface is highly polished, the rest is not. The rotation, therefore, varies the reflected light and pulsates the photocell current at rotor frequency. This means of voltage generation obviously does not impede motion of the rotor or the frame.

## Vibration Instruments

The first requirement of the vibration instrument is that it must permit adjustment of the phase of the output voltage. In practically all other balancing methods, the phase of the reference voltage is adjusted to be in or out of phase with the vibration voltage. But it is inconvenient to adjust the phase of the reference voltage in this device because in moving the optical system around the axis of rotation, the light beam would be intercepted by the frame work. The vibration instrument shown in figure 6 is an ordinary electromagnetic phonograph pickup. It is mounted to rotate on the axis of the needle which rests on the top of the rotor frame. Vibration of the frame is transmitted to the pickup through the needle, thus generating a voltage. The frame vibration is circular around the spin axis but the pickup generates a voltage by only that component of the vibration that lies in one axial plane. Now, to advance or retard the phase of the voltage, it is necessary only to advance or retard the axial plane in which the pickup is sensitive.

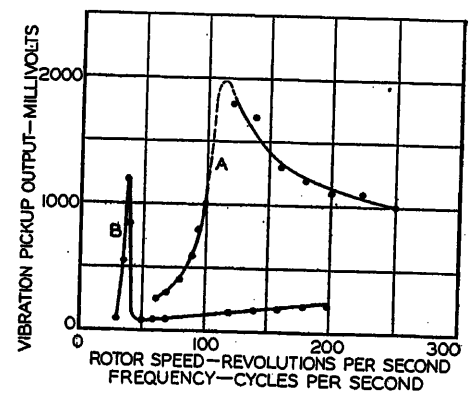



**Figure 3. Resonance curves**

*A*—Phonograph pickup

*B*—Ring pickup

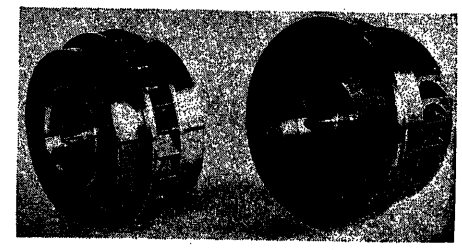


**Figure 4. Gyroscope rotors**

This means that rotation of the pickup about the needle axis, adjusts the phase of the output. The dial indicates pickup position. It is apparent that the voltage magnitude is not affected by angular position of the pickup as long as the rotor axis describes a circular path under the influence of an unbalanced rotor.

The voltage output of the pickup is proportional to frequency ($\omega$) and amplitude of the vibration ($\rho$) and is, therefore, a measure of unbalance ($Wr/g$) at any given speed, where $W$ is the unbalanced weight, $r$ is its radial distance from the spin axis, and $g$ is acceleration of gravity. The position of the unbalance is determined by adding to the vibration voltage the reference voltage. The magnitudes are first made equal by attenuation. The pickup is then rotated to the point where the sum of the 2 voltages is zero. The dial reading indicates the position of the unbalance as measured in degrees from some arbitrary reference mark on the rotor. The phonograph pickup was tried first because of its availability and simplicity but it was not entirely satisfactory, as will be discussed later. First, another necessary feature of the system will be discussed.

## Filtering

Figure 7 is what might be called a vibration spectrum of a rotor with bearings and frame. It indicates the relative magnitude (not taking into account the fact that the voltage induced in the pickup is proportional to frequency), of all the harmonics that are present in the vibrations of a fairly well-balanced rotor. The rotor speed is 200 revolutions per second and the amplitude at that frequency is considerably less than some near-by frequencies. Naturally, these other frequencies tend to give an erroneous voltage reading in measuring magnitude and make it impossible to phase against the reference voltage for position. Obviously, filtering is necessary. If the precision of balance required were not so high, the vibration component at rotor speed would still be large and filtering would not be necessary. Under existing conditions, it is, however, a prime requisite. The reference signal also has a high harmonic content so it must be filtered too. The combined output is filtered after the 2 voltages are added together. This precludes the possibility of uncompensated phase shifts in filtering. The schematic wiring diagram, figure 8, shows the method of adding voltages, filtering, and amplifying. A very sharp bandpass filter is used.

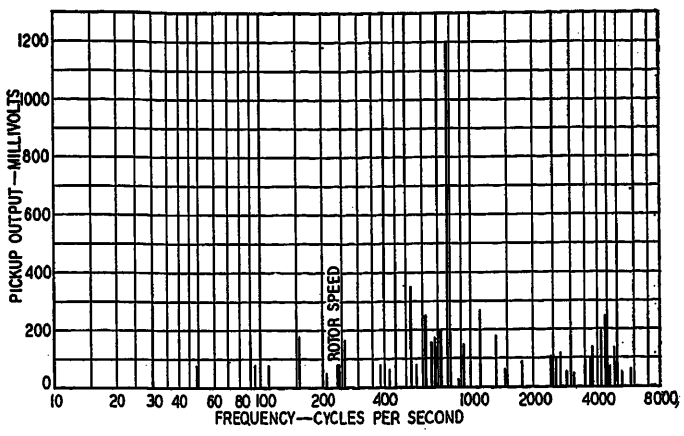



**Figure 7. Gyroscope vibration spectrum**

Vibration frequencies present in a balanced directional gyro rotor case; bearings not perfect

Pickup response is not a measure of amplitude of vibration at various frequencies because output is proportional to frequency

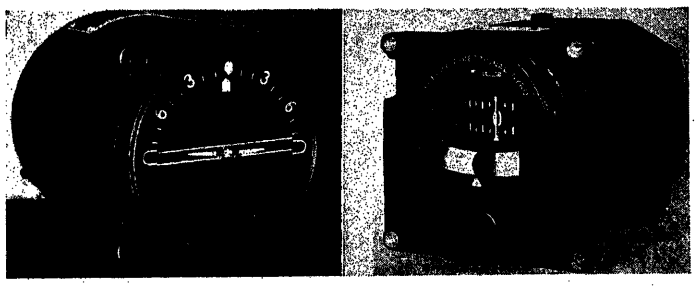


**Figure 5. Flight instruments**

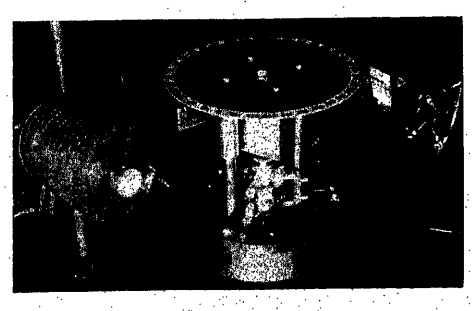


**Figure 6. Experimental machine with phonograph pickup**

## Voltage Balance

In practice, it is found that in order to obtain an accurate indication of unbalance position, the 2 voltages must be very nearly equal. At least one of them must therefore be adjustable. The reference signal is the one adjusted. The effect of imperfectly balanced voltages is shown in figure 9. The slope of the curves is a measure of sensitivity in locating the correct position. The abscissas of this family of curves is the angle ($\alpha$) between minus $e_v$ and plus $e_r$, and the ordinates are their sum ($e$) in per cent of the vibration voltage ($e_v$). Plots at several ratios ($P$) between $e_v$ and $e_r$ are given to show the effect of inequality of the signal voltages. It should be noted that $\alpha$ is the angular error in locating the unbalanced weight.

Let

$$e_v = E_v \cos(\omega t + \alpha - 180°)$$
$$e_r = E_r \cos \omega t$$

When $E_v = E_r$ by adjustment and $\alpha = 0$. Then

$$e_v + e_r = E_v \cos(\omega t - 180°) + E_v \cos \omega t = 0$$

It can then be shown that

$$e/e_v = \sqrt{1 - 2P \cos \alpha + P^2}$$

For small angles this relation can be simplified to

$$e/e_v = \sqrt{(P-1)^2 + P\alpha^2}$$

The curves of figure 9 are a plot of this equation.

Since the slope of the curves is proportional to sensitivity in setting $\alpha$ equal to zero, it is apparent that the voltages must not be unequal by more than approximately one per cent to measure position with an accuracy of one-half a degree. Furthermore, to obtain the same sensitivity of position for small magnitudes, as for large magnitudes, a tapered attenuator on the reference voltage must be used.

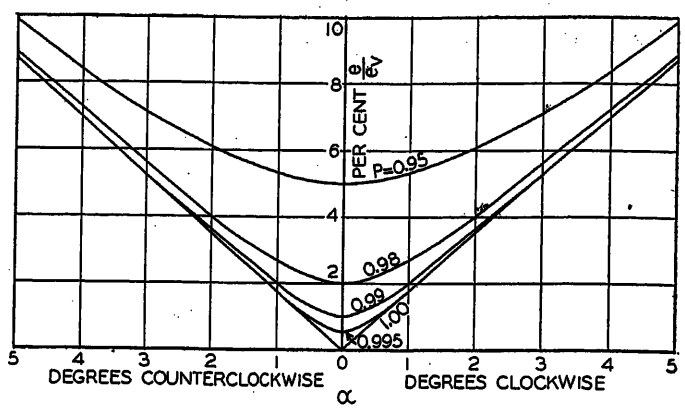



**Figure 9. Positioning error curves**

In order to determine accurately the position of unbalance $\alpha$ must be made zero. To obtain high accuracy in setting $\alpha$ to zero, $P$ must be close to unity

## Phonograph-Type Pickup

The resonance curves of figure 2, curve $A$, and figure 3, curve $A$, indicate that damping is considerable because the angular position is never independent of speed in the operation range. In fact, at 200 revolutions per second a change of 20 revolutions per second results in position change of $2^1/_2$ degrees. Of course, the band-pass filter limits the possible variation in speed, but with air driven rotors, speed changes of less than 10 revolutions per second are difficult to control. Such changes in frequency will not appreciably change the attenuation of the desired signal. A more serious difficulty was the unsuitable critical speed. The curves, figure 2, curve $A$, and figure 3, curve $A$, show resonance at about 115 cycles. Experience indicated that 150 revolutions per second (9,000 rpm) is a good compromise speed at which to balance the rotor. It is undesirable to balance at full speed, 12,000 rpm, because initial unbalance forces are a hazard to rotor pivots. Balancing at 2 speeds was found unnecessary, hence the compromise. Since 150 revolutions per second was found to be the best balancing speed, resonance at 115 revolutions per second put the knee of the curve right at running speed. Such a condition would produce bad errors in position with imperceptible changes in speed. In attempting to lower the resonance speed, several modifications of the mounting and vibration pickup were tried. The pivoting springs were made longer to lower the free resonance of the frame. But, in doing so, the loading effect of the pickup on the system was accentuated to such an extent that all gain in reduced frame resonance speed was lost. This was caused partly by the phenomenon of 2 resonances in series, one of which is the spring mounted frame and the other the natural frequency of the magnetic pickup. They are mechanically connected together by the needle. Various attempts to reduce damping and lower the resonance of the pickup were made but decrease of one effect tended to increase the other. This was an indication that the pickup was the wrong type of instrument. It became necessary to investigate the use of other types of vibration measuring devices. A piezoelectric microphone was given a trial but with little success.

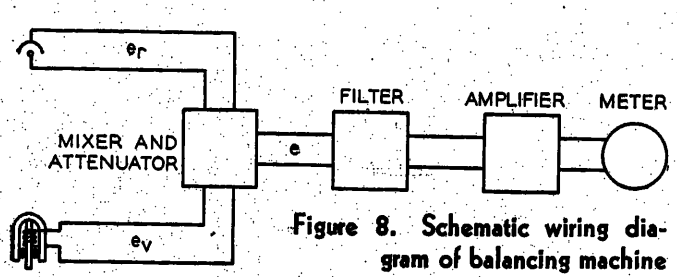



**Figure 8. Schematic wiring diagram of balancing machine**

In the course of experiments, it became apparent that the important requirement of the system is a very loose coupling between the oscillating frame and the pickup. The next section describes such a vibration instrument.

## Ring-Type Pickup

Figures 10 and 11 illustrate the type of instrument that was finally evolved. This pickup has the desirable feature of having a very loose coupling with the rotor frame. It is noted that there is no mechanical coupling between these parts.

The instrument comprises a permanent horseshoe magnet with a center pole of soft iron on which is wound a coil and a soft iron ring attached to the moving element (rotor frame). The iron ring oscillates with the rotor axis under influence of rotor unbalance. This oscillation is such that the ring moves in an eccentric path around the central pole of the pickup. This motion varies the flux through the center pole periodically and generates a voltage in the coil the frequency of which is rotor frequency. Examination will show that the phase of the voltage can be changed by turning the permanent magnet on the axis of the center pole. The voltage ($e_v$) is proportional to the amplitude ($\rho$) of the circular oscillation and, therefore, is also proportional to unbalance ($Wr/g$) at fixed speed.

With this device, it was possible to obtain the resonance curves as shown on figure 2, curve $B$, and figure 3, curve $B$. The resonance, it is noted, occurs at 40 revolutions per second as compared to 115 revolutions per second with the phonograph type of pickup. This critical speed is sufficiently low to allow very satisfactory operation at 150 revolutions per second. It will be noted that there are several slopes to the $\theta$ curves. $\theta$ is the angle between the displacement vector ($\rho$) and disturbing force ($Wr\omega^2/g$). Number 1 is the first result. It has a

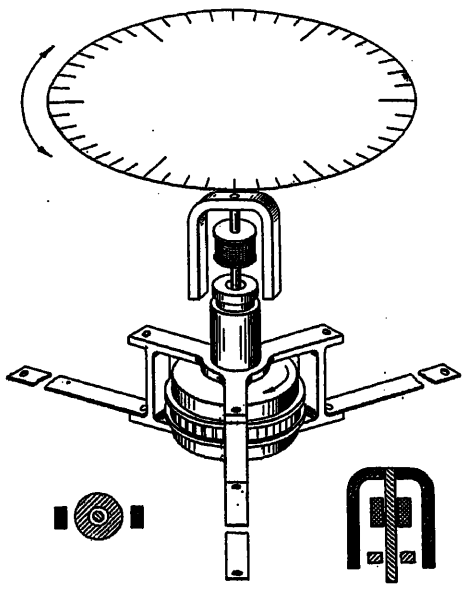


**Figure 10. Ring-type pickup**

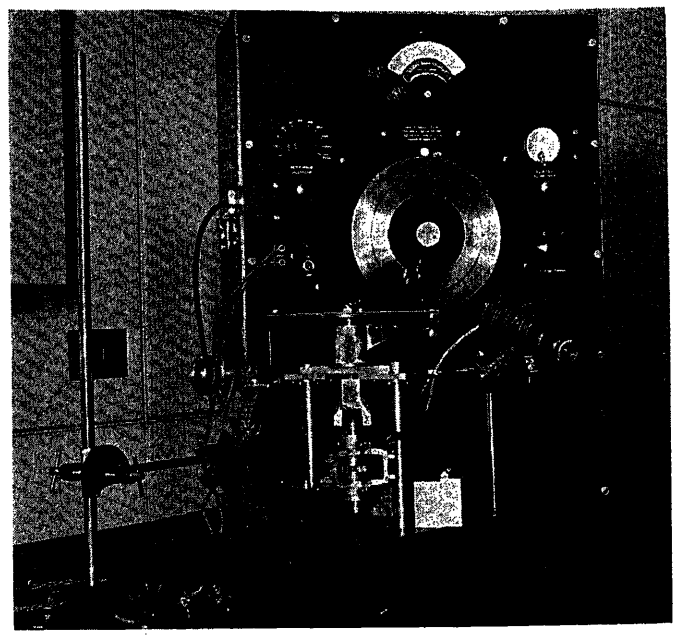


**Figure 11. Experimental machine with ring-type pickup**

slight change of $\theta$ with speed. This condition is not entirely satisfactory and experiments were made to remedy it. This condition, it was possible to correct in the circuit. Capacity across the photoelectric cell coupling transformer was found to provide means of compensating this relative phase shift. Several values of capacity were inserted across the transformer and the results are shown. One value of capacity, it will be noted, produced practically constant $\theta$ with speed variation in the 150-revolution-per-second region. This is the final arrangement.

The critical speed of the system and phase shifts were now reduced to a very satisfactory value. The basic features of the system were now developed. However, some doubt was raised concerning the practicability, owing to the difficulty in mechanically keeping the axis of the ring concentric with the pole of the pickup. Since the frame on which the ring is mounted is supported on 3 springs, it is apparent that close mechanical alignment is not easy to maintain. The air gaps when the ring is centered are 0.040 inch from pole to ring and 0.40 inch from ring to magnet. It is quite possible that a misalignment of less than 0.005 inch would be difficult to maintain on a production machine. In this system it is essential that the phase of $e_v$ can be changed the whole 360 degrees with respect to $e_r$ at constant magnitude. Also, voltage $e_v$ should be constant with given unbalance and its phase with respect to $e_r$ should always indicate true position of unbalance. The curve on figure 12 shows, experimentally, the effect of misalignment on sensitivity. It is noted that the misalignment may be as great as 15 per cent before the calibration is affected more than 1 per cent.

## Sensitivity

Earlier in this paper some indication of required accuracy in balancing was given. Measurements show that it is desirable to detect and correct an unbalance of the order of 0.00001 ounce inch. This unbalance produces a very slight vibration in the frame. The initial unbalance is of the order of 0.001 ounce inch. The maximum unbalance produces about 2 millivolts which reduces to roughly 20 microvolts for the minimum reading. The internal impedance of the pickup is about 1,400 ohms, so the power output is very low. A high-gain amplifier is necessary to produce the power necessary for even a sensitive meter. A fairly simple, 3-stage full a-c operated amplifier can be made to give satisfactory results.

An attenuator to serve as a meter multiplier is necessary to allow the use of the meter on full scale on minimum signal for phasing purposes. The signal may change in the ratio of 100 to 1 or more, so changing of meter scale is mandatory.

Figure 13 shows the very linear relation that exists between magnitude of unbalance and voltage output. In balancing the rotor, the magnitude and position of unbalance is observed and recorded for both ends of the rotor. Then the 2 ends of the rotor are drilled the indicated depth at their proper respective positions. All weight correction is accomplished by drilling. Figure 14 is a calibration curve of drill depth against voltage. The nonlinear characteristic is due to the conical shape of the drill point.

It would be very advantageous to balance the rotor perfectly in one reading. Consideration shows the impossibility of this. First, the unbalance indication must

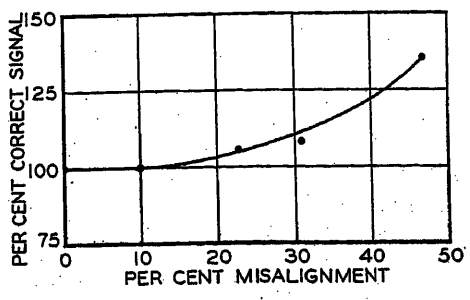



**Figure 12. Effect of misalignment on calibration**

be reduced from 2 millivolts down to less than 10 microvolts, a ratio of 200 to 1. Secondly measuring instruments have inherent errors that in practice cannot be eliminated. A voltmeter is never accurate to better than 1 per cent. Taking the combined inaccuracies of amplifier attenuators, etc., the errors will be not less than 5 per cent. If the error is 5 per cent, the initial unbalance indication can be reduced by a ratio of 100 to 5 or from 2 millivolts to 100 microvolts. Experience shows that 3 "shots" usually are required at each end. It can be shown that a balance in 3 readings can be obtained with over-all calibration errors of as much as 10 per cent.

## Production Balancing

Figure 15 shows the form of the machine that is replacing older methods in production balancing. It is designed especially for speedy manipulation in the factory. The main features of this device are (1) duplicate pickups, one at the top and one underneath and (2) one set of supporting springs for each correction plane. The springs are controlled by cams operated simultaneously by a handwheel for the purpose of changing the support from one correction plane to the other. When the support is shifted to the top springs, a switch operates automatically to connect the bottom pickup to the circuit and vice versa. The 3-sided rotor frame is designed to permit quick insertion or removal of the rotor without damage to the pivots.

This system is the only one to our knowledge which provides the extreme sensitivity required in balancing airplane instrument gyroscope rotors without depending on superkeen perceptions in the operator. Also, the speed of balancing is several times faster than the most skilled operator could make with former methods. Rejections due to defective rotor balancing are reduced from nearly 50 per cent to zero because the machine, in largely removing the human element in the measurements, can obtain exactly the same degree of balance on every unit.

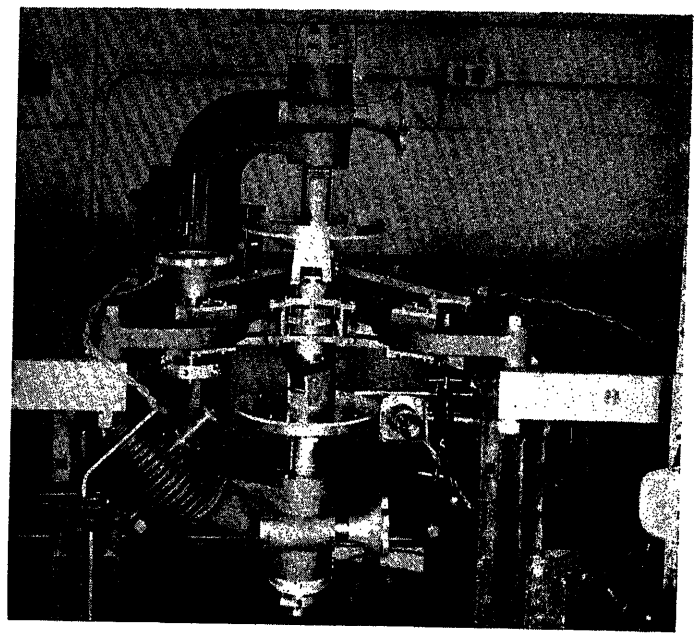


**Figure 15. Production rotor balancing machine**

Another valuable feature of the machine, which has not yet been thoroughly investigated, is its use as a "stethoscope" for checking vibrations caused by sources other than unbalance. In this use, the fixed band-pass filter is taken out and replaced by a "wave analyzer." Such an instrument is shown in figure 11. Frequency spectrums similar to the one shown in figure 7 can then be taken. This information is important in the study of ball bearings, case resonances, high-speed gyroscopic nutations, etc. It has enabled us to measure effect of looseness and out of balance in ball-bearing retainers. All of the possible uses for such a machine have obviously not been explored. However, they appear to be numerous and, no doubt, several other interesting applications will follow.

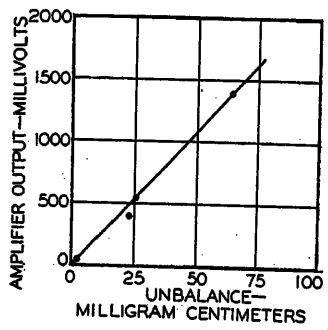



**Figure 13. Unbalance versus output of ring-type pickup**

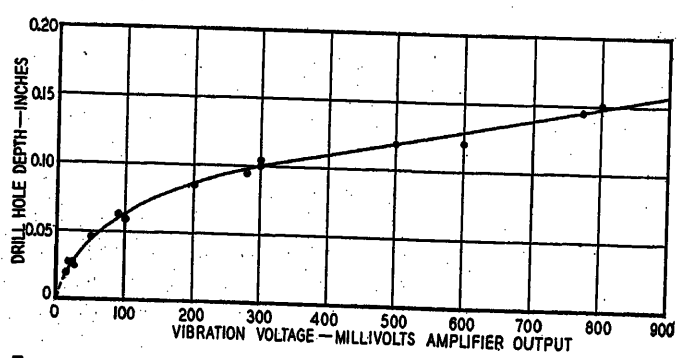



**Figure 14. Calibration curve of output versus drill depth for weight correction**

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# The Vibration Isolation of Machinery

By L. H. HANSEL

THE GENERAL purpose of isolating machinery is to reduce the amount of noise and vibration transmitted to the structure in which the machine is housed, or to adjoining structures. The general subject of isolation and isolation materials is receiving increasing attention with the tendency to speed up machinery. Machine designers recognize the fact that increased speed has resulted in troublesome vibration problems that previously had not reached "nuisance" or "damage" levels. The great majority of manufacturing tools are inherently unbalanced. To design a ba'anced drop hammer, loom, punch press or automatic machine is not feasible. In such cases the use of isolation material becomes a necessity.

Unfortunately, in many instances, isolation has been tried and the desired results have not been attained. These failures have been generally caused by a lack of understanding as to the principle of isolation and the absence of practical knowledge as to how and where the material should be installed.

The first principle of isolation is that the natural frequency of the machine on its isolation must be considerably less than the operating vibration frequency of the machine. As an example, let us assume that we have a machine which gives rise to vertical vibrations of frequency 30 per second. The machine weighs 1,600 pounds and is to be supported upon 4 equal springs. Furthermore, we desire to reduce the vibrations transmitted to the surroundings to $^1/_9$ of the value when springs are not used. If $k$ is the "stiffness coefficient" of the 4 springs, $n$ the frequency, $A_1$ the amplitude of transmitted vibration without the springs, and $A_2$ is the transmitted vibration with the springs, then

$$\frac{A_2}{A_1} = \frac{k}{4\pi^2 n^2 \frac{w}{g} - k} \qquad (1)$$

substituting

$$\frac{1}{9} = \frac{k}{4\pi^2 \times 900 \frac{1600}{32.2} - k}$$

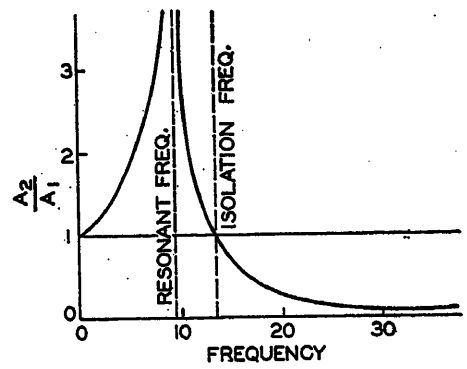
and $k = 176{,}000$ pounds per foot.

For one spring the stiffness coefficient is 44,000 pounds per foot or 3,660 pounds per inch. Four springs each giving a deflection of one inch for a 3,660-pound load solve the requirements.

It is noted, that the stiffness coefficient is an important property of an isolator. From equation (1) we can calculate what isolation will be obtained at frequencies other than the operating frequency of 30 vibrations per second. When $k = 4\pi^2 n^2 w/g$, $A_2/A_1$ becomes theoretically infinite. The transmitted vibrations at this frequency are very much higher with the springs than without them. This occurs at a frequency of 9.5 vibrations per second. At a frequency of 12.4 vibrations per second $A_2 = A_1$, and the transmitted vibrations are the same with the springs as without them. This frequency is called the "isolating frequency." A plot of the calculated values of $A_2/A_1$ for various frequencies is shown in figure 1.

Examination of this curve shows that below the isolating frequency (where $A_2/A = 1.0$) the transmitted vibrations are larger with the spring isolators than without them. The system only becomes effective at frequencies higher than 12.4 vibrations per second.

Figure 1




If the springs are stiffened the natural and isolating frequencies become higher, and consequently their effectiveness at the operating frequency of 30 per second is lessened. If the springs are reduced in stiffness the situation is improved. Questions of stability will determine what minumum stiffness coefficient is permissible.

The resonance peak is undesirable in the majority of cases. During the starting and stopping of the machine the transmitted vibrations are large and, in addition, the machine on the springs oscillates through a very large amplitude, both of which are objectionable. To remedy these difficulties it is desirable that the isolation material possess "damping" qualities.

Damping has 2 principle effects. It greatly reduces the height of the resonance peak, but the installation is less effective than isolation with no damping at frequencies higher than the isolation frequency. The curves of figure 2 show a material with little damping and one with considerable damping.

Experience has shown that the improvement obtained at frequencies lower than the isolation frequency with the

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material with appreciable damping properties is of great practical importance.

If the material has appreciable damping qualities the $A_2/A_1$ equation 1 becomes:

$$\frac{A_2}{A_1} = \sqrt{\frac{r^2 + \frac{k^2}{4\pi^2 n^2}}{r^2 + \left(2\pi n \frac{w}{g} - \frac{k}{2\pi n}\right)^2}} \qquad (2)$$

Where $r$ is the damping constant.

This constant is measured by taking a record of the damping curve. One method of doing this is illustrated in figure 3.

The test piece is loaded with 2 suitably sized weights. A small stylus bears on the top bearing plate. Any motion of the isolation material causes the mirror to move about its axis and a beam of light to move across the slit of a constant film speed moving picture camera. The lower weight is suddenly moved and a record of the oscillations is made on the film. From measurements on the damping record the value of $r$ can be evaluated.

Control of materials and manufacturing processes makes it possible to make felts covering a very wide range

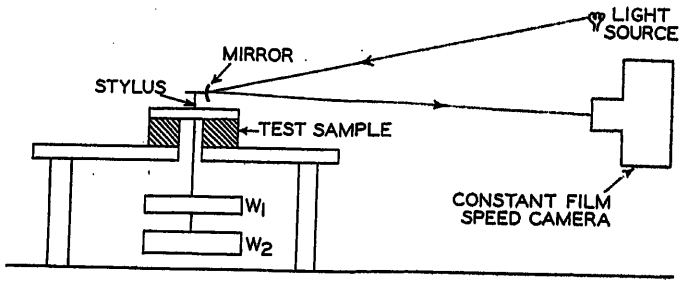



Figure 3

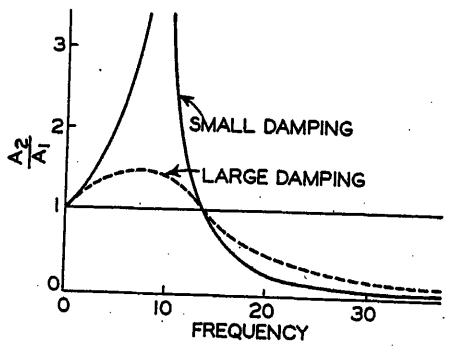



Figure 2

of stiffness coefficients. For example, felts can be made which are suitable for loadings from 2 to 500 pounds per square inch. In determining the properties of these load-deflection curves were measured together with the damping or "resistance" coefficients. Curves similar to that shown in figure 4 were then calculated.

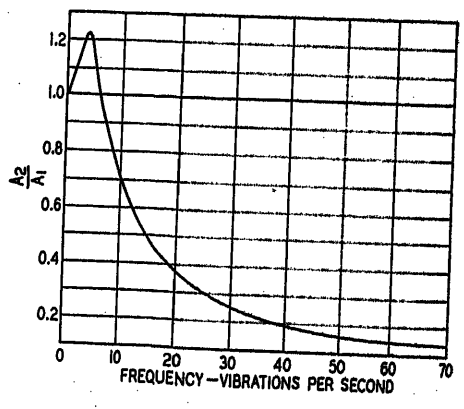
These curves have been checked at numerous points by measuring transmitted vibrations in the following manner.

The vibrations of an eccentrically loaded motor were measured with no isolation, thus giving the value of $A_1$. The test material was installed at the desired loading and the vibrations transmitted to the surroundings were again measured, thus giving the value of $A_2$. The readings so made served as a direct check upon the determination of $A_2/A_1$ by means of equation 2.

For purely rotative devices such as electric motors, the frequency to be isolated is the speed in revolutions per second. The frequency to be isolated for more complex machines is not so easily determined. The satisfactory method is to obtain a photographic record of the vibrations. There are 3 general types of instruments used: displacement recorders, velocity recorders, and accelerographs. Each gives a different recorder, and what is measured as the predominate frequency of the frequency giving the biggest displacement on the record is not necessarly the same for the 3 instruments. As an illustration of this, let us assume that a record similar to figure 6*a* is obtained with some type of velocity recorder. If a record is now made with an accelerograph it appears as in figure 6*b*. An examination of the 2 records discloses that the frequency to be isolated as determined by the accelerograph is 4 times as high as is determined by the velocity recorder. A record of the same vibrations taken on a displacement recorder would give a much smoother curve than 6*a*, and the slight irregularities of 6*a* would be much smaller on the displacement record.

The only case where records from the 3 instruments would be similar is when the vibratory motion is simple harmonic, such as an unbalanced rotor. The question then arises as to which of the 3 should be used in a determination of the frequency to be isolated, where the machine is more complex. Since we are interested in damage to the structure or annoyance to persons, the measurement which best measures damage or annoyance is the proper one to use. Since acceleration is proportional to unbalanced force it seems reasonable to accept acceleration as the best measure of damage. Through evidence collected by seismologists and engineers acceleration is a better measure of structural damage than velocity or displacement.

Figure 4



Experiments have been made in order to establish a unit of "nuisance level" of vibrations, that level at which people term a vibration an annoyance. Neither acceleration, velocity nor displacement are satisfactory as a unit. When the vibrations are accompanied by noise, it very often happens that eliminating the noise results in the opinion that the vibration difficulty has been overcome. What one person calls an objectionable vibration, another does not, so that the establishment of a satisfactory

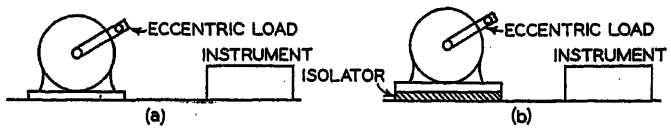



**Figure 5**

nuisance level does not seem possible. Such being the case and accepting the fact that acceleration is the best measure of damage, the accelerograph is preferable to the velocity or displacement recording instruments.

It is well to examine the more practical aspects of vibration isolation with the idea of pointing out the more common errors made in installation. The most common of these is "bridging." Many installations are found in the field where the use of holding-down bolts makes the application useless.

A "bridged" isolator is shown in figure 7*a*. Here the holding-down bolt or lag screw is rigidly connected to the

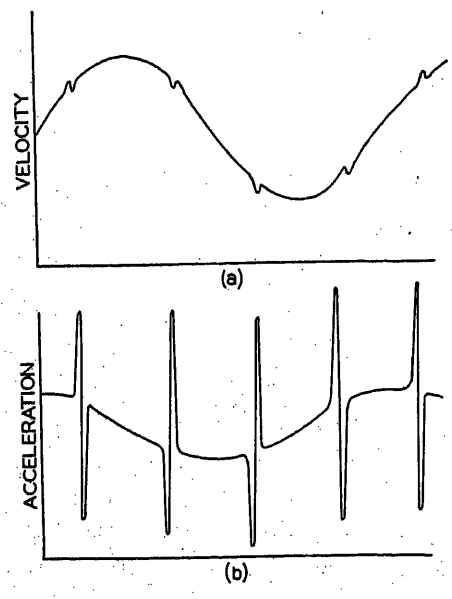



**Figure 6**

machine foot and to the floor, and offers a direct path for the transmission of vibration. Where holding-down bolts are necessary the installation can be made as in figure 7*b*, where no direct path for the transmission of vibrations is available, except through the isolating material. In such arrangements clearance must be provided between the bolt and the machine footing. The lower pad takes the sum of bolt load plus machine load, and the upper pad, the bolt load. Generally the bolt load is in excess of the mass load of the machine. The efficiency of the isolation is determined by the mass load and not by the bolt load. Consequently, it is necessary to use a material which is capable of taking the bolt plus machine load without deterioration. This is necessarily a stiffer material than one which would have to withstand the machine load alone, and isolation efficiency is sacrificed. Many machines have to be bolted down.

It has been found that a great many others which are ordinarily bolted do not require bolts provided the pad can be cemented to the foot of the machine and to the floor. It has been found, for example, that a satisfactory

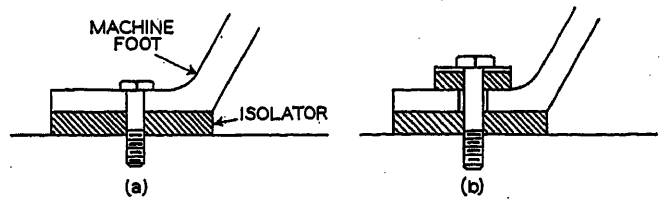
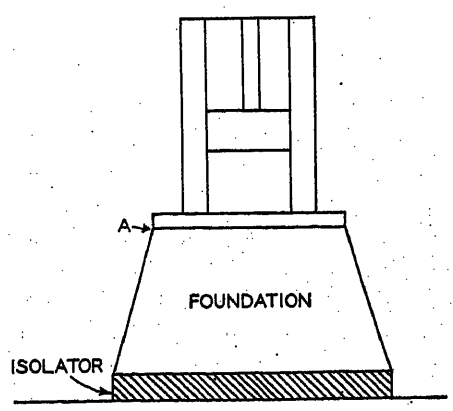



**Figure 7**

and preferable method of mounting looms is by eliminating the bolts or lag screws, and cementing the pad. The loom stays fixed in its location, the mass loading on the pad is correct, and the cost of the pads themselves is largely offset by the saving in the cost of installing the lag screws or bolts.

In connection with the loom problem, it is interesting to note that many loom sheds have very large horizontal

**Figure 8**




vibrations. This occurs when a number of looms get in phase and the disturbing force is high. The natural frequency of the structure in which the looms are housed is often in the neighborhood of the loom speed so that a condition approaching the resonance peak exists. With the advent of increased loom speeds it is probable that in many cases the loom speed will more nearly agree with the natural frequency of the structure and the vibration situation will be very much worse.

One of the most troublesome of vibration transmitting

machines is the drop hammer. Unisolated drop hammers give rise to vibration which are transmitted long distances and seriously affect adjoining property owners. To isolate a hammer already installed is an expensive job to do properly. The machine must be taken down and the isolation material installed underneath the foundation as in figure 8.

Placing the isolation material directly under the hammer (at *A*) will result in a loss of hammer efficiency. The material must withstand the mass loads of machine and foundation, and be capable of long life under the effect of the hammer blows. The magnitude of the blow is difficult to determine since it depends upon the size of the hammer, the drop and the temperature and nature of the work. However, on large hammers the impact blow is of the order of 2,000,000 pounds.

Punch presses are serious offenders. The record shown in figure 9*a* is of an unisolated punch press. The film speed of this record was 3.5 inches per second. The calibration of the instrument showed that a displacement of the light source of 0.23 inches from its median position indicated an acceleration of 10 per cent of gravity. The blows occur about every 1.3 seconds. This, however, is not the frequency which has to be isolated. The frequency of vibration at the impact is of the order of 100 vibrations per second. Figure 9*b* shows the effect of installing isolation material.

Machine footings are of all sizes and shapes. The loading on the footings cover a wide range. In the use of pad materials we can vary the thickness and area of the



Figure 9a (top) Figure 9b (bottom)

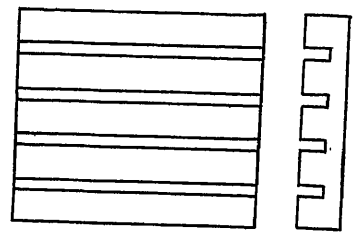
pad to get the desired load-deflection conditions. Furthermore if the material itself can be manufactured to get various load-deflection properties for a given thickness, all conditions of loading met within practice can be properly treated.

We have previously talked almost entirely of vertical vibrations. These are greater sources of disturbance ordinarily than horizontal vibrations. Where horizontal vibrations are large, then the isolator must be installed with the viewpoint of simultaneously correcting for both vertical and horizontal vibration. This may be accomplished by grooving or slotting the pad in the proper direction, as shown in figure 10.

The pad is placed under the machine so that the direction of maximum horizontal vibrations is perpendicular to the slots. Various other arrangements of grooving or slotting are possible.

Ship vibrations are exceedingly troublesome. These are caused by machinery within the ship and by disturbances originating at the propeller. Very little has been done in isolating the machinery of a ship. Proper alignment of shafting and the demand for stability during the rolling and tossing of the ship are additional demands which must be met by the isolation installation. Recent work on smaller pleasure cruisers has shown, however, that annoying vibrations can be greatly reduced by isolation of the main motor and a suitable flexible coupling in the propeller shaft.

Figure 10



Any isolation material to be effective allows the machine more freedom of motion than an installation with no isolation. In advertising one frequently sees charts of the vibrations of an isolated machine, compared with the vibrations of the surroundings. Such a comparison is unfair. The only fair comparison is a record of the vibrations of the surroundings due to an unisolated machine, as compared to an isolated one operating under the same conditions.

Structurally borne noises are a source of disturbance frequently found in factories particularly where offices are located adjacent to manufacturing operations. Correction can be made by isolating the disturbing machines. Quite frequently attempt has been made to quiet the office by the installation of sound absorbing material on the walls or ceilings. These applications do not give the desired results. The sound absorbing material is effective in correcting air borne disturbances. Those noises which are structurally borne are best handled by attacking the problem as near the source of disturbance as possible and installing proper machine isolation.

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# New Oil-Filled Cable Lines in Chicago

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Several recent developments in cable, joints, reservoir layout, and installation are incorporated in the 4 66-kv single-conductor oil-filled underground lines being installed in Chicago in 1936–37. The main results are economies and simplification. The emergency ratings of the lines are 115,000 kva in summer and 135,000 kva in winter.

DURING 1936 and 1937 the Commonwealth Edison Company is installing in Chicago 4 66-kv underground lines consisting of about 100 miles of single-conductor oil-filled cable. A summary of developments made in connection with these lines, which have a nominal rating of 100,000 kva, is given in this paper. The main objectives were to simplify oil-filled cable systems and make them adaptable for installation in standard underground conduits and manholes, and to reduce costs.

The principal results obtained as compared with previous oil-filled cable installations were as follows:

1. Ten or 12 per cent reduction in insulation thicknesses.
2. Substitution of copper-bearing lead sheath for more expensive 2 per cent tin sheath.
3. Smaller, simpler, and more economical stop and feeder joints.
4. Use of simpler and more economical reservoirs, and development of staggered system of oil feed.
5. Simplified layout, and development of joints and reservoirs that could all be installed in standard manholes, instead of requiring special manholes or towers.

The changes made during this development work in insulation thicknesses, kind of lead sheath, joint design, reservoir layout, etc., have been adopted in principle for oil-filled cable work in the United States. Employing these and other new ideas developed during the past 10 years, including sheath loss elimination, the cost of an oil-filled 132-kv line to have the same carrying capacity as the 1926–27 Chicago line[1] would be only 55 per cent of the cost of the actual installation.

## Economics

These 4 oil-filled lines are additions to a 66-kv system which connects 5 generating stations and 2 distribution stations, power through transformers being fed in at some stations and being taken out at other stations. See figure 1. The system is divided into 2 parts throughout the city with bus tie switches available at the terminal for special use.

The original 66-kv lines installed in 1926 to 1931 consist of 280 miles of 750,000-circular-mil cable of the ordinary solid type with 1,000,000-circular-mil cable in the warmer conduits, and the carrying capacities in the summer for normal and emergency conditions are, respectively, 52,500 and 56,000 kva. System growth warranted the installation of lines having an emergency rating in the middle of the summer of 115,000 kva. As compared to the former standard lines, these new lines result in a saving of about 25 per cent in cost per kva of carrying capacity and in a substantial saving in cost and space for the terminal facilities.

Satisfactory cables of both the ordinary and oil-filled type were available. Early in 1933, 2,100,000-circular-mil segmental-conductor cable of the ordinary type was used for a 9,000-foot line between Calumet and State Line stations because of a 10 per cent advantage in costs over an oil-filled cable installation for the same copper temperature. For the 1936–37 lines, oil-filled cable was used mainly because of the larger emergency carrying capacity and lower annual charges per kilovolt-ampere. Figure 2 illustrates the 3 main types of 66-kv cable that have been used in Chicago.

From the standpoint of over-all economy as well as from the need to avoid overcrowding principal routes for conduits between stations, it was desirable to use existing conduits for the new lines as much as possible; this has been done for 60 per cent of the oil-filled 66-kv cable installed. It was necessary to limit the average losses of the new lines in order to avoid overheating the existing cables in the conduits. This limitation required the use of 2,100,000-circular-mil conductors for either the oil-filled or the ordinary type of cable in most of the conduits, and 2,800,000- or 2,600,000-circular-mil conductors, respectively, in the congested conduits near stations. Studies and experience with the first line, however, showed that with 2,100,000-circular-mil oil-filled cable it was possible to allow its temperature to be a few degrees above the maximum permissible for cable of the ordinary type. As a result, only 4 per cent of the length of 4 lines will consist of 2,800,000-circular-mil cable, whereas 15 per cent of the length would have had 2,600,000-circular-mil conductor if ordinary cable were used. The oil-filled cable had a hollow core 0.69 inch in diameter, while the ordinary cable considered had a conductor consisting of 3 segments to obtain reduced copper losses. For the emergency ratings of the oil-filled cable, this meant copper temperatures in the warmer conduits about 10 degrees centigrade below the guaranteed maximum value of 75 degrees centigrade.

When the peak loading necessitated by emergency system conditions begins to approach the maximum rating of

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1. For all numbered references see list at end of paper.

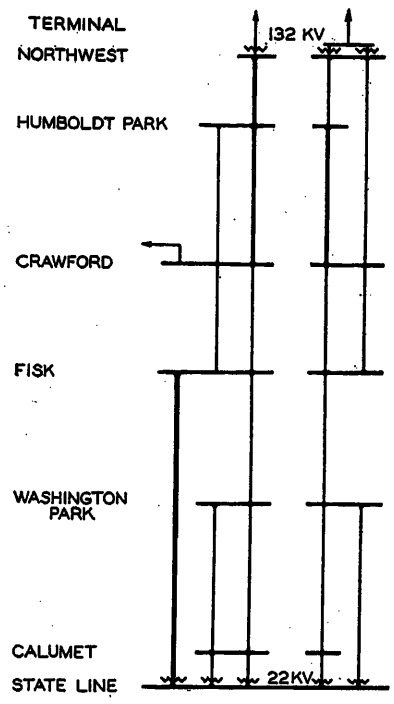



**Figure 1. Underground system for 66 kv in Chicago at end of 1937**

Heavy lines represent oil-filled cable; light lines represent cable of ordinary type

Drawing is practically to scale; State Line-Fisk line is 15 miles long

All terminals are generating stations except Humboldt Park and Washington Park

a line, then an additional line must be installed, in spite of the fact that the carrying capacity of the existing line under normal conditions may be adequate. The emergency ratings for the solid type cable were limited not only by the maximum allowable specification temperature of 60 degrees centigrade, but also by operating experience which indicated that the use of large temperature ranges would create undue internal pressures and sheath expansion. Based on operating experience and measurements of internal pressures on 750,000- and 2,100,000-circular-mil cables in service, and taking the expected normal loading into account, the maximum allowable daily range in copper temperature during emergency loading of the 2,100,000-circular-mil solid-type cable lines considered (656 mils of insulation and 156 mils of sheath) appeared to be about 15 degrees centigrade in summer and 17 in winter. With such daily temperature changes, it was expected that the internal cable pressures might be 50 or 75 pounds per square inch, even after a line had been in service and had experienced some sheath stretching.

The emergency rating for the oil-filled cable in the summertime was limited by the temperature requirements for other cables in the same conduit, while for winter conditions it was determined by what was considered the limit of possible future requirements. The winter rating could have been made larger by the installation of a few more reservoirs.

The relative costs for the 2 types of 2,100,000-circular-mil cable, shown in table I, were determined on the basis (1) of bid prices obtained in the fall of 1935 for cable and accessories and (2) of the experience of the Commonwealth Edison Company in installing, maintaining, and loading somewhat similar lines. Incidentally, the estimated cost of the first line installed differed from the actual cost by only 1 per cent. The costs shown include indirect or overhead costs such as engineering, storeroom, superintendence, and interest during construction.

The total annual charges for the 2 types of cable were almost the same. Due to the higher emergency carrying capacities of the oil-filled cable, however, the annual charges per kilovolt-ampere of carrying capacity were about 9 per cent less for the oil-filled system in summer, and 18 per cent less in winter. Oil-filled cable was, therefore, selected for the new lines. Later experience showed that the saving with oil-filled cable was slightly greater than originally expected.

To figure the fixed charges on the investment, the authors used the same rate of depreciation for both types of cable, although the use of a lower rate for oil-filled cable would have been defensible. The annual charge for "maintenance" includes the cost of (*a*) repairing oil leaks, (*b*) routine inspection of cable in manholes for sheath cracks and checking of reservoirs, and (*c*) the cost of repairing failures. The assumed rate of failures for oil-filled

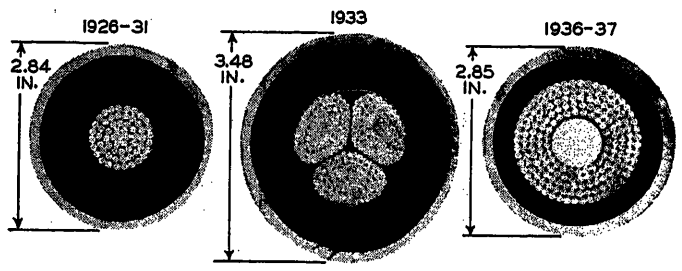



**Figure 2. Changes in 66-kv cables in Chicago**

| | 1926–31 | 1933 | 1936–37 |
|---|---|---|---|
| Type of insulation | Ordinary | Ordinary | Oil-filled |
| Insulation thickness, mils | 750 | 688 | 315 |
| Conductor size, circular mils | 750,000 | 2,100,000 | 2,100,000 |
| Maximum summer rating, kva | 56,000 | 105,000 | 115,000 |

cable was one cable or joint burnout per 100 miles of cable per year, with no anticipated failures.

One factor that was hard to evaluate for solid type cable was the effect of its maximum diameters being about 3.4 and 3.6 inches, respectively, for its 2 sizes. A slight amount of conduit used had $3^1/_2$-inch ducts, which would not have been usable. Experience showed also that some of the standard 4-inch ducts would have had to be rebuilt for the 2,100,000-circular-mil cable and probably the 2,600,000-circular-mil cable could not have been installed in most of these ducts.

## Insulation

The 1934 edition of the AEIC cable specifications gives an insulation thickness of 350 mils for oil-filled cable having a rating of 69 kv, except that above 2,000,000 circular mils the cable was to have 25 mils more of insulation. The manufacturers first thought that it would be satisfactory to use a thickness of 350 mils for the 2,100,000-circular-mil cable, but that for the 2,800,000-circular-mil cable the extra thickness would be necessary. The thickness used on the only oil-filled 69-kv cable previously

made in this country (in 1930 for Cincinnati) was 406 mils. After some discussion of American and European experience, the thicknesses agreed upon were 315 mils and 330 mils, respectively, for the 2 Chicago sizes.

The Commonwealth Edison Company has been making periodic measurements of the power factors of 2 short oil-filled 132-kv lines put in service early in 1930. The insulation thickness is 719 mils. Figure 3 shows that the power factors at 15 degrees centigrade and operating voltage have remained practically constant, which indicates that the insulation has been quite stable.

About 8 years ago, this utility installed 4 1,000-foot lengths of experimental cable which were tapped to an overhead 132-kv line and were subjected also to heating by means of current transformers. The insulation thicknesses ranged from 386 to 526 mils. For 2 years these cables were

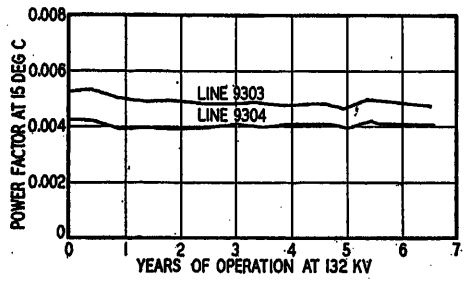



**Figure 3. Power factor of the insulation of 2 commercial oil-filled 132-kv lines**

subjected to daily load cycles with temperatures as high as 75 degrees centigrade. Subsequently, the heating has been continuous to temperatures as high as 85 degrees centigrade, except that occasionally the cables were allowed to cool for power factor measurements. The results of these tests have shown the following:

(*a*) The voltage did not appear to cause any deterioration of the insulation. The maximum stresses ranged from 188 to 250 volts per mil.

(*b*) Temperatures up to about 80 degrees centigrade did not appear to cause any deterioration of the insulation.

(*c*) The changes which have been observed in some of these cables have been of a type that accompanies chemical reactions. If the insulating oil becomes oxidized, chemical action with the metals may result, causing the oil in the cable to darken in color and to increase in power factor, although its dielectric strength remains practically unchanged.

In 1932 it was necessary to remove from a commercial line in Chicago 3,000 feet of 132-kv oil-filled cable that had been installed in 1930, because of deterioration of this kind resulting from oxidation of the oil. The dielectric losses of the cable insulation had increased so much that the cable was fully heated when carrying almost no load. Although extensive investigations were conducted over a period of several years, the origin of this oxidation was not discovered other than that it was due either to overheating of the oil or to contamination of the cable, or both.

This experience indicated again the necessity of preventing overheating of the oil and preventing entrance of air into the cable. Now extensive tests of core oil from the completed cable at the factory, including a power factor or resistance test at 100 degrees centigrade of a sample of oil from each length, and tests of oil used in the field, are made as a routine procedure. Also, as discussed later, special precautions are taken in the field.

The experience with the experimental cables indicates that within limits the thickness of insulation was of little or no importance in connection with the chemical action. Results of tests of power factor, acidity, etc., obtained on samples of core oil removed periodically from the 4 commercial oil-filled 132-kv lines in Chicago have indicated that an initial period of deterioration occurred as a result of minute impurities in the installed line; but this core oil deterioration has caused no perceptible increase in dielectric losses of the cable as a whole. The initial reaction of impurities appears to have taken about 2 years.

In view of all these considerations and of the successful operation of large amounts of oil-filled cable in Chicago and elsewhere, reductions in insulation thicknesses were obviously warranted. The recommended thicknesses are now 315 and 560 mils of insulation for

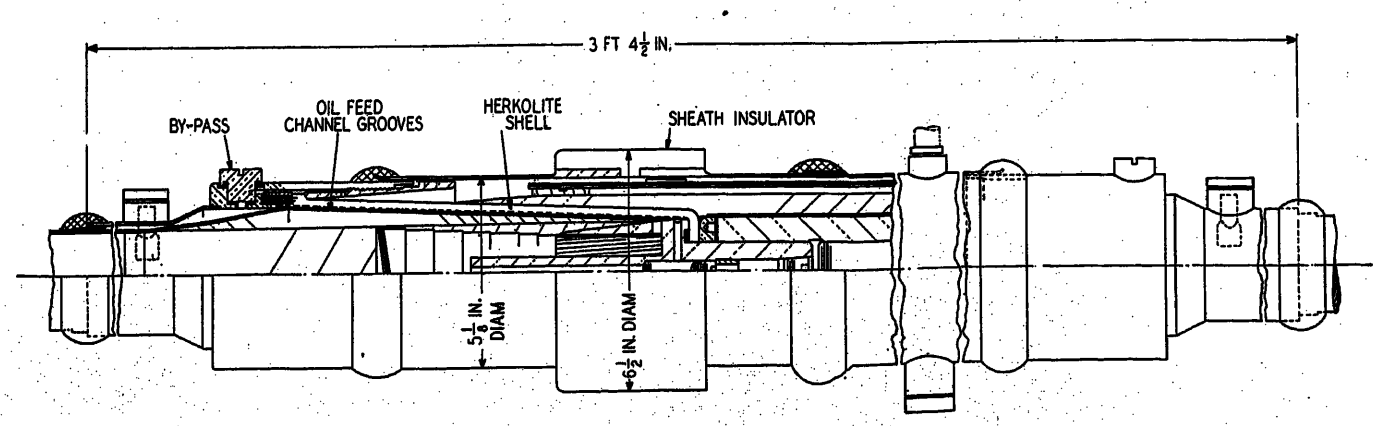



**Figure 4. Herkolite shell stop and feeder joint for 69-kv hollow-core 2,100,000-circular-mil single-conductor oil-filled cable**

cable rated at 69 and 138 kv, respectively, except that slight increases are made for extra-large conductors.

The indications are that, perhaps, even smaller thicknesses may be used from the standpoint of steady voltages, but that further reductions will be retarded by the limitation of impulse strength of the insulation to withstand surges incidental to failures, switching, or lightning.

## Lead Sheath

Until recently, oil-filled cables in the United States were furnished with 2 per cent tin in the lead sheath in order that the cable would present a hard surface during pulling to minimize abrasion. Improvements in the installation of conduit and in the mandreling of ducts to remove small pebbles and other obstructions have made a special hard surface sheathing unnecessary.

Research done at the University of Illinois for the Utilities Research Commission showed that the rate of creep of copper-bearing sheath under tension was usually considerably less than the rate of creep of other sheaths in normal use including 2 per cent tin-lead sheath. The rate of creep is important because oil-filled cables operate continuously with positive internal pressures. Copper-bearing lead may be obtained without any extra expense at present as ASTM grade II lead, or as a mixture of highly refined grade I or III lead and about 0.055 per cent copper having a pure lead content of at least 99.85 per cent.

It was, therefore, decided to use copper-bearing sheath at a saving of almost 5 per cent in the cost of the cable.

In order to prevent excessive expansion of the sheath during the normal life of oil-filled cable, the tensile stress on the sheath has been usually limited to 120 or 150 pounds per square inch, based on the nominal sheath thickness. This corresponds to an internal pressure of 12 or 15 pounds per square inch for the Chicago cables. Important improvements have been made in the manufacture of cable sheaths during the past few years. Better uniformity in sheath thickness and in exclusion of nonmetallic impurities has resulted. It seemed, therefore, especially with copper-bearing lead, that it was feasible to increase the maximum allowable internal pressure with variable pressure reservoirs to 17 pounds per square inch. This was particularly safe for the new lines, since the maximum operating pressures will usually be 8 or 10 pounds. The sheath thicknesses used were $^{9}/_{64}$ and $^{10}/_{64}$ inch, respectively, for the 2,100,000- and 2,800,000-circular-mil cables.

Where differences in elevation give a considerable hydrostatic head of oil within the cable, a double sheath is used, having 2 parallel copper ribbons wound between the 2 sheaths to reinforce it. Such lengths are being installed in Chicago in tunnels under the rivers and where the cable rises to upper levels in a distributing station. The maximum internal pressure in these lengths is 30 pounds.

## Design and Manufacture of Cable

The design and manufacture of oil-filled cable were rather fully developed by the time the first of these 66-kv lines was planned. Consequently, the general process of manufacture did not differ materially from past practice. New features introduced were for purposes of further reducing cost or giving additional assurance of uniformity and freedom from impurities. The cable was furnished by 4 American manufacturers.

The conductor design was of the conventional hollow-core type with a supporting spiral of steel strip. The reduction in insulation thickness has already been discussed. The inner third (approximate) of the insulation consisted of high-density paper tape. The rest was of paper of more conventional density. Previous study had shown these proportions to give a good balance, from both a technical and a cost standpoint. The dielectric power factor, ionization factor, and time of impregnation treatment are not appreciably affected, as they would be with too much high-density paper; and, in return, there is gain in the way of mechanically stronger foundation tapes and increased impulse strength (10 to 15 per cent).

Thoroughly washed wood-pulp paper was used, and a system of testing all paper to assure uniformity and freedom from impurities was followed. Likewise, a system of handling and checking the impregnating oil for uniformity before and after treatment was closely followed. Such oil was used only once, and any oil exposed to the atmosphere or to excessive heat in sealing the cable ends was flushed out and discarded.

The final electrical and physical tests to which every reel length is subjected leave little possibility of nonuniformity. These tests consist chiefly of dielectric power factor and ionization measurements on finished lengths, chemical, electrical, and physical tests on withdrawn samples of core oil, a continuous oil pressure leakage test, and an expulsion test for detection of trapped air.

The change to copper-bearing lead sheath and the

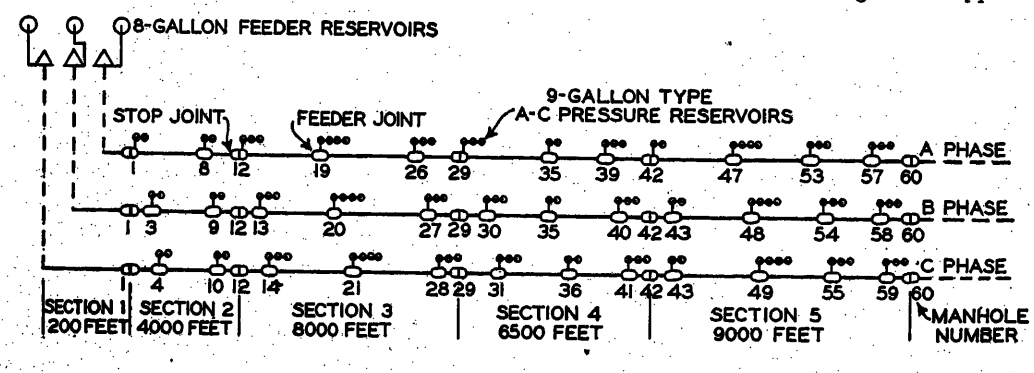



**Figure 5. Typical layout of oil feed system**

Distance between manholes is assumed to average about 500 feet, except adjacent to terminals

factory improvements leading toward a more uniform sheath have already been mentioned. Trouble with single-wall lead sheath, limited to low working pressure (15 pounds per square inch), has been almost negligible in the past. This, of course, is due to the exact control of pressure in oil-filled cable. With sheath of improved quality, practically entire absence of sheath trouble due to working pressure strains may be reasonably expected.

## Design and Manufacture of Accessories

Some general comments on accessories will be given before describing some of them in detail. These high-voltage accessories consist of a surprisingly large number of parts; and, since most of them must be assembled directly in the field, rather than in the factory, it is much more difficult than generally supposed to assure that these parts will always fit together exactly, in the simplest possible way and in minimum time. Perfection of these details requires constant close co-operation between the manufacturer and user. All of the accessories were furnished by one American manufacturer, except that some of the joints for the later lines were furnished by another American manufacturer.

Normal joints and stop joints, and, in most cases, terminals require application of reinforcement insulation wrappings in the field. In Europe these wrappings usually consist of pretreated paper sheet or tape. In this country bias-cut varnished cloth tape has usually been used because it is easier to apply, is more economical, and there is less chance of absorbing impurities during exposure. In the past a vacuum-treated tape made with black asphaltic varnish has been used. This type of varnish is slightly soluble in oil and increases the power factor of oil exposed to it. While this property is not desirable, it has caused no failures in service.

To overcome this, a new and oil-resistant yellow varnished cloth tape was developed and used for the first time in the Chicago 66-kv accessories. (All accessories were rated at 69 kv.) This new tape also has lower dielectric power factor and is mechanically superior.

One primary requirement was that all joints and reservoirs be sufficiently compact to fit in standard-sized manholes and avoid the inconvenience and expense of manhole enlargement. Normal joints of conventional design easily met this requirement as the internal diameters were 5 or $5^1/_2$ inches and the lengths were 32 to $34^1/_2$ inches. A molded or porcelain sheath insulator was incorporated directly in the copper casing, with a resultant material saving in cost and compactness when compared with separate sheath insulators.

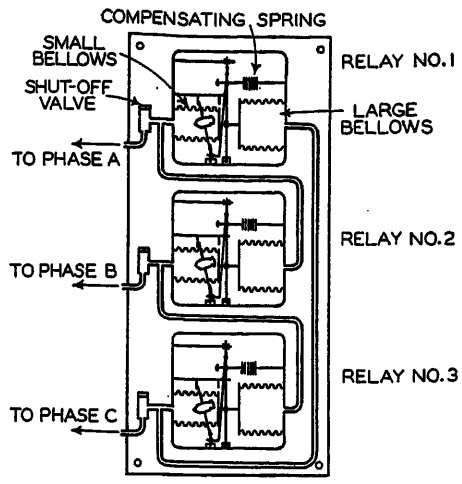



**Figure 7. Diagram of phase differential alarm relays arranged for connection to 3 phases**

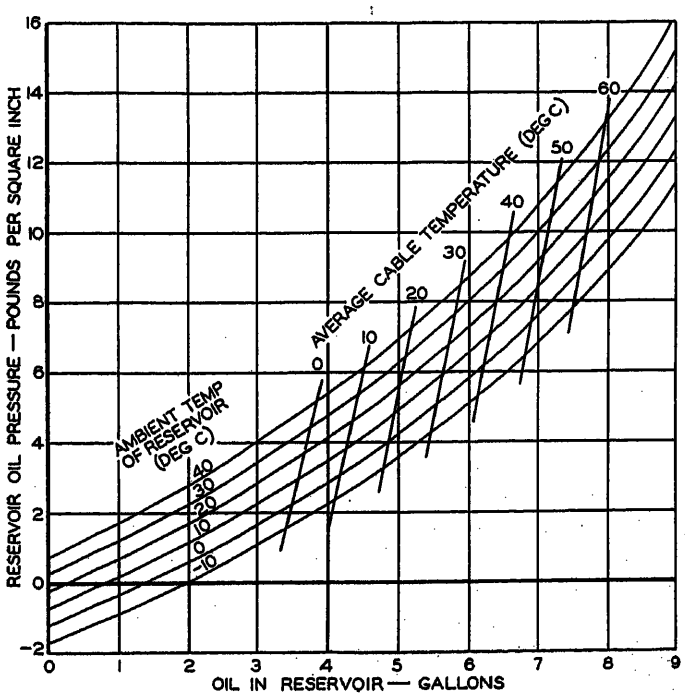



**Figure 6. Operating characteristics of AC reservoirs at one feed point**

At this feed point the oil pressure would be 8 pounds per square inch when the average cable temperature is 40 degrees centigrade and the ambient reservoir temperature is 20 degrees centigrade. At adjacent feed points the pressure on the same phase-section would be higher or lower, in accordance with the intervening hydrostatic head pressure

## Stop and Feed Joints

### Herkolite Shell Joint

The ground contour in Chicago is practically flat. It played no part in determining the best location for stop joints with which a line is segregated into sections, except for a few special cases. Other factors, to be described later, determined this. The length of section in Chicago is of the order of 8,000 feet. Because of pressure drop along the cable core and the requirement of keeping maximum allowable pressure within the limits of single lead sheath, it is necessary to have reservoir feed points at intervals of 2,500 to 3,500 feet along the cable. This requires feed joints at these points, intermediate to stop joints, for purposes of connecting the reservoir to the cable core. As this same requirement holds for stop joints also, there is actually no difference in design but only in method of oil

connection. The stop-joint connection definitely shuts off oil flow across the joint while the feed-joint connection allows this flow by means of a controlled by-pass. These joints will be referred to merely as stop joints.

Prior to the 66-kv Chicago installations, the conventional stop-joint design consisted of 2 porcelain shell terminals placed end to end on a horizontal axis, connected electrically together and enclosed in an oil-filled cylindrical copper casing. Each shell assembly is similar in internal construction and appearance to the usual porcelain cable terminal, except that the petticoats are omitted.[2] A stop joint of the porcelain shell design for the 66-kv Chicago installations would be 9 inches in internal diameter and 49 inches in length. This is too large to fit in standard manholes and too costly for frequent intermediate feed points. The development of a smaller and less costly design was an important requirement.

In designs of this type, Herkolite has decided advantages over porcelain. It consists of paper laminations impregnated and cemented together under heat and high pressure. It is only recently that the art of constructing this material in such shapes as required for stop-joint shells has been perfected. It is stronger than porcelain, both mechanically and electrically, and can be molded and machined to exact dimensions. Another advantage is that longitudinal oil-feed channels can be machined on the inner surface of the shell, whereas, with porcelain a clear annular space of much larger dimensions, and with a corresponding reduction in allowable stressing of the oil gap, is necessary.

Changing to Herkolite shells resulted in a material reduction in diameter and length of stop joint. This in turn allowed simpler and more compact methods of compressing the sealing gaskets at each end of the shell. The result has been a stop-joint design retaining the proved ruggedness of the gasketed shell principle but sufficiently compact for standard-sized manholes and little larger than a normal joint.

Figure 4 shows the new Herkolite shell design. The joint dimensions are 5 inches by $40^1/_2$ inches and its internal volume is only 25 per cent of that of the old porcelain design. Its small size allows the incorporation of a sheath insulator in the joint casing, which is another advantage.

When used as a stop joint, it must have one end hydraulically connected to the central casing enclosure for purposes of maintaining oil pressure in this enclosure. If oil feed to the cable in one or both directions is desired with the stop-joint connection, it is necessary to connect separate reservoirs to one or both ends of the joint. When used as an intermediate feed joint, both ends and the central enclosure are connected to a common reservoir.

In the past, the latter connections consisted of short sections of external by-pass piping with necessary fittings and control valves. This method of connection was followed for the joints developed for the first Chicago 66-kv installation. Further study showed, however, a more economical and better mechanical assembly could be realized by incorporating the by-pass connections directly in the joint casing, as illustrated in figure 4. Oil passages connect the end enclosure to the central enclosure at both ends of the joint. The passages can be shut off or left open at will by means of threaded, gasketed plugs, as shown.

### Condenser Joint

The condenser principle of controlling longitudinal and radial stresses in electrical designs is well known. It consists of intermediate electrodes, usually sheets or strips of metal foil, incorporated in the main body of insulation and resulting in a series of small capacities that divide the electrical stress, with a resulting reduction in dimensions. The condenser principle lends itself to stop-joint design, and the details of earlier developments have been described.[3] The condenser unit, representing the main insulation, of the joint, is factory made and materially reduces the field application of insulation wrappings.

The condenser joint designed for the 66-kv system in Chicago meets the main requirement of fitting in standard-sized manholes. It is $5^3/_8$ inches in internal diameter and $42^7/_8$ inches long. This makes it much smaller than previous similar designs. A porcelain sheath insulator is incorporated in the casing by the method of metal-to-porcelain soldering. The oil stop tubes used in the earlier design of joint were eliminated and the oil stop was obtained at the center of the joint by means of an oil-resistant rubber gasket between the connector and the metal tube forming the central inner surface of the condenser unit; the rest of this inner surface is of insulation. Two spring valves in the connector, one on each side of the oil-stop gasket, control the oil passages between the cores of the 2 cable ends and the 2 halves of the joint. The valves are manipulated during joint construction by treated cloth ribbons threaded along the oil-feed space to levers directly under plug openings in the ends of the joint casings; and the ribbons have no function during service as the valves are then open. Passages for by-passing the oil-stop are incorporated in the joint assembly.

The condenser stop-joint design requires more straight cable in the manhole and more care in assembly than the Herkolite shell design, and requires less time for assembly.

## Reservoir Feed System

Considerable time and expense has been given to the possibility of developing new and more economical designs of oil reservoirs. So far, the cell-type reservoir, consisting of a stack of individual cells with corrugated metal diaphragms enclosed in a cylindrical tank, has proved the best. There are 3 modifications of the cell-type reservoir available, all of which are described elsewhere[4] in detail.

The type *CC* gravity-feed reservoir has all cells connected to a common manifold, with the cells filled with oil. The enclosing tank is open to the atmosphere through a breather. It is, consequently, necessary to elevate this reservoir to obtain pressure feed to the cable. On level ground such as exists in Chicago, this involves expensive feed towers.[1] In the present 66-kv Chicago system, type *CC* reservoirs are used only at the vertical terminal ends where the desired elevation is already available on the switching structure.

The type *DC* balanced-pressure reservoir is similar to the type *CC* except that the enclosing tank has extra length and is sealed full of gas. The gas pressure may be adjusted as desired, and so it is not necessary to elevate this type of reservoir. Rather exact control of the oil feed can be obtained even with reservoirs at different elevations.[5,6] In making the type *DC* reservoir, there is a great deal of brazing and other hand work in paralleling the cells to the manifold, which increases cost.

The type *AC* reservoir has a simpler and more economical cell arrangement. The cells are individually sealed off full of air at atmospheric pressure by automatic welding. Elimination of manifold connections materially reduces hand work and cost. The oil is in the enclosing tank instead of the cells. The pressure on the oil is obtained by forcing in enough oil to compress the air cells, and for this reason is not under complete control. Unlike the type *DC* reservoir, a relatively high oil pressure cannot be obtained when the reservoir is nearly empty, or a relatively low pressure when the reservoir is nearly full. The maximum safe operating pressure is about the same as the limit dictated by the strength of the sheath, i.e., 15 pounds per square inch.

**Table I. Economics of 2,100,000-Circular-Mil 66-Kv Lines in Fall of 1935**

Figures Include Indirect Costs

| | Type of Insulation | |
|---|---|---|
| | Oil Filled | Ordinary |
| **Costs per Mile of Line** | | |
| INVESTMENT: | | |
| Cable | $ 55,900 | $ 71,800 |
| Accessories | 15,740 | 6,010 |
| Installation | 12,800 | 9,580 |
| Conduit, prorated | 21,870 | 21,000 |
| | $106,310 | $108,390 |
| ANNUAL CHARGES: | | |
| Fixed: Cable at 11½ per cent | $ 9,700 | $ 10,040 |
| Fixed: Conduit at 10½ per cent | 2,300 | 2,210 |
| Copper losses | 1,550 | 1,490 |
| Dielectric losses | 320 | 250 |
| Maintenance | 440 | 330 |
| | $ 14,310 | $ 14,320 |
| **Emergency Carrying Capacity, Kilovolt-Amperes** | | |
| Summer | 115,000 | 105,000 |
| Winter | 135,000 | 115,000 |
| **Annual Charges per Kilovolt-Ampere of Carrying Capacity** | | |
| Summer: cents | 12.4 | 13.6 |
| Summer: per cent | (100) | (109) |
| Winter: cents | 10.6 | 12.5 |
| Winter: per cent | (100) | (118) |

In spite of its simplicity, the type *AC* reservoir is not so economical as the type *DC* on hilly contour because the hydrostatic head pressure on the reservoirs at low elevations causes them to become partly filled with oil, thus wasting much of the capacity. With type *DC* reservoirs, it is only necessary to pump up the gas pressure to avoid this.

On reasonably level contour, as in Chicago, a material saving may be realized by using type *AC* reservoirs, even though the efficiency is rather low. The ratio of useful to total capacity of the *AC* reservoirs in Chicago is 50 per cent.

This means that about twice as much manhole space is required for the *AC* reservoirs as for corresponding *DC* reservoirs. In the past it has been customary to install *DC* reservoirs for all 3 phases of single-conductor cable in the same manhole. There is not room to do this with *AC* reservoirs without having a great number of feed points, and so a staggered feed system has been adopted. The reservoirs and the feeder joint for one phase are installed in a given manhole with those for the other 2 phases in usually the next manhole on each side. This method gives ample space with standard-sized manholes and results in economy in the use of feeder joints. Figure 5 illustrates diagrammatically some typical arrangements of stop joints, intermediate feeder joints, and reservoirs for various lengths of line sections used in Chicago.

From 2 to 4 9-gallon type *AC* reservoir units were connected in parallel at each feed point, depending upon the ground contour and the length of cable to be fed. In each section the total useful reservoir capacity was calculated to take care of the thermal expansion of the oil in the cable and accessories over the full annual temperature range, and without exceeding an allowable pressure range for the cable and reservoirs. Thirty per cent or more surplus reservoir capacity was added to the cable oil requirement for emergency use. The pressure limits were 0.5 pound per square inch above atmospheric pressure at the highest point of the section with all surplus exhausted and 17 pounds at the lowest point in the cable at maximum load temperature. In addition, it was necessary to make sure that the available reservoir pressure was sufficient to take care of maximum pressure drop in oil piping connections and along the cable core under all conditions of oil demand by the cable and accessories,[7] due both to temperature changes and exchange of oil between reservoirs caused by the semibalanced system of feed adopted.

Semibalanced pressure feed of the type just described makes the calculation of reservoir settings as a function of cable temperature more difficult and complicated than balanced pressure feed. The general mathematical formulas involved have been published,[6] but yet it is necessary also to resort to a cut-and-try method.

As previously explained, the reservoir oil pressure is practically equal to the gas pressure in the cells. This means that the ambient temperature of the reservoir affects the pressure. The complete pressure-volume-temperature characteristic of the 9-gallon *AC* reservoir is shown in figure 6 (curves slanting upward to right). Using this characteristic, oil pressures and corresponding oil volumes satisfying the following conditions are determined (by cut-and-try):

1. The total volume of oil in all the reservoirs on a phase of a line section at a given cable temperature must be in accordance with the calculated thermal expansion of the cable and accessories at that temperature.
2. The corresponding pressures in each group of reservoirs must lie within the allowable range, and the differences in pressure between reservoir groups must be equal to the hydrostatic pressures due to the differences in elevation.

After a sufficient number of such points has been determined, they are plotted on the reservoir characteristic, and points for equal cable temperature are connected by the vertical cross-lines shown in figure 6. One of these graphs is prepared for each feed point along the line. With the help of these, it is easy to determine the correct reservoir pressure for all stable conditions of cable and reservoir temperature. A short circuit heat run on the first Crawford-Humboldt line showed the calculated reservoir pressures to agree closely with the actual.

## Oil Relay Protection

Oil-filled cable furnishes an opportunity that usually does not exist with solid-type cable to detect leaks in the system, by means of oil relays, before electrical service failures develop from entrance of impurities. Such leaks as slight defects in the sheath, pipe fittings, or lead wipes, may be slow and require weeks to exhaust the reservoirs. Practically all of the leaks that have developed in previous oil-filled lines have been of this type. As long as the reservoirs are not exhausted, positive pressure is maintained and leakage of oil outward prevents entrance of impurities. Fast leaks may be caused by electrical failure or direct mechanical rupture of oil piping. Such fast leaks may exhaust the reservoirs in from 1 to 4 hours, depending upon restrictions offered and oil viscosity, and require a well-organized emergency repair system to prevent such exhaustion.

Regardless of the type of leak that develops, it is obviously desirable that the station operator learn of it as soon as possible. Relays set for minimum oil reservoir volume or pressure are necessarily slow in action, the reservoirs being fairly well exhausted before an alarm comes into the station. With 3-conductor cable, minimum setting relays are the only type that are economically acceptable. For gravity feed with single-conductor cable, differential-volume relays are fast and satisfactory. For single-conductor cable with balanced or semibalanced pressure reservoir feed, fast relay action is obtained by utilizing differential oil pressure between phases.

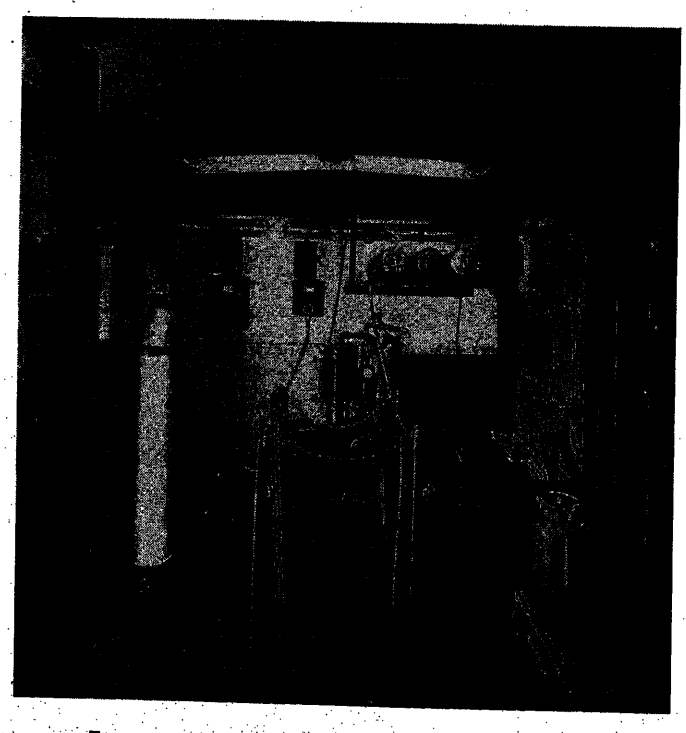


**Figure 8. Trailer over manhole during jointing**

Under normal balanced load conditions, the oil pressure in the different phases varies in the same way at any given point in a section. In case of oil leakage, the pressure decreases in the faulty section. The possibility of pressure in all 3 phases decreasing at exactly the same rate due to leakage is so remote that differential pressure between phases furnishes a reliable way of obtaining fast oil-relay action. It was necessary, however, to devise a phase differential relay that would do 2 things. First, means had to be found for compensating for differences in hydrostatic head pressure between different phases or at different points in any one section, caused by differences in elevation. Second, the reservoir pressure normally varies over a relatively wide range from no load in winter to full load in summer, which in extreme cases might be from one pound to 15 pounds. A differential setting of a small fraction of one pound would be necessary to properly take care of no load conditions, but this same setting would be too sensitive and lead to false alarms under full load conditions. What was desired was a differential relay having an operating differential pressure that would increase proportionately with the line oil pressure.

Both of these things are accomplished in the design shown diagrammatically in figure 7, first used in the 66-kv Chicago system. The relay consists essentially of 2 small opposing sylphon bellows having predetermined differences of area (the smaller has 25 per cent less area than the larger). Each opposing bellows is connected by oil piping to cable or reservoirs in different phases. At any point in the working pressure range the oil pressure in the large bellows must drop 25 per cent below the oil pressure in the small bellows to actuate the mercury switch shown This switch is connected through relay wiring to any desired type of alarm system at the station. By connecting 3 pairs of opposing bellows as shown in figure 7, not only will the relay operate if the pressure in any phase drops 25 per cent below that in the other 2 phases, but it will also operate if there is a 33 per cent increase in any phase, the operation in this latter case being reversed.

Since the compensating spring across each of the large bellows may be adjusted to compensate for and nullify hydrostatic head pressure, the relay is actuated entirely by variable working pressure, or rather by a constant percentage differential pressure within this working range.

## Bonding of Sheaths

With such large lines, the ratio of sheath losses to copper losses in case the sheaths are solidly bonded together would be about 225 per cent. Since experience showed that satisfactory insulating sleeves and methods of bonding had been developed to eliminate sheath losses, they were used.

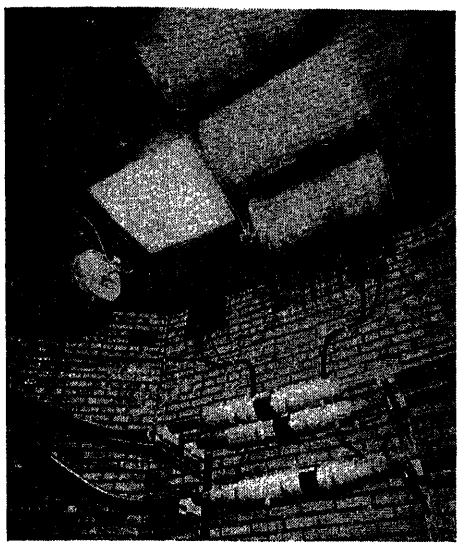


**Figure 9. Accessories installed in manhole**

Lower center—Two normal joints in upper position and Herkolite shell-type feeder joint in lower position. Note sheath insulators in joint casings and porcelain insulators under cables

Top—Four type AC 9-gallon reservoirs connected to feeder joint; reservoirs are placed with valves accessible from manhole opening

Upper center—Two bonding transformers, one connected on each side of sheath insulators in joint casings

Note: Cable and joints are fireproofed before line goes in service

Operating experience in Chicago indicated that for normal maximum loads of about 95,000 kva, the maximum allowable induced sheath voltage to ground from the standpoint of avoiding a-c electrolytic corrosion was about 11 volts. For emergency loading, the corresponding potential is about 15 volts. If the ordinary schemes of bonding were used, such as cross-bonding, then the maximum allowable length of cable between insulating sleeves would be about 320 feet based on normal loading, and somewhat less if based on emergency winter loads. The use of sheath bonding transformers[8] to reduce the voltage to ground to about 50 per cent of the induced voltage between insulating sleeves made it possible to use conduit sections up to 615 feet. During emergencies, the induced voltage from sheath to ground is about 16 volts, but the flow of exciting current through the sheath and bonding transformers reduces this potential to 15 volts with negligible sheath losses.

Cable lengths of the order of 615 feet are satisfactory also from the standpoint of allowable cable movement because during normal loading the daily cable movement at a duct mouth would be 0.4 to 0.55 inch and during emergencies the movement would be 1 to $1^1/_4$ inches. Chicago experience indicates that movements 40 or 50 per cent larger would be safe from the standpoint of obtaining long life of the sheath in the manhole without cracking.

The 3 phases of the lines had to be transposed frequently in order to minimize the induction of voltages and currents in other cables in the same conduits. The piping from the reservoirs was connected to the joints through pipe insulators. On end laterals, the practice was to ground the potheads and to have an insulating sleeve in the first joint.

## Installation

Theory and experience have indicated that special care must be exercised, not only in the factory but also during installation and operation, to avoid the ingress of impurities in oil-filled cable. In view of this situation, and the need for considerable engineering work on development of suitable accessories and on the reservoir layout system, it was found desirable to have more engineers employed in connection with the new lines than would have been the case with cable of the ordinary type. Such engineers also follow the work continuously during installation and are of considerable assistance to the field force.

The installation of the various types of joints requires in each case more than the usual working day of 8 hours. As a matter of efficiency in the use of equipment and man power, a new method of underground work was developed, that is, to construct in series all 3 joints and related work in a manhole on a continuous basis. In the 1937 work, 2 field crews each comprising 3 gangs and substitutes worked continuously 7 days a week, night and day, doing manhole work. By this means, the overtime payroll is kept down to a negligible amount and the efficiency of supervisors and splicers is not impaired by long working hours. Another advantage is that practically all the work in a manhole is completed in *one* set-up with a substantial saving in transportation and labor costs.

A further improvement adopted is the use of 2 specially built trailers. The trailer is set over a manhole opening, access to which is provided by means of an opening in the floor. This arrangement provides increased protection for the men against inclement weather and traffic hazards, in addition to keeping moisture and dirt from entering the manhole. See figure 8. Gasoline-engine-driven generators were used for power supply for equipment such as oil heater, water pump, air blower, and vacuum pump. Excellent lighting, which is conducive to good workmanship and a minimum of fatigue, was also provided thereby.

The following items briefly outline checks or procedures in the field to carry out the principle of preventing the ingress of impurities in the lines:

1. A final expulsion test and pressure check are made on each reel of cable immediately before installation.

2. The oil pressure in temporary reservoirs is frequently checked to make sure that the cable is under positive pressure and adequate oil supply is available for the flushing during jointing.

3. Care is taken during the installation to maintain the cable oil pressure *above* atmospheric pressure at all times. Only 2 short-time exceptions to this rule are permissible, namely:

(*a*) At the end of the time of installing the cable in the duct, when the source of oil feed to the cable is transferred from the reel reservoir to the temporary reservoir in the manhole.

(*b*) On soldering the connectors onto the conductors.

4. Vacuum tests are made on each completed joint prior to final filling with degasified oil.

5. The application of vacuum is always localized, i.e., the principle of not subjecting a cable length to vacuum in the field is followed.

6. Flow checks are made shortly after completion of each line section in order to determine the presence, if any, of partial or complete restrictions to oil flow in the joints or in the connecting piping.

7. Impregnation checks are made shortly after completion of joint work on each section, as an over-all check on the presence of air.

Tests and procedures used in the field designed to prevent the use of contaminated or overheated oil are as follows:

1. All degasified oil used in constructing the joints, filling the temporary oil reservoirs, and for additions to the permanent reservoirs is treated in Chicago. Such oil is the same as that furnished in cable and in reservoirs. Each lot of treated oil is required to meet the following requirements:

| Item | Temperature | Limiting Values | |
|---|---|---|---|
| | | Maximum | Minimum |
| Power factor—per cent | 100 deg C | 0.50 | |
| Resistivity—ohms per $cm^3$ | 100 deg C | | $15 \times 10^{12}$ |
| Gas content—per cent | Room | 1.0* | |
| Dielectric strength | Room | | 25 kv 1 min. |
| Color number | | | 1½ minus |
| Organic acidity—mg KOH/g | | 0.020 | |

* Reduce to 0 degrees centigrade and 76 centimeters mercury.

2. The maximum temperature to which the oil is subjected in the degasifying plant is 100 degrees centigrade.

3. After each soldering operation during installation of joint connectors, oil is drained from the cable to remove overheated oil and residual flux.

4. Dried oil used for flushing purposes during the construction of joints is heated by indirect means to 110–125 degrees centigrade. The supply of heated oil is changed daily and the tank is cleaned frequently.

5. The principle of not soldering accessories or piping containing oil that could thereby be overheated is followed.

6. Hot flushing oil is admitted to the joint casings after wiping and before proceeding with the vacuum and filling treatment.

7. All piping is swabbed, flushed, and temporarily sealed preparatory to installation. Wherever possible, the piping is vacuum treated and filled with oil at the time the joints are treated. When this cannot be done, the tubing is treated and filled separately and then joined to the filled joint with oil flowing out of the fittings to preclude entrance of air or moisture.

A view of completed construction work, excepting fireproofing, in a manhole is shown in figure 9.

Before the installation of the 1936 line was considered completed, a thorough load test at reduced voltage was made. One purpose of the load test was to heat the line and distribute any traces of moisture that might have entered the joints or oil system. Records of load currents, conductor temperatures, oil volumes and pressures in reservoirs, induced sheath voltages, cable movement, and performance of oil-pressure signal system equipment were obtained. The results were satisfactory, inasmuch as the performance under load agreed closely with the calculations on which the line design was based.

When the load test was made on the 1936 line, other future lines of the same type were under consideration and it was felt desirable to check thoroughly the many new developments incorporated in the line. Such was not considered necessary for the 1937 installations. In general, it appears probable that, for future oil-filled lines, special heat runs will be unnecessary.

The installation tests of 140 or 150 kv direct current for 15 minutes were made with the permanently installed kenotrons of the utility.

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## Italian State Railway Acquires New Electric Trains



The first of several new electric trains, being constructed by Società Breda for the Italian State Railway system, recently was placed in service. Said to be capable of attaining a maximum speed of 180 kilometers (about 112 miles) per hour, the train consists of 3 intercommunicating cars resting on 4 2-axle carriages, is 62.5 meters long, has a maximum breadth of 2.92 meters, and weighs 100 tons. The motive power is supplied by 6 3,000-volt series-wound d-c motors with a total rating of 1,200 horsepower. Two motors are mounted on each of the end carriages, and each of the middle carriages carries one motor. Air braking is used. Each of the 3 cars is air conditioned; the middle car contains a single first-class salon with 35 seats, and the end cars contain second-class compartments with seating accommodations for 59 passengers. The kitchens are in one end car, and the baggage and mail compartments in the other.

# Insulation Strength of Transformers

## Purpose

THIS PAPER is presented to review the work of the transformer subcommittee in setting up standards for the insulation strength of transformers. An effort will be made to present the steps in the development of the insulation co-ordination problem in regard to transformers and to clarify certain points on which misunderstandings have arisen. The present insulation strength standards and tests will be given so that the margin between the protective level and insulation strength as demonstrated by test may be given proper consideration.

As the transformer subcommittee has before it a proposal for changes in standards necessary for the use of kilovolts as the basis for impluse tests instead of the use of the spacing of the test (rod) gaps, these proposals will also be given.

## General

Transformers have an impulse insulation strength as actually demonstrated by the standard insulation tests, and an ultimate breakdown strength somewhat higher. The margin between the demonstrated strength and the ultimate breakdown strength represents the safety factor which is provided by the designer. Logically, only the strength as demonstrated by test should be used in the application and co-ordination of transformers. In the operation of the transformers, a reasonable margin between the tested strength of the transformer and the protective level should be established and maintained as an additional safety factor in view of unpredictable conditions.

The insulation strength of transformers may be considered from 2 points: the 60-cycle strength and the impulse strength. The 60-cycle strength determines the ability of a transformer to withstand continuous 60-cycle voltages, most switching surges, and arcing ground overvoltages. The impulse strength is that strength which resists lightning overvoltages and the higher switching surges. Initially the insulation was determined by 60-cycle tests as a measure of ability to withstand all normal service requirements but as experience was gained more attention was given to the impulse strength. The present 60-cycle insulation test level has been in existence for some time and appears to have been adequate.

Before the present knowledge with regard to lightning and transformer insulation properties was obtained experience was the only guide. In the development of transformer insulation to withstand lightning overvoltages, changes in design were made where experience indicated it was necessary. Accordingly, when sufficient knowledge of lightning overvoltages and transformer insulation properties were obtained insulation levels and the corresponding insulation tests could be intelligently set up. The 60-cycle test has been retained and an impulse test has been added as a means of demonstrating impulse strength of the transformer.

## Historical

The standards for insulation tests have had a varied history. The first insulation standards were adopted June 26, 1899, and were as follows, as applicable to transformers:

**38.** The following voltages are recommended for apparatus not including transmission lines or switchboards

| Rated Terminal Voltage | Capacity, Kilowatts | Testing Voltage |
|---|---|---|
| Not exceeding 400 | Under 10 | 1,000 |
| Not exceeding 400 | 10 and over | 1,500 |
| 400 and over, but less than 800 | Under 10 | 1,500 |
| 400 and over, but less than 800 | 10 and over | 2,000 |
| 800 and over, but less than 1,200 | Any | 3,500 |
| 1,200 and over, but less than 2,500 | Any | 5,000 |
| 2,500 and over | Any | (Double the normal rated voltages) |

Modifications were made from time to time during the intervening years until the present insulation standards for the low frequency tests were issued May 1930. These are essentially as given below:

### Dielectric Test

**13–400 Standard Test Voltage to Be Applied Between Windings and Between Windings and Ground.** Transformers and other induction apparatus, except as listed below, shall be tested by applying between each winding successively and ground an alternating voltage from an external source of twice the rated voltage of the circuit to which the winding under test is to be connected plus 1,000 volts. All other electric circuits and metal parts shall be grounded during this test.

**13–401 Standard Test Voltage Between Turns to Be Induced in the Windings.** Transformers and other induction apparatus, except as listed below, shall, in addition to the tests provided in 13–400, be tested by applying between the terminals of one winding a voltage of twice the normal voltage developed in that winding, corresponding voltages being induced in the free windings.

### Exceptions:

(*n*) Transformers with graded insulation: Transformers, if for use on circuits of 66,000 volts and above, and having windings directly and permanently grounded and designed to take advantage of the fact that the neutral or other point of the circuit is to be directly and permanently grounded,* shall be tested by induced voltage with connections so made that the ungrounded or line

A report of the transformer subcommittee of the AIEE committee on electrical machinery compiled by J. E. Clem and A. C. Monteith; recommended for publication by the AIEE committees on power transmission and distribution, protective devices, and electrical machinery. Manuscript submitted March 20, 1937; released for publication April 24, 1937.

Personnel of transformer subcommittee of AIEE committee on electrical machinery: I. W. Gross, *chairman;* J. E. Clem, *secretary;* B. S. Bundy, L. H. Hill, V. M. Montsinger, A. C. Monteith, J. R. North, M. S. Oldacre, H. B. Scholz, and F. J. Vogel.

* A circuit shall be considered directly grounded when transformer connections and characteristics are such that not less than twice the combined rated line currents from the bank or banks of transformers supplying the circuit will flow to ground when a line is grounded at a terminal of any of the transformers supplying the circuit.

## Table I. Progress of Requirements for Impulse Strength* of Transformers

| Limit of Rated Trans. Voltage (Kv) | November 1930 | | December 1932 | | January 1933 | | December 1934 | | January 1937 | |
|---|---|---|---|---|---|---|---|---|---|---|
| | No. of Line Insulators | Impulse Flashover (Kv) | Co-ordination Gap Spacing (Inches) | Impulse Flashover (Kv) | Test Gap Spacing (Inches) | Impulse Flashover (Kv) | Test Gap Spacing (Inches) | Impulse Flashover (Kv) | Test Gap Spacing (Inches) | Impulse Flashover (Kv) |
| 1.2 | | | | | | | 0.8 | 32 | 0.8 | 32 |
| 2.5 | | | | | | | | | 1.6 | 53 |
| 5.0 | | | | | 2.25 | 63 | 2.2 | 63 | 2.2 | 63 |
| 8.7 | | | | | 3.375 | 81 | 3.3 | 80 | 3.3 | 80 |
| 15.0 | | | 4.25 | 95 | 4.75 | 102 | 4.5 | 100 | 4.5 | 100 |
| 25.0 | | | 6.25 | 128 | 7.00 | 141 | 6.9 | 140 | 7.1 | 150 |
| 34.5 | | | 9.25 | 180 | 10.25 | 190 | 10.2 | 190 | 10.2 | 190 |
| 46.0 | | | 12.25 | 228 | 13.5 | 250 | 13.5 | 250 | 13.5 | 250 |
| 69.0 | 4 | 440 | 18.75 | 335 | 20.5 | 360 | 20.6 | 360 | 20.6 | 360 |
| 92.0 | 6 | 610 | 25.0 | 430 | 27.5 | 470 | 27.5 | 470 | 27.5 | 470 |
| 115.0 | 7 | 695 | 31.5 | 525 | 34.75 | 570 | 34.7 | 570 | 34.7 | 570 |
| 138.0 | 8 | 780 | 38.25 | 625 | 42.0 | 680 | 42.1 | 680 | 42.1 | 680 |
| 161.0 | 10 | 945 | 44.5 | 720 | 49.0 | 790 | 49.0 | 790 | 49.0 | 790 |
| 196.0 | 12 | 1,105 | 54.5 | 860 | 60.0 | 950 | 60.0 | 950 | 60.0 | 950 |
| 230.0 | 14 | 1,265 | 64.0 | 1,000 | 70.5 | 1,100 | 70.4 | 1,100 | 70.4 | 1,100 |
| 287.5 | | | | | | | 88.0 | 1,360 | 88.0 | 1,360 |
| 345.0 | | | | | | | 105.6 | 1,620 | 105.6 | 1,620 |

* Flashover voltages lifted in table are present day values and are crest of $1\frac{1}{2} \times 40$ microsecond impulse wave with flashover on wave tail (minimum wave to produce flashover of square cut rod gap).

terminals shall receive test voltage to ground not less than 2.73 times the normal voltage developed by the winding, plus 1,000 volts.

If testing circuit conditions are such that the induced voltage test just specified does not at the same time produce between adjacent 3-phase line terminals twice the related voltage of the circuit, additional test with the same or other circuit connections shall be made to produce this voltage between line terminals; i.e., twice the rated circuit voltage.

Transformers having graded insulation shall be so marked.

Some time prior to the 1930 revision it was realized that it was necessary to supplement the low-frequency test with an additional test to insure that transformers were insulated more in proportion to the overvoltages to which they might be subjected. In some cases line insulation was increased to reduce lightning outages. It was becoming more and more recognized that the most important source of the damaging overvoltages was lightning and that some effort should be made to correlate the insulation strength with the lightning overvoltages. Considerable discussion on this problem took place in the transformer subcommittee and a series of reports have been issued from time to time, the essential features of which are given in table I and discussed in the following paragraphs.

In November 1930[31] the first report was issued in which it was required that

> Apparatus conforming with the standards of dielectric test should be so designed that their impulse strength against lightning is greater than the impulse flashover voltage to earth of nonshielded suspension type insulators. . . .

and it was also proposed that no line entering the station have insulation exceeding these values for half a mile from the station.

The manufacturers tried to design to these levels but in as much as there was no established testing procedure, it is not possible to know whether they were successful.

This was the first effort at what for a long time has been called "co-ordination of transformer insulation." The use of insulators as the basis of comparison did not last very long for many reasons, the most important being the obvious disadvantage of the large and inflexible steps and the fact that the proposed reduction of the last half mile of line insulation to these values was not generally adopted.

In December 1932[21] a revision was published in which the impulse strength against lightning was given in terms of the spacing of a rod (co-ordination) gap of specified construction and the tabulation was extended to include the 15-kv circuit.

The previous proposal of November 1930 balanced the transformer insulation strengths against a specified number of line insulators in half a mile of line adjacent to the station while the revision of December 1932 balanced it against the "co-ordination gap." It was thought if one flashover point was established where the lines entered the station instead of 3 or 4 spaced one half a mile out that the single gap should be about 10 per cent less in flashover value to establish the same level on account of attenuation. Consequently, the spacing of co-ordination gap was selected to give about 10 per cent less flashover than the line insulators. However, in comparing the impulse flashover values in table I it should be remembered that the numerical values on which the comparison was made then was not the same as those used today.

The transformer subcommittee continued its studies and in January 1933 presented[16] a tentative test code. In this test code the use of the term "co-ordination gap" was definitely abandoned as a means of expressing transformer insulation strength. The use of test gaps at 110 per cent of the co-ordination gap spacing was introduced, the tabulation was extended to include the 4,600-volt class, a standard test wave was established, and a schedule of 5 tests adopted. These tests are as follows:

TESTS TO BE APPLIED

Each terminal of the transformer to be tested should be tested with waves of positive polarity having respectively:

1. A voltage not more than 10 per cent less than the minimum impulse voltage permitted by the specified test gap directly connected to ground.

31. For all numbered references see list at end of paper.

2. A voltage just sufficient to flashover the specified test gap directly connected to ground.

3. A crest voltage at least 10 per cent greater than the minimum flashover voltage of the test gap directly connected to ground.

4. A voltage of sufficient magnitude to flashover the bushing.

5. A voltage as great as that specified in number 3 or 4, but with the means for maintaining the excitation voltage across all parts of the winding.

In December 1934[9] the number of impulse tests was reduced from 5 to 3 and the tabulation was extended up to 345 kv and down to 1.2 kv. A slight modification of the impulse test gap spacings, and a change in the low-frequency test voltage for transformer ratings 23 kv and below were also reported.

At this time a standard bushing level was considered. The values adopted were 15 per cent above the co-ordinating gap for distribution transformers. The power transformer bushings 69 kv and above followed the values, but on account of past practice with power transformers in the lower voltage classes, it was felt that the bushing should have a higher level and values essentially those of table III were adopted.

In January 1937[2] some slight changes were reported. These changes consisted in the correlation of circuit voltages with corresponding maximum apparatus voltage

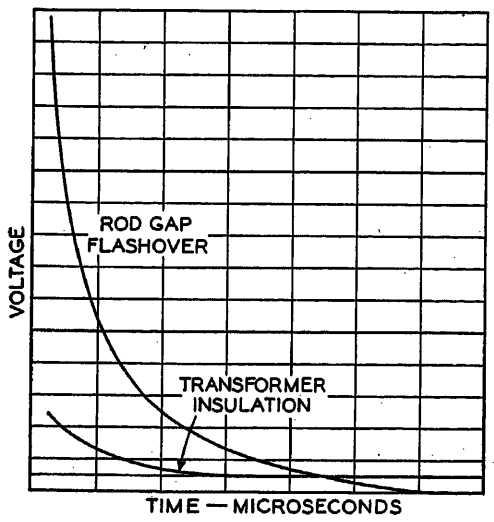



**Figure 1. Typical volt-time characteristics of rod gap and transformer insulation**

ratings and the conclusion of the low-frequency test voltage in the tabulation. The wording of the 3 impulse tests were changed slightly to read as follows:

IMPULSE TESTS

(*a*) Apply a wave just sufficient to cause flashover of the specified test gap under existing conditions of humidity and air density.

(*b*) Apply a wave sufficient to cause flashover of the bushing. For this test the applied voltage must be at least 5 per cent in excess of the standard minimum flashover voltage for the standard bushing under standard conditions of humidity and air density.

*Note*—When oversized bushings are used they shall be equipped with suitable gaps to provide the same standard minimum impulse flashover as for the standard bushing.

(*c*) Apply a wave having a crest not less than 90 per cent of the standard minimum flashover voltage of the standard bushing under existing conditions of humidity and air density. No flashover of the bushing shall occur during the test.

## Comments

### INSULATION STRENGTH "YARDSTICK"

It has frequently been asked why insulators and rod gaps were initially used as a means of expressing insulation levels. The reason is as follows: Impulse testing was a new development and the technique had not been established. The impulse flashover of a given number of insulator units or of a given gap spacing was reported differently by different laboratories. It was felt that the actual voltage required to flashover a specified rod gap or a specified number of insulators would be the same in all the laboratories regardless of the variation in reported values. Consequently it was felt that if the impulse strength level of a transformer was specified in terms of the impulse flashover of a given number of line insulators or a given gap spacing, it would result in a common "yardstick" for expressing the insulation strength of transformers.

### POLARITY OF TEST WAVE

Many have asked why the positive polarity wave was selected instead of a negative polarity wave. These questions were prompted by the fact that it was later definitely established that the severest lightning overvoltages on transmission lines were of negative polarity. At the time the positive wave was selected, which actually was some time prior to the issuance of the proposed impulse test code, it was not generally accepted that the negative waves were predominant in the lightning overvoltages on transmission lines. The reason for the adoption of a positive polarity is the fact that the problem of impulse testing was in the development stage at the time, and laboratory technique was being built up with the use of positive polarity. As a result, by far the greater amount of impulse data had been obtained with positive waves and it was felt that co-ordination could be accomplished to better advantage if the positive wave was selected for transformer testing.

### CO-ORDINATION GAP AS PROTECTIVE DEVICE

When the problem of co-ordination was first considered the reduced line insulation as proposed in November 1930 or the "co-ordination gap" as proposed in December 1932 was presumed to offer adequate protection to transformers. The expression "co-ordination gap" signified not only a particular type of gap, but also a particular spacing for each voltage. This idea that the "co-ordination gap" was an adequate protective device has persisted in spite of the increased knowledge of the divergence of volt-time characteristics of rod gaps and transformer insulation.

The volt-time characteristic of rod gaps and transformer insulation may be the same in general, but they are decidedly different in detail. As the time to flashover becomes shorter the flashover voltage of the gap increases considerably faster than the breakdown voltage of the transformer insulation. This is illustrated in figure 1, and it is very evident from the curves that the "co-ordination gap" offers no protection when the time to gap flashover is short and when protection will most likely be needed. In order to establish the same margin of protection at half a micro-

second, it would be necessary to reduce the gap spacing to about $^1/_2$ to $^1/_3$ of the co-ordination gap; If this was done the number of service interruptions would very likely be increased.

In general it may be said that plain air gaps or rod gaps will limit by flashover the magnitude of the stress applied to station apparatus but their volt-time characteristics are so different from transformer insulation that they may be considered as affording a definitely limited amount of protection. The economics of the situation and the grade of service acceptable are the governing factors.

### Standard Insulation Levels for Transformers

The transformer subcommittee at its meeting January 27, 1937, authorized the change from gap spacing to kilovolts as the measure of transformer insulation strength. A new tabulation is presented in table II which converts the present test code values from inches to kilovolts, and omits the minimum flashover voltage of the gap. There is given, also, the low-frequency test voltage values. The kilovolt values are practically identical with those required by the present test code through the requirement of bushing flashover, although the testing procedure has been altered. A discussion of the impulse test values in the light of the present test recommendations and basic insulation levels adopted by the EEI-NEMA joint committee on insulation co-ordination may be helpful.

The present impulse test code provides for application of 3 1.5x40 positive test waves to transformers, with specified tolerances, one a full wave at 90 per cent of the flashover voltage of the proposed standard bushing, one a wave chopped late on the tail by the test gap, and one a wave chopped early on the tail by bushing flashover with an applied voltage of 105 per cent of the standard flashover voltage of the bushing. Expressed in per cent these are:

Applied voltage—test gap flashover = 100 per cent
Applied voltage—bushing flashover = 110 per cent
Applied voltage—full wave test = 95 per cent

except for power transformers rated 69 kv and below where the bushings have an impulse flashover higher than on distribution transformers which results in correspondingly higher impulse test voltages being applied to power transformers. This higher impulse strength of power transformers in the 69 kv class and below is inherent in these transformers and is required by the present test code which bases maximum impulse tests on the flashover of the transformer bushing.

It should be noted that the basic insulation levels adopted January 1937 by the EEI-NEMA joint insulation committee on system insulation correspond to the test gap flashover (minimum impulse flashover—full wave) of 100 per cent given above. The test gap flashover voltages are listed in table I in the January 1937 columns. Therefore in order to insure that when the tests are expressed in kilovolts they shall be of the same severity as when formerly ex-

**Table II. Standard Insulation Test Level—Distribution and Power Transformers**

| Rated Circuit Voltage (1) (Volts*) | Limit of Rated Trans. Voltage (2) (Kilovolts**) | Standard Insulation Test Level: Impulse Test—1.5x40 Microsecond Wave: Distribution Transformers: Full Wave: Voltage (3) (Kilovolts) | Distribution Transformers: Chopped Wave: Voltage (4) (Kilovolts) | Distribution Transformers: Chopped Wave: Min. Time to Flashover (5) (Microseconds) | Power Transformers: Full Wave: Voltage (6) (Kilovolts) | Power Transformers: Chopped Wave: Voltage (7) (Kilovolts) | Power Transformers: Chopped Wave: Min. Time to Flashover (8) (Microseconds) | Low Frequency Test Voltage (9) (Kilovolts) |
|---|---|---|---|---|---|---|---|---|
| 120<br>240<br>480<br>600 | 1.2 | 30 | 36 | 1.0 | 60 | 69 | 1.5 | 10 |
| 2,400<br>2,500 | 2.5 | 50 | 59 | 1.25 | | | | 15 |
| 4,160<br>4,330<br>4,800 | 5.0 | 60 | 69 | 1.5 | 76 | 88 | 1.6 | 19 |
| 6,900 | 8.66 | 76 | 88 | 1.6 | | | | |
| 11,500<br>13,800 | 15.0 | 100 | 115 | 1.8 | 95 | 110 | 1.8 | 26 |
| 25,000 | 25.0 | 140 | 165 | 2.5 | 112 | 130 | 2.0 | 34 |
| 34,500 | 34.5 | 185 | 210 | 3.0 | 153 | 180 | 3.0 | 51 |
| 46,000 | 46.0 | 240 | 275 | 3.0 | 195 | 225 | 3.0 | 70 |
| 69,000 | 69.0 | 340 | 395 | 3.0 | 245 | 290 | 3.0 | 93 |
| 92,000 | 92.0 | 445 | 515 | 3.0 | 345 | 405 | 3.0 | 139 |
| 115,000 | 115.0 | 540 | 625 | 3.0 | 445 | 515 | 3.0 | 185 |
| 138,000 | 138.0 | 645 | 750 | 3.0 | 540 | 625 | 3.0 | 231 |
| 161,000 | 161.0 | 750 | 870 | 3.0 | 645 | 750 | 3.0 | 277 |
| 196,000 | 196.0 | 900 | 1,055 | 3.0 | 750 | 870 | 3.0 | 323 |
| 230,000 | 230.0 | 1,050 | 1,210 | 3.0 | 900 | 1,055 | 3.0 | 393 |
| 287,500 | 287.5 | 1,290 | 1,495 | 3.0 | 1,050 | 1,210 | 3.0 | 461 |
| 345,000 | 345.0 | 1,540 | 1,785 | 3.0 | 1,290 | 1,495 | 3.0 | 576 |
| | | | | | 1,540 | 1,785 | 3.0 | 691 |

* These circuit voltages are those agreed upon by the "NEMA-NELA Preferred Voltage Ratings for A-C Systems and Equipment," NELA publication No. 043, page 12, and supplemented by the AIEE transformer subcommittee, Electrical Engineering, January 1937, page 32, table I.
** These values represent the maximum transformer voltage rating normally associated with the corresponding insulation level. These figures may be used to designate the insulation class.

pressed in terms of gap spacing, the following percentages apply:

| | |
|---|---|
| Basic insulation level | = 100 per cent |
| Applied voltage—chopped wave test | = 110 per cent |
| Applied voltage—full wave test | = 95 per cent |

When the impulse flashover of the bushing is higher than the required minimum standard of 105 per cent of the test gap flashover, as for power transformers 69 kv and below, the applied voltage for the chopped wave and full wave test is 105 per cent and 90 per cent respectively of the actual bushing flashover voltage recommended as standard.

In table II a minimum time to flashover is given. This is to insure a reasonable length of wave so as to retain the severity of the present tests.

## Insulation Level

DISTRIBUTION (500 KVA AND LESS) TRANSFORMERS
POWER (LARGER THAN 500 KVA) TRANSFORMERS

*A. Insulation Level*

1. Table II gives the proposed standard relationship between the established rated circuit voltages and corresponding limits of rated transformer voltage, and the standard insulation level for distribution (500 kva and less) and power (larger than 500 kva) transformers.

2. The standard insulation levels are expressed in terms of the full wave impulse test voltage, the chopped wave impulse test voltage with minimum time to flashover, and the low-frequency test voltage. The impulse test voltage is the crest value of the standard 1.5x40 microsecond impulse test wave.

*B. Choice of Insulation Level*

1. The insulation level for a given installation should be selected in accordance with the operating conditions, the volt-time performance characteristic of the protective equipment, and economics.

BUSHING CHARACTERISTICS

1. Table III gives the minimum impulse flashover voltage (full wave) with the positive 1.5x40 microsecond wave, and the guaranteed 60-cycle dry and wet flashover voltage, for distribution and power transformers. These values are for standard atmospheric conditions.

2. The impulse flashover voltage and the guaranteed 60-cycle flashover voltages are subject to a tolerance of minus 5 per cent.

To keep the impulse flashover voltage of transformer bushings 5 per cent above the impulse flashover of the transformer test gap, a slight revision in bushing characteristics is being considered. All changes have resulted in slight increases in bushing impulse flashovers.

BUSHING GAPS

The practice of supplying transformers with bushings gapped to meet the recommended flashover standards has been in use some 3 years or so. It has been maintained by some users of such transformers that the gaps are undesirable in many cases, particularly in the lower voltage power transformer class. It would be particularly helpful to the transformer subcommittee to get the opinion of others on the desirability of equipping transformer bushings with gaps.

**Table III. Bushing Characteristics—Distribution and Power Transformers**

| Rated Circuit Voltage (Volts) | Limit of Rated Trans. Voltage (Kv) | Bushing Flashover in Kilovolts: Distribution Trans. 500 Kva and Smaller — Impulse* Flashover Average | 60-Cycle Guaranteed Flashover — Dry | 60-Cycle Guaranteed Flashover — Wet | Power Transformers Larger than 500 Kva — Impulse* Flashover Average | 60-Cycle Guaranteed Flashover — Dry | 60-Cycle Guaranteed Flashover — Wet |
|---|---|---|---|---|---|---|---|
| 120, 240, 480, 600 | 1.2 | 34 | 11 | 7 | 66 | 25 | 12 |
| 2,400, 2,500 | 2.5 | 56 | | | | | |
| 4,160, 4,330, 4,800 | 5.0 | 66 | 27 | 18 | 84 | 40 | 27 |
| 6,900 | 8.66 | 84 | 40 | 27 | 105 | 50 | 35 |
| 11,500, 13,800 | 15.0 | 110 | 53 | 37 | 125 | 65 | 45 |
| 25,000 | 25.0 | 158 | 78 | 55 | 170 | 85 | 60 |
| 34,500 | 34.5 | 200 | 110 | 80 | 215 | 115 | 85 |
| 46,000 | 46.0 | 265 | 140 | 105 | 275 | 150 | 120 |
| 69,000 | 69.0 | 375 | 205 | 155 | 385 | 215 | 165 |
| 92,000 | 92.0 | 500 | 280 | 210 | 500 | 280 | 210 |
| 115,000 | 115.0 | 600 | 340 | 260 | 600 | 340 | 260 |
| 138,000 | 138.0 | 715 | 405 | 310 | 715 | 405 | 310 |
| 161,000 | 161.0 | 825 | 460 | 355 | 825 | 460 | 355 |
| 196,000 | 196.0 | 1,000 | 555 | 430 | 1,000 | 555 | 430 |
| 230,000 | 230.0 | 1,155 | 640 | 500 | 1,155 | 640 | 500 |
| 287,500 | 287.5 | 1,430 | 760 | 610 | 1,430 | 760 | 610 |
| 345,000 | 345.0 | 1,705 | | | 1,705 | | |

* 1½x40 microsecond positive full wave.

## Proposed Standard Impulse Tests

IMPULSE TEST

A proposal is being considered to simplify the present impulse test code as follows:

The standard impulse test shall consist of 2 applications of a specified chopped wave followed by one application of a full wave. Either a positive or a negative wave may be used. The chopped wave may be obtained by flashing over either the bushing or an external rod gap.

1. *Chopped Wave.* For this test the applied voltage wave shall have a crest voltage and time to flashover in accordance with table II, columns 4 and 5 or columns 7 and 8 respectively for distribution transformers (500 kva and less) or power transformers (larger than 500 kva) respectively.

2. *Full Wave.* For this test the applied voltage wave shall have a crest value in accordance with table II, column 3 or column 6 for distribution and power transformers, respectively. For this test bushing gaps may be removed and negative wave can be used.

## Standard Low-Frequency Tests

The standard low-frequency test consists of an applied potential test followed by an induced potential test.

1. *Applied Potential Test.* The applied potential test shall be made by applying between each winding successively and ground, a low-frequency alternating voltage from an external source in accordance with table II, column 9. All other electric circuits and metal parts shall be grounded during the test.

2. *Induced Potential Tests.* The induced potential test shall be made by applying between the terminals of one winding a voltage of twice the normal voltage developed in that winding.

If testing circuit conditions are such that the induced voltage test just described does not at the same time produce twice the rated voltage of the circuit between adjacent line terminals of a 3-phase transformer an additional test with the same or other circuit connections shall be made to produce this voltage between line terminals.

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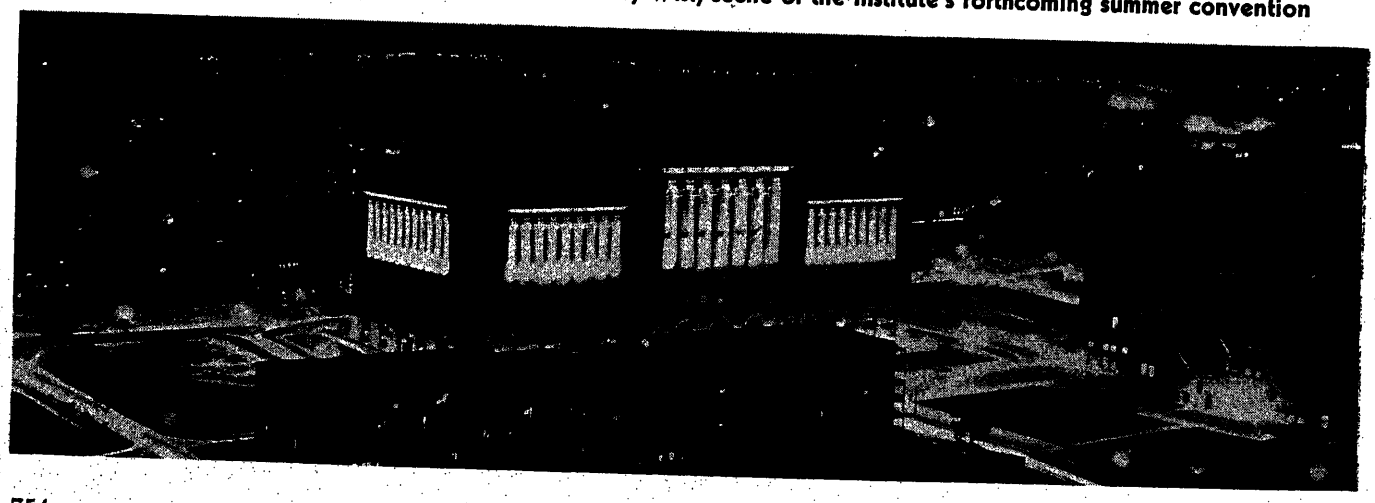
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**Night view of the new Court House at Milwaukee, Wis., scene of the Institute's forthcoming summer convention**



# News
## Of Institute and Related Activities

## The AIEE Summer Convention This Month at Milwaukee, Wis.

ALL ARRANGEMENTS have been made for the fifty-third annual summer convention which will be held at Milwaukee, Wis., June 21–25, 1937, with headquarters in the Schroeder Hotel. The summer convention committee, under the chairmanship of K. L. Hansen, has arranged an attractive program of sports, inspection trips and entertainment built around the annual business meeting, 10 technical sessions, and 1 general session. The convention also affords opportunity to combine business with a few days vacation. For a more complete account of the convention features, including a schedule of events and the tentative technical program, see ELECTRICAL ENGINEERING for May, pages 635–9.

### TECHNICAL PROGRAM

The tentative technical program as announced in the above reference is complete with the following changes. The paper "Approximating Potier Reactance" by Sterling Beckwith, Allis-Chalmers Manufacturing Co., has been added to the session on power generation and electrical machinery scheduled at 10:00 a.m., Thursday, June 24. The date for scheduling the conference on field problems has been interchanged with the date for scheduling the conference on electrical apparatus for 3-phase arc furnaces. The programs for these conferences are as follows:

**Wednesday, June 23**

**2:30 p.m.—Conference on Field Problems, Ernst Weber, presiding**

1. Introduction: The field concept in physics and engineering
2. Topics:
   - (*a*) Graphical field plotting (special applications to magnetic fields)
   - (*b*) Analytical solutions of fields (special applications to heat problems)
   - (*c*) Conformal representation (special applications to electric fields)
   - (*d*) Experimental methods of field exploration (special applications to hydrodynamics)

**Thursday, June 24**

**2:30 p.m.—Conference on Electrical Apparatus for 3-Phase Arc Furnaces**

1. Introduction: Modern arc furnace apparatus—lantern slides—Samuel Arnold
2. Discussions:
   - (*a*) Kilovolt-ampere ratings—Frank Brooke
   - (*b*) Voltages—C. C. Levy
   - (*c*) Reactance—F. V. Andreae
   - (*d*) Regulation—F. E. Ackley
   - (*e*) Protective equipment—E. L. McClure
   - (*f*) Methods of supplying power—L. W. Clark

### DOCTOR VANNEVAR BUSH TO SPEAK

One of the high lights of the summer convention will be a lecture Tuesday evening by Doctor Vannevar Bush on the subject "The Engineer and His Relation to Government." This meeting very appropriately precedes the general session Wednesday morning on economic aspects of engineering and Institute activities.

This evening lecture will be open to the public, fellow-engineers from other founder



Vannevar Bush

and local societies and the ladies as well. The Engineers' Society of Milwaukee has already chosen to dispense with its regular June meeting and join with the Institute on this occasion. Special plans are also being made for groups to come from Chicago and Madison for this evening lecture.

Doctor Vannevar Bush is noted for his achievements in research and his contributions to engineering progress and to technical education. For the development of the product integraph he was awarded the Levy Medal of the Franklin Institute in 1928. For "his development of methods and devices for application of mathematical analysis to problems of electrical engineering" he was awarded the AIEE Lamme Medal for 1935. He has lectured at Cambridge, England, at the International Congress of Applied Mechanics and he has delivered the Josiah Willard Gibbs lecture of the American Mathematical Society. Doctor Bush designed the differential analyzer and under his direction the network analyzer at Massachusetts Institute of Technology was built. He is also known for his contributions to the development of vacuum tubes and for his investigations in electric power transmission, transients in machines, and dielectric phenomena.

The career of Doctor Bush as a teacher has been no less notable than his work in research and in 1932 he was appointed vice-president and dean of the school of engineering of the Massachusetts Institute of Technology.

### SPORTS

Excellent facilities will be available for golf and tennis enthusiasts. Golf events will include competition for the Mershon, Lee, and District Team Trophies and special events. Golf on Monday and Tuesday will be on the course of the Tripoli Country Club, on Wednesday and Thursday at the Ozaukee Country Club, and on Friday at the Bluemound Golf and Country Club. Qualifying play for the Mershon Trophy, which is on a handicap basis, will be on Monday with match play rounds on Tuesday, Wednesday, and Thursday. The Lee Trophy in golf which is on a handicap basis, 36 holes of medal play, will be on Monday and Tuesday.

The District team event, the winner of which is decided on the basis of the gross medal score for the 4 lowest out of a team of 6 players from each District for 36 holes will be played Monday and Tuesday. It is suggested that each District organize a team before leaving for the convention.

The annual tennis tournament for the Mershon Tennis Trophy will be held on the clay courts of the Milwaukee University School. Numerous prizes for both golf and tennis have been provided and these will be awarded at the informal farewell dinner to be held Friday evening at the Bluemound Golf and Country Club.

In order to facilitate imposing fair handicap, the sports committee has requested that those who intend to play golf furnish the following information: average of their 5 best scores in 1936; par of their regular courses.

### WOMEN'S ENTERTAINMENT

While the men are busily engaged in the technical sessions and inspection trips the women will not be overlooked. A committee, under the leadership of Mrs. A. C. Flory, has provided a wide variety of interesting and entertaining events. These include a varied assortment of parties, a tea, luncheon, inspection and shopping trips, golf, and a day at a country club. These, of course, are in addition to the combined events—the boat trip on Lake Michigan, the trip to the Schlitz Brewery, president's reception and dinner dance Thursday evening, and the farewell party at the Bluemound Golf and Country Club Friday night. The aim of the women's committee is to make every woman visitor feel Milwaukee's traditional and gracious hospitality and to let no one leave the convention without learning the real meaning of *gemutlichkeit* (see May 1937 issue, page 638).

# Institute Prize Awards Announced for 1936 Papers

THE committee on award of institute prizes has announced the award of 4 national prizes for papers presented during the calendar year 1936. Personal presentation of the prizes will take place during the summer convention to be held in the Hotel Schroeder, Milwaukee, Wis., June 21–25, 1937. The personnel of the committee consists of H. S. Osborne (A'10, F'21), *chairman*, O. W. Eshbach (A'17, M'30), W. B. Kouwenhoven (A'06, F'34), W. R. Smith (M'18, F'30), and I. Melville Stein (A'18, M'27).

Rules governing the award of future prizes were published in ELECTRICAL ENGINEERING for April 1937, page 492. In accordance with these rules, papers for the District Branch paper prize and the newly established graduate student prize, will be awarded on the basis of the academic year, and must be submitted on or before July 15, 1938. The Branch papers which have been presented from January to June 1937, may also be submitted at that time for consideration.

### NATIONAL PRIZES

After due consideration of all highly recommended papers, the committee on award of Institute prizes made the following awards of national prizes for papers presented in 1936:

#### BEST PAPERS

*Best Paper in Engineering Practice.* This prize was awarded to P. S. Millar (A'03, M'13) for his paper "The Qualities of Incandescent Lamps," published in ELECTRICAL ENGINEERING for May 1936, pages 516–23, and discussed at the summer convention, Pasadena, Calif., June 22–26, 1936.

Honorable mention was made of the following papers: "The Relation between Load, Capacity, and Service Continuity on an Electric Power System" by W. J. Lyman (A'25), presented before the Pittsburgh Section, December 8, 1936; "Modernization of Power Distribution Systems" by H. P. Seelye (A'19, M'28), published in ELECTRICAL ENGINEERING for January 1936, pages 75–84, and discussed at the winter convention, New York, N. Y., January 28–31, 1936.

*Best Paper in Theory and Research.* This prize was awarded to H. E. Edgerton (A'27, M'32) for his paper "High Speed Motion Pictures," published in ELECTRICAL ENGINEERING for February 1935, pages 149–53, and discussed at the winter convention, New York, N. Y., January 28–31, 1936.

Honorable mention was made of the following papers: "Pull-In Characteristics of Synchronous Motors" by D. R. Shoults (A'35), S. B. Crary, Jr. (A'31), and A. H. Lauder (A'24), published in ELECTRICAL ENGINEERING for December 1935, pages 1385–95, and discussed at the winter convention, New York, N. Y., January 28–31, 1936; "Laboratory Studies of Conductor Vibration" by J. S. Carroll (A'24), published in ELECTRICAL ENGINEERING for May 1936, pages 543–7, and discussed at the summer convention, Pasadena, Calif., June 22–26, 1936.

*Best Paper in Public Relations and Education.* In view of the fact that only 2 papers eligible for this prize were presented last year the committee deemed it advisable to make no award under this classification. Under the rules these 2 papers will be eligible for consideration the next time prizes are awarded.

#### INITIAL PAPER

Prize for initial paper was awarded to D. H. Rowland (A'26) for his paper "Porcelain for High Voltage Insulators," published in ELECTRICAL ENGINEERING for June 1936, pages 618–26, and discussed at the summer convention, Pasadena, Calif., June 22–26, 1936.

Honorable mention was made of the following papers: "Induction Heating at Low Temperatures" by E. L. Bailey (A'19, M'25), published in ELECTRICAL ENGINEERING for November 1935, pages 1210–12, and discussed at the winter convention, New York, N. Y., January 28–31, 1936; "Earth Resistivity and Geological Structure" by R. H. Card (A'22, M'35), published in ELECTRICAL ENGINEERING for November 1935, pages 1153–61, and discussed at the winter convention, New York, N. Y., January 28–31, 1936.

#### BRANCH PAPER

Prize for Branch paper was awarded to W. James Walsh for his paper "Heat Transfer Efficiency of Electric Range Surface Units," presented at a joint meeting of the Portland Section and Oregon State College Branch, AIEE, Corvallis, Ore., May 16, 1936.

Honorable mention was made of the following papers: "A Direct Reading Linear Accelerometer" by Harry B. Fuge, presented at a meeting of the Polytechnic Institute of Brooklyn Branch, AIEE, April 1936; "Tidal Power," by D. R. Barney, presented at the annual student convention District No. 3, AIEE, New York, N. Y., April 22, 1936; "A High-Speed Vibration Analyzer," by William R. Harry, presented at the North Eastern District Meeting, New Haven, Conn., May 6–9, 1936; "Frequency Multipliers," by Ronald F. Huminski and Everard M. Williams, presented at the North Eastern District Meeting, New Haven, Conn., May 6–9, 1936.

The committee has considered all the eligible papers and in connection with papers in all classifications except Branch papers had the benefit of the recommendations of the technical committee chairmen relative to the best papers in their respective fields.

### DISTRICT PRIZES

District prizes as announced by 4 Districts to date include 3 awards of $25 each, together with appropriate certificates. Other District awards will be announced later, as the information becomes available.

#### DISTRICT 1

Prize for best paper was awarded to E. M. Hunter (A'28, M'36) for his paper "Tests on Lightning Protection for A-C Rotating Machines," published in ELECTRICAL ENGINEERING for February 1936, pages 137–44, and discussed at the North Eastern District Meeting, New Haven, Conn., May 6–9, 1936.

Prize for initial paper was awarded to E. A. Harty (A'22, M'36) for his paper "Aging in Copper Oxide Rectifiers," presented at the North Eastern District Meeting, New Haven, Conn., May 6–9, 1936.

Prize for Branch paper was awarded to W. R. Harry for his paper "A High-Speed Vibration Analyzer," presented at the North Eastern District Meeting, New Haven, Conn., May 6–9, 1936.

#### DISTRICT 2

Prize for initial paper was awarded to A. C. Herweh for his paper "An Open Arc Type of Stroboscope," presented before a joint meeting of the Cincinnati Section and University of Cincinnati Branch, AIEE, May 19, 1936.

#### DISTRICT 7

Prize for Branch paper was awarded to J. H. Treadwell for his paper "A Rotating Ball Slip Meter," presented at the South West District Meeting, Dallas, Texas, October 26–28, 1936.

#### DISTRICT 9

Prize for Branch paper was awarded to W. James Walsh for his paper "Heat Transfer Efficiency of Electric Range Surface Units," presented at a meeting of the Oregon State College Branch, AIEE, Corvallis, Ore., May 16, 1936.

**ASTM Annual Meeting.** The fortieth annual meeting and fourth exhibit of testing apparatus and related equipment of the American Society for Testing Materials will be held in New York, N. Y., from June 28 to July 2, 1937, with headquarters at The Waldorf-Astoria Hotel. A program of entertainment and inspection trips will supplement the technical program. Many companies will display and demonstrate the latest developments in instruments for various phases of the production, control, and testing of materials and products of all kinds. Certain educational and research institutions will also be invited to display special equipment and devices which they have developed for unusual testing and research in the materials fields.

# Coast IRE and AIEE Plan Joint Convention at Spokane

An innovation in Pacific Coast convention procedure that is being enthusiastically developed by the local committees in charge will bring together for a concurrent convention in Spokane, Wash., the Pacific Coast members of the Institute of Radio Engineers and of the AIEE. The annual Pacific Coast AIEE convention is scheduled to be held from August 30 to September 3, inclusive. The IRE Pacific Coast convention, the first to be held, is scheduled for September 1 and 2.

Plans in progress as announced by the committee in charge provide for a joint technical session to be held September 2, to which both AIEE and IRE members will contribute technical papers of common interest. Other sessions of the AIEE Pacific Coast convention program will be held as usual, and separate technical sessions are being planned by the radio engineers.

# 1937 Lamme Medal Nominations Due Nov. 1

Special attention is directed to the fact that the names of Institute members who are considered eligible for the Lamme Medal, to be awarded in the fall of 1937, may be submitted by any member in accordance with Section 1 of Article VI of the by-laws of the Lamme Medal committee, as quoted in the following:

The committee shall cause to be published in one or more issues of ELECTRICAL ENGINEERING, or of its successors, each year, preferably including the June issue, a statement regarding the "Lamme Medal" and an invitation for any member to present to the national secretary of the Institute by November 1, the name of a member as a nominee for the medal, accompanied by a statement of his "meritorious achievement" and the names of at least 3 engineers of standing who are familiar with the achievement.

Each nomination should give concisely the specific grounds upon which the award is proposed, and also a complete detailed statement of the achievements of the nominee to enable the committee to determine its significance as compared with the

achievements of other nominees. If the work of the nominee has been of a somewhat general character in co-operation with others, specified specific information should be given regarding his individual contributions. Names of endorsers should be given as specified above.

The Lamme Medal, founded as a result of a bequest of the late Benjamin Garver Lamme, chief engineer of the Westinghouse Electric and Manufacturing Company (deceased July 8, 1924), provides for the annual award by the Institute of a gold medal —together with bronze replica thereof— to a member of the AIEE "who has shown meritorious achievement in the development of electrical apparatus or machinery"; and for the award of 2 such medals in some years if the accumulation of funds warrants.

The ninth (1936) Lamme Medal has been awarded to Doctor Frank Conrad (A'02, F'37), assistant chief engineer of the Westinghouse Electric & Manufacturing Company, East Pittsburgh, Pa., "for his pioneering and basic developments in the fields of electric metering and protective systems." Presentation will be made during the AIEE summer convention at Milwaukee, Wis., June 21–25, 1937. A biographical sketch of Doctor Conrad appeared in ELECTRICAL ENGINEERING for March 1937, pages 395–6.

## Additions to Member-for-Life List

Membership for life is granted by the Institute for either of the following 2 reasons: a member has paid annual dues for 35 years; or has reached the age of 70 and has paid dues for 30 years.

The fiftieth anniversary issue of ELECTRICAL ENGINEERING published in May 1934 and the September 1935 number included lists of all members who had been enrolled upon the Institute records as Members for Life during the period up to May 1, 1935. Those who became Members for Life between 1935 and 1936 were listed in the June 1936 issue.

The list that follows indicates those members who have become Members for Life since the publication of the list in the June 1936 issue:

Addicks, L.
Aitken, William
Atkinson, A. A.
Atkinson, W. S.
Averrett, A. E.
Barnes, W. J.
Beam, Victor S.
Bell, A. C.
Bennett, Edward
Bennett, W. S.
Blakeslee, H. J.
Brown, Carlton E.
Brown, R. C.
Brown, W. E.
Butler, W.
Carpenter, H. C.
Coldwell, O. B.
Conwell, W. L.
Cowles, J. W.
Dick, W. A.
Dixon, James
Dodge, K.
Edmonston, E. D.
Eglinton, W. M.
Erwin, F. B.
Everit, E. H.
Feldmann, C.
Ferguson, L. A.
Ferguson, S.
Firman, L. D.
Foster, W. J.
Gear, H. B.
Gibson, J. J.
Gill, Frank
Graham, W. P.
Graling, V.
Harisberger, J.
Hodgkinson, F.
Hunt, F. L.
Keller, C. A.
Kingsbury, Albert
Kruesi, P. J.
Lanphier, R. C.
Lesley, Hugh
Leyden, H. R.
Lillibridge, R. D.
Lincoln, J. C.
Lowenberg, L.
Magie, L. D.
Manville, C. B.
Marburg, L. C.
McAllister, A. S.
McGrath, W. H.
Medbery, S. C., Jr.
Moody, W. S.
Morris, J. W.
Nash, L. R.
Pearson, E. R.
Pierce, A. L.
Potts, L. M.
Pratt, W. H.
Rea, N. L.
Reber, H. L.
Reynolds, W. H.
Roberts, T. M.
Rosenthal, L. W.
Ruckgaber, A. F.
Ruffner, C. S.
Rugg, W. S.
Sage, D.
Sawyer, W. H.
Schildhauer, E.
Schluederberg, C. G.
Smith, F. W.
Smith, W. N.
Soren, T. H.
Sporborg, H. N.
Stevenson, F. L.
Storer, S. B.
Stovel, R. W.
Tuttle, H. B.
Van Dyck, W. V.
Waddell, C. E.
Wagoner, P. D.
Waldo, E. H.
Warren, H. E.
Waters, W. L.
White, F. J.
Whittemore, G. W.
Wilder, S.
Wilson, R. L.
Winslow, C. G.

## AIEE Sections Members of Indiana Engineering Council

Growing out of a reorganization of the Indiana Engineering Society, the Indiana Engineering Council has been formed to function in the State in the same manner in which the American Engineering Council functions nationally. The Indiana Engineering Society was in operation for many years, and was composed principally of members of the 3 national societies: American Society of Civil Engineers, American Society of Mechanical Engineers, and the AIEE. This society was an incorporated body with the objective of bringing together these engineers and the land surveyors of the State to encourage professional intercourse and the development and advancement of its membership.

In the opinion of the officers of this society it would serve its purpose better if organized in the manner of American Engineering Council. Accordingly, at the last annual meeting of the society held February 16, 1937, and through the counsel of Dean A. A. Potter of Purdue University, president of AEC, steps for a reorganization were taken which resulted in the formation of the Indiana Engineering Council.

Both the Central Indiana and the Fort Wayne AIEE Sections are participating in the new organization.

According to Foster L. Stanley, chairman of the AIEE Central Indiana Section, who supplied the information for this news item, organization plans are now being developed by the following officers:

**President:** M. R. Keefe, chief engineer, Indiana State Highway Commission.

**Vice-President:** F. R. Weaver, vice-president, ASME, and an influential engineer in the State.

**Secretary-Treasurer:** Homer Ruppard, assistant chief engineer, Indianapolis Water Company.

**Executive Board:** Harry O. Garman (A'08, M'23) consulting engineer, past-president of the Indiana Engineering Society and past-chairman of the Central Indiana Section (1917–18). Charles Brossman (M'28) chief engineer, Indianapolis Water Company; Professor F. C. Hockema, assistant to president of Purdue University, chairman Central Indiana Section, ASME; Foster L. Stanley (A'34) plant extension engineer, Indiana Bell Telephone Company.

**Map of Illinois Lines.** A comprehensive map of electric transmission and distribution lines in Illinois has been prepared by the state rural electrification committee which shows all rural electric lines, transmission lines, points of interconnection, generating stations, and other electric facilities. All lines built up to January 1, 1937, are included. Copies of the map are printed in 3 colors and 30 inches by 50 inches in size may be obtained directly from the State Rural Electrification Committee, 220 Centennial Building, Springfield, Ill., at nominal cost.

## Membership—

Mr. Institute Member:

Vacation season is here! Many of our Sections have held their last meeting until fall and the membership committees have done the major portion of their work. They have done well too for the AIEE has the largest membership reported for the past 4 years, as of May first.

Now is the time when the help of the Institute members is most needed in membership work. Do not wait until fall to get your prospective member an application blank, but send his name to New York headquarters if your local membership committee is away on vacation. Your prospect will appreciate being "in" on the beginning of the new Section year and the Institute will appreciate your co-operation.

Fred B. Doolittle

Vice-Chairman, District No. 8
National Membership Committee

# Industrial Applications and Power System Problems Discussed at Buffalo—Students Also Hold Busy Session

A DISTINCTLY industrial flavor was one of the more attractive features of the AIEE North Eastern District meeting held May 5–7 at Buffalo, N. Y. Supplementing and giving point to 2 special informal papers that were devoted to a discussion and explanation of current trends in the design and application of the electrical equipment that is playing so vital a part in modern steel-mill electrification, was a correlated inspection trip through the new 72-inch continuous hot- and cold-strip mill of the Bethlehem Steel Company at nearby Lackawanna.

That lightning still holds its interest for power system operating engineers, electrical equipment manufacturers, and others was evidenced by the scope and character of the active discussion resulting from the presentation of 3 papers pertaining in one way or another to this subject. Other power-system problems were touched upon by papers describing the operating performance of a relay protective system for a large interconnected power system, operating performance of one of the newer steam-electric generating stations, experimental study of "dancing" cables, and the organization and operating procedure incident to the conduct of research and test work by 2 large electric utilities. An interesting informal paper describing the steps involved in surveying telephone requirements for a large industrial or commercial user gave an insight into some of the engineering and traffic problems incident to the modern facility of communication that today is taken very much for granted.

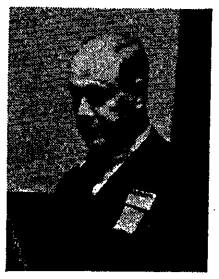
President MacCutcheon was an interested and active participant in practically all phases of the District meeting program. Presiding at the various sessions were: C. T. Sinclair, Pittsburgh, Pa., opening session; Robert Treat, Schenectady, N .Y., first general session; R. W. Graham, Lackawanna, N. Y., second general session; D. C. West, Buffalo, dinner meeting. J. Leo Scanlon, chairman of the Niagara Frontier Section, Buffalo, acted on behalf of the Section as host and general factotum.

### Steel Mill Electrification

Speaking on "Design Trends in Steel Mill Electrification," L. A. Umansky (A'16, M'27) of the General Electric Company, Schenectady, N. Y., graphically illustrated and dramatically described the ever-increasing extent to which modern sheet-steel production is directly dependent upon electric driving and controlling mechanisms. He pictured briefly the evolution of sheet rolling from the old simple single stand for sheets now regarded as small, to a modern mill where sheets 100 feet or more in length pass simultaneously through several rolls in tandem, to emerge at speeds of from 1,200 to 2,000 feet per minute. The intricacy and the importance of the electric driving and controlling equipment involved in such an operation can be understood when it is realized that each successive stand of rolls operates at a different speed in accordance with the progressive elongation of the strip, all being interlocked to maintain a predetermined setting.

Mr. Umansky's talk served also to emphasize the decisiveness of a trend, noted also in other branches of industry, toward an increasingly wider use of d-c machinery, because of its flexibility and susceptibility to precise control.

F. D. Egan (M'34) of the Bethlehem Steel Company described in some detail the "electrical applications" in that company's 72-inch continuous hot- and cold-strip mill at Lackawanna, N. Y. Although other mills now are under construction, this is one of the newest of the large mills now in operation, and is regarded as a typical example of a modern electrified steel mill. It has an annual capacity of 800,000 tons of hot-rolled strips, sheets, and light plates, of which 360,000 tons can be converted into cold-rolled finished products, and is capable of producing strips up to 72 inches in width by 0.078 inch in thickness, as well as light plates up to $1/2$ inch in thickness. It is designed to handle stock slabs ranging from 20 to 40 inches in width, from 3 to 6 inches in thickness, and from 5 to 15 feet in length.



R. W. Graham of Lackawanna, N. Y., presided at one of the general sessions

Electrically as well as mechanically, heavy-duty equipment is a prominent characteristic of such a mill. Mr. Egan emphasized the vital importance of a continuity of electric service, pointing out that the power supply for the Lackawanna mill is obtained from 3 different sources over 6 lines from 2 different directions. One of the problems incident to serving the 22,500 horsepower of d-c finishing-mill motors was that, under short-circuit conditions, currents of the order of 300,000 amperes might be expected on the 600-volt d-c bus. Special designs were adopted, including wide separation of the positive and negative busses, to reduce or control the resulting tremendously heavy physical forces that would be exerted on the bus conductors and fittings under short-circuit conditions.

### Lightning

In areas where lightning prevails, it still appears on system operating records as the Number 1 cause of interruptions to electric-power circuits, as confirmed by the discussion of the subject at Buffalo. Consequently, there is a prevalent active interest in the subject, although the outward manifestation of the studies that have continued for so many years has shifted gradually from heated debates over conflicting theories to colder analyses of accumulating operating statistics and observed test data. Authorities seem pretty well agreed that, although effective progress has been made in the development of practical preventives or palliatives, further progress in the prevention or control of lightning disturbances on electric-power systems will come from extensive correlation of existing data as well as from a continuation of laboratory and field investigations.

I. W. Gross (A'12) of the American Gas and Electric Company, New York, N. Y. S. K. Waldorf (A'27, M'36) of the Pennsylvania Water and Power Company, Baltimore, Md.; and G. A. Powell (A'23) of the New York Power and Light Corporation, Albany, N. Y., presented, respectively, the following papers, which were published as noted in earlier issues of Electrical Engineering:

Lightning Currents in 132-Kv Lines, Philip Sporn and I. W. Gross. Published in February issue, pages 245–52.

Probable Outages of Shielded Transmission Lines, S. K. Waldorf. Published in May issue, pages 597–600.

Special Uses for the Automatic Oscillograph, G. A. Powell and R. E. Walsh. Published in April issue, pages 438–40.

These presentations, and the conclusions drawn by the authors, brought forth a variety of discussion. K. B. McEachron (A'14, M'20) of Pittsfield, Mass., commented at some length on the quantity and variety of statistical data that has been accumulated and now is available concerning the operation of electric power systems under lightning-storm conditions, the character of lightning strokes, the probability of lightning disturbances affecting a given line, and other aspects of the subject. He emphasized the present need for correlation among these various data and between them and weather-bureau data pertaining to the number of storm-days experienced in various areas. Discussing the question of ground resistance as it might affect the operation of equipment installed for protection against lightning damage, Mr. McEachron observed that data received from London, England, indicate definitely that the higher the tower the less important the matter of ground resistance becomes; this is because for very high towers the time required for the wave to travel down the length of the tower is enough to permit the wave to approach crest value at the tower top, thus causing flashovers.

W. F. Davidson (A'14, M'26) of the Brooklyn (N. Y.) Edison Company, urged that "further thought be given to the matter of 'silent discharges.'"

Speaking with reference to the "zone of protection," usually assumed to be afforded by a high grounded structure, S. K. Waldorf described troubles that had been experienced by a certain street railway company wherein flashovers occurred across insulators on which trolley feeders were supported from buildings along either side of a "downtown"

street flanked by buildings several stories high. He reported that a study of this situation indicated that lightning impulses were conducted down through the buildings to points where the resistance to ground was lower across the trolley-feeder insulators than it was down through the frame of the building, resulting in flashovers from building to trolley feeder and on to ground through railway equipment. An increase in the insulation at these points overcame the trouble.

Commenting on the characteristics of lightning, R. E. Walsh observed that waves resulting from lightning strokes "do not rise nearly as rapidly nor as steeply as some theories and some studies have indicated."

### Power System Operation

Four special presentations featured a general session devoted to power system problems:

Development and Operating Performance of a Relay System, L. J. Audlin (M'35), Syracuse, George Steeb (A'26, M'34), Buffalo, and G. A. Powell (A'23) of Buffalo, who constitute the relay committee of the Niagara-Hudson operating companies.

Operating Performance of C. R. Huntley Station. Presented in 2 parts: Electrical, J. M. Geiger (A'28, M'34); Mechanical, Donald Scranton; both of the Buffalo General Electric Company

Research and Testing in a Large Electric Utility, W. F. Davidson (A'14, F'26) director of research and test of the Consolidated Edison Company of New York, Inc.

Research and Testing in the Hydro-Electric Power Commission of Toronto, W. P. Dobson (A'13, M'19) chief testing engineer, Hydro-Electric Power Commission of Ontario, Canada.

These papers were developed especially for the Buffalo meeting, and have not been published in Electrical Engineering.

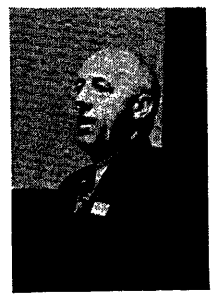
L. J. Audlin described briefly the operating, switching, and relaying problems involved in the gradual evolution of several distinct operating systems into what is in effect a single coordinated interconnected system covering a large portion of the State of New York. Extensive calculating-board studies of short-circuit conditions were described as having revealed the principal difficulties to be overcome for successful operation: that more rapid relay and circuit breaker operation would be required to avoid system instability; that phase relays would not provide adequate protection against certain types of ground faults. Replacements of circuit breaker and relay equipment have been effected until now about 44 per cent of the 140 or so switch positions on the interconnected transmission system are equipped with "distance" relays and high-speed oil circuit breakers (8-cycle) of heavy interrupting capacity. Further improvements now under way will bring this figure to about 54 per cent of the total line-switching positions. For main transmission circuits, differential protection (pilot relaying) for each individual circuit is considered to be the "ideal." This ideal is approached between the generating sources of the Niagara-Hudson power system and New York City by the supplemental use of carrier relay equipment for the control of directional relays. Operating records for the period 1933 to 1936 inclusive, showed a total of 1,185 disturbances, of which the 3 most prominent causes were: lightning, 56.1 per cent; sleet, wind, and jumping conductors, 12.4 per cent; and closing in on faults, 11.4 per cent. Relay operating records for the same period showed a total of 2,764 disturbances, of which 92.2 per cent were correct and desired, 5.3 per cent correct, but undesired, and 2.1 per cent incorrect or faulty, and 0.4 per cent failure to operate. A point raised for discussion was whether or not to separate 2 parts of an interconnected transmission system when synchronism is lost between them, some operating experiences indicating the possibility of re-establishing synchronism without interruption and without damage to equipment.



Robert Treat of Schenectady, N. Y., presided at one of the general sessions

The Huntley steam-electric generating station No. 2 was built in 1929, expressly for the purpose of providing for the change-over in the domestic and commercial load in the Buffalo area from 25-cycle to 60-cycle service. In describing the electrical operation of the station, J. M. Geiger pointed out that inasmuch as the bus bars of this one station would have to carry, for at least several years, all the 60-cycle energy for a large metropolitan area, provision for the highest order of reliability in the electrical equipment was a necessity. The station generating equipment comprises 2 8,000-kw 12,000-volt generators, each tied solidly to an autotransformer, the 22-kv windings of which normally are connected to opposite busses. This "split bus" scheme also is applied to the large transformers for the 110-kv transmission ties, for the frequency changer connections, and for the outgoing 22-kv feeders. The neutral leads of the generators and large transformers are connected to a common neutral bus and grounded through a 5-ohm resistor to limit fault currents to ground. Experiments with this resistor in service and out of service indicate that its use has no bearing on the rate of electric cable failures in the local system. Circuit arrangements and operating procedures were such, according to the report, that since the station was built there has not been a single interruption in the low-voltage-network service that is wholly dependent upon the station.

Research and test work are as vital to the effective and economical operation of the electric service utilities as they are to the success of other industrial enterprises. Descriptions of their respective organizations, methods of procedure, and types of work were given by W. F. Davidson of the Consolidated Edison Company of New York and W. P. Dobson of the Hydro-Electric Power Commission of Ontario. In Mr. Davidson's organization, all testing, except that involving mechanical equipment in generating stations, is assigned to the test bureau of the system engineering department. The scope of this department includes all testing of the transmission and distribution system and associated substations, all electrical equipment in the generating stations, maintenance of the standards laboratory and portable test instruments, and the testing of materials and such apparatus as require special laboratory facilities. The production department has a test organization in each generating station to handle the testing of mechanical equipment. A research bureau in the system engineering department is responsible for the conduct of research connected with the electrical operations (as distinguished from gas operations). To insure effective co-ordination of these separate agencies, the heads of research bureau and the test bureau report to the director of research and tests, and the station test groups report to the production economy engineer. These 2 men jointly handle those cases which concern more than one unit of the testing organization. For convenience and administration, the test bureau of the system engineering department is organized into 2 divisions: laboratory, and field tests, the names of which indicate the general scope of their activities and responsibilities. An important function of the laboratory division is the maintenance of reference standards. Another important function is the performance of acceptance tests on materials and apparatus. As to the research work, new problems constantly are arising, each to be dealt with in accordance with its requirements and importance.



President A. M. MacCutcheon was an interested and active participant

In the Hydro-Electric Power Commission of Ontario, the testing and research department is responsible for the testing and inspection of all materials and equipment purchased, and for the conduct of special investigations and research. W. P. Dobson pointed out that a comprehensive inspection and testing policy is followed and applied not only to new material and equipment, but also to material in service, with the object of detecting signs of failure and of devising remedial measures. Research problems are suggested by the difficulties encountered in construction and operation, and the work is carried on under the general direction of a research committee composed of 5 department heads. Projects are assigned to subcommittees containing representatives from all departments interested. Results accomplished were reported as including improved methods of operation, improved methods of treating materials to prolong their life, the development of new specifications or improvements of existing specifications for the purchase of materials, and the development of new equipment for special applications.

### Dancing Cables

"Dancing" or "galloping" cables on transmission and distribution lines have been observed under certain weather conditions for many years. At the Buffalo meeting, D. C. Stewart (A '25, M'35) assistant electrical engineer for the Buffalo, Niagara, and Eastern Power Corporation, presented the results of an experimental study of this condi-

tion. During dancing periods the cables had been observed to oscillate violently with amplitudes and motions of alarming proportions. As the cables do not move in synchronism, there is a resulting threat of contact or flashover and consequent interruption to service. Mr Stewart, in discussing the various theories that have been offered mentioned that propounded by A. E. Davison (A'13) of Toronto at the AIEE convention held in that city in June 1930 which was to the effect that the wind acting on irregular icy formations adhering to the cables exerts aerodynamic forces that initiate and maintain the cable motion. Mr. Stewart stated that although this theory failed to explain some cases where cable dancing has been reported when no ice was on the cable it does seem to account for the great bulk of reported cases. For his experimental span, Mr. Stewart reported the use of a 104-foot span of number 4 ACSR 7-strand cable strung at right angles to the direction of the prevailing wind. To this cable were affixed wax formations to simulate ice or snow deposits that had been observed under storm conditions when dancing prevailed. With special arrangements for observation and measurement, Mr. Stewart found that the cable on this test span under storm conditions swung in a path of approximately elliptical proportions and having a vertical axis of some 3 feet and a horizontal axis of some 2 feet, which swing carried the cable at midspan to a point considerably above the axis of support at the ends of the span. He found also that there was a periodic twisting of the conductor to the extent of more than 180 degrees above its longitudinal axis, as it swung in its elliptical path. With a wind velocity of about 61 feet per second, the cable traveled around its elliptical path at an average speed of some 14 feet per second. The experimental results reported were considered to confirm the theory that cable dancing results from wind blowing against irregular ice formations adhering to the cables; further, that the varying twists in the cable plays its part in the vibration phenomena. In the resulting discussion it was suggested that electromagnetic phenomena sometimes might be responsible for the initiation of vibration. The scope and character of this discussion indicated a broad interest in the problem as a possible cause of circuit interruption and seemed to indicate conclusively the desirability of further research and analysis.

### Student Technical Sessions

Although many students attended the other technical sessions, principal student attention was focused upon the session devoted to the presentation and discussion of the following student papers:

The Design, Construction, and Testing of a Miniature Cathode-Ray Oscilloscope, N. I. Korman, Worcester Polytechnic Institute.

A Transmission-Line Slide Rule, R. R. Gay and C. H. Hunter, Cornell University.

Television, D. O. Wood, Massachusetts Institute of Technology.

A High-Voltage Electrostatic Voltmeter, E. M. Williams (graduate student), Yale University.

Power-Circuit Filters for A-C Generators, Abner Crumb (graduate student) Worcester Polytechnic Institute.

The Iconoscope, the Eye of Television, S. S. Dufford, Rensselaer Polytechnic Institute.

Single-Phase Railway Motors, W. Malthamer, Jr., Rensselaer Polytechnic Institute.

The Sliding Electrical Contact, D. P. Miles, Rensselaer Polytechnic Institute.

Under the excellent chairmanship of R. W. Kunkle, engineering student, Cornell University, this busy session was conducted with order and dispatch, with the time carefully budgeted between presentations and discussions. Many of the approximately 150 students that attended the session took an active part in the discussion of the papers.

President MacCutcheon, in addressing the group, paid tribute to the student authors for the general excellence of their papers, and the effectiveness with which they were presented, to Student Chairman Kunkle for his efficient handling of the meeting, and to Professor F. N. Tompkins, counselor of the Brown University Student Branch and chairman of the student activities committee for the North Eastern District meeting under whose general supervision the program was arranged and presented. A committee of judges made up of Professors A. R. Powers of Clarkson, E. A. Walker of Tufts, and C. W. Henderson of Syracuse, returned the verdict awarding prizes *for presentation* as follows: first, to Mr. Korman; second, to Messrs. Gay and Hunter; and third, to Mr. Miles. Mr. Williams and Mr. Crumb were awarded honorable mention.

### Conference on Student Activities

At a luncheon business conference held Friday, May 7, a total of 36 persons interested in Student Branch activities gathered together for a discussion of the problems incident to that phase of the Institute's activity in the North Eastern District. This group included student and faculty representatives from 13 of the 16 Student Branches in the North Eastern District, District Secretary R. G. Lorraine of Schenectady, Editor G. R. Henninger of New York, Vice-President A. C. Stevens of Schenectady, National Secretary H. H. Henline of New York, President A. M. MacCutcheon of Cleveland, Professor T. H. Morgan of Worcester Polytechnic Institute, Professor Lynn C. Holmes, counselor-elect of the Branch at Rensselaer Polytechnic Institute, and the following representatives:

**Student Branch Counselors and Alternates**

F. N. Tompkins, Brown University, Providence, R. I.
A. R. Powers, Clarkson College of Technology, Potsdam, N. Y.
E. M. Strong, Cornell University, Ithaca, N. Y.
J. D. Cobine, Harvard University, Cambridge, Mass.
W. H. Bliss, University of Maine, Orono
W. H. Timbie, Massachusetts Institute of Technology, Cambridge
L. W. Hitchcock, University of New Hampshire, Durham
F. M. Sebast, Rensselaer Polytechnic Institute, Troy, N. Y.
C. W. Henderson, Syracuse University, N. Y.
E. A. Walker, Tufts College, Tufts College, Mass.
E. R. McKee, University of Vermont, Burlington
Victor Siegfried, Worcester Polytechnic Institute, Mass.
A. G. Conrad, Yale University, New Haven, Conn.

**Student Branch Chairmen or Alternates**

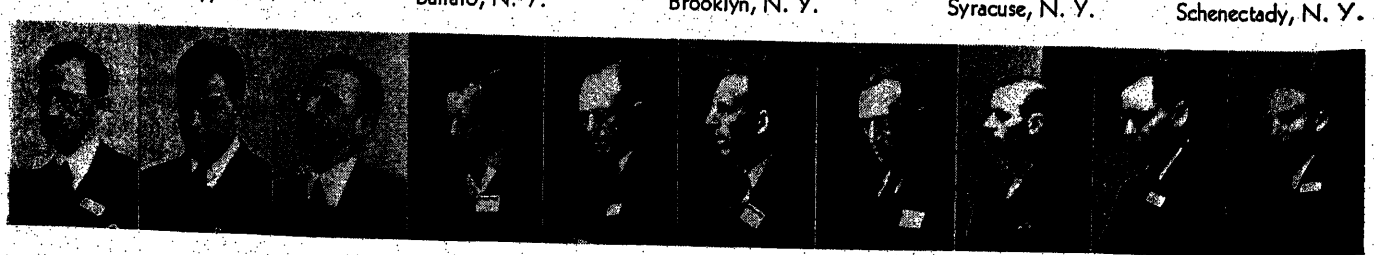
Gerald Smithson, Brown University, Providence, R. I.
J. F. Frazier, Clarkson College of Technology, Potsdam, N. Y.
F. J. Skinner, Cornell University, Ithaca, N. Y.
L. P. Winsor, Harvard University, Cambridge, Mass.
H. O. Saunders, Massachusetts Institute of Technology, Cambridge
H. C. Kenneson, University of Maine, Orono
R. W. Tolles, University of New Hampshire, Durham
J. S. Dufford, Rensselaer Polytechnic Institute, Troy, N. Y.
F. C. Tuck, Syracuse University, N. Y.
F. A. Spindell, Tufts College, Mass.
J. R. Tozer, Jr., University of Vermont, Burlington
R. P. Day, Worcester Polytechnic Institute, Mass.
R. D. Scott, Yale University, New Haven, Conn.

Among the various items of business discussed, principal attention was given to: (*a*) the desirability of providing more and better housing arrangements and entertainment features for students attending these District student conventions; (*b*) the desirability of divorcing the student conventions from District meetings; (*c*) the question of a proper basis for the competitive grading of student papers.

The weight of student opinion was to the effect that adequate attention already is being given to the provision of facilities for students in connection with District meetings, and that any further efforts in that direction would nullify some of the educational benefits accruing to the students by virtue of having to do a bit of caring for themselves in a strange community, a situa-

**A group of authors who presented papers at the Buffalo meeting**

S. K. Waldorf, Baltimore, Md. — I. W. Gross, New York, N. Y. — Donald Scranton, Buffalo, N. Y. — W. P. Dobson, Toronto, Can. — D. C. Stewart, Buffalo, N. Y.
G. A. Powell, Albany, N. Y. — J. M. Geiger, Buffalo, N. Y. — W. F. Davidson, Brooklyn, N. Y. — R. E. Corey, Syracuse, N. Y. — L. A. Umansky, Schenectady, N. Y.





R. W. Kunkle, chairman, Cornell — P. H. Hunter, Cornell — S. S. Dufford, Rensselaer — Abner Crumb, Worcester — D. P. Miles, Rensselaer

N. I. Korman, Worcester — D. O. Wood, M.I.T. — E. M. Williams, Yale — W. Malthaner, Jr., Worcester

**A group of student authors who presented papers at the Buffalo meeting**

tion they all expect to face upon graduation. The general consensus of opinion among both students and counselors was to the effect that electrical engineering students do not need to be "spoon fed." Likewise, the suggestion to separate the student conventions from the regular District meeting program was talked down by a wide margin, 2 important facts being stressed by several speakers: first, that many advantages to students from attending such meetings would be lost if the opportunity to attend the general technical sessions and otherwise mingle with the practicing engineers were eliminated; second, that any need or desire for conclaves devoted wholly to student matters could be satisfied by arranging such conclaves without interferring with the joint District student convention and District meeting which was regarded as having been highly successful over a period of years.

Referring to the basis for the competitive grading of technical papers as published on page 492 of the April 1937 issue of ELECTRICAL ENGINEERING, there was a strongly expressed and apparently widely held opinion among Student Branch counselors that the published basis was not satisfactorily applicable to student papers. Two factors were pointed out as being of particular significance in connection with the grading of student papers: first, "the broad interpretation and importance of 'originality' " ; second, "the lesser expectancy of 'value' to the profession in student papers and the unimportance of attempting to segregate it into the present 'value in its field,' and 'value to electrical engineering.' " A committee of counselors that has been studying this matter recommended the following basis for grading student papers:

| | |
|---|---|
| Preliminary analysis | 20 per cent |
| Logical presentation | 20 per cent |
| Originality in handling subject | 20 per cent |
| Unity of composition | 20 per cent |
| Value to electrical engineering | 20 per cent |

This report and recommendation was accepted by a vote. Also there was expressed a desire for continued study of grading "in favor of more drastic revision" and Chairman Tompkins was requested to appoint a committee for the purpose.

### ENTERTAINMENT—ATTENDANCE

The principal feature of the entertainment program at the Buffalo meeting was a very nicely arranged dinner held the evening of the second day, and departing from common practice in that it was not a dinner dance. President and Mrs. A. M. MacCutcheon were the guests of honor. Entertainment as well as instruction was afforded through an interesting demonstration lecture "Kodachrome Colored Film," given by L. D. Mannes of the Eastman Kodak Company, Rochester, N. Y., co-inventor of a color photography process in which a single negative comprises 3 successively deposited sensitized films, each sensitive to a different primary color, and each separated from its neighbors by a neutral deposit which enables the complicated developing process to be carried on step-by-step, progressively bringing out the several layers, the composite of which is an accurate color reproduction. The reported attendance was 273.

### DISTRICT EXECUTIVE COMMITTEE MEETS

A luncheon meeting of the North Eastern District executive committee was held Thursday, May 6, during the Buffalo meeting. After routine matters had been disposed of, there was considerable discussion concerning the registration of professional engineers in connection with the discussion of the general topic of "broadening" of Institute activities. Pittsfield, Mass., was selected as the site for the 1938 District meeting.

The meeting was attended by the following delegates:

A. C. Stevens, vice-president, AIEE
R. G. Lorraine, secretary, North Eastern District
F. N. Tompkins, chairman, District Committee on student activities
R. F. Chamberlain, chairman, Ithaca Section
C. L. Dawes, chairman, Boston Section
C. M. Foust, chairman, Schenectady Section
E. M. Hunter, secretary, Schenectady Section
K. B. McEachron, chairman, Pittsfield Section
R. M. Pfalzgraff, chairman, Lynn Section
H. C. Rankin, chairman, Providence Section
J. Leo Scanlon, chairman, Niagara Frontier Section
V. Siegfried, vice-chairman, Worcester Section
B. M. Werly, secretary, Rochester Section

The meeting was attended also by President A. M. MacCutcheon, Chairman W. H. Timbie of the Sections committee, National Secretary H. H. Henline, Editor G. R. Henninger, Chairman V. G. Smith of the Toronto, Ontario, Section, Chairman-Elect Ralph M. Darrin of the Niagara Frontier Section, and B. K. Northrop of the Ithaca Section.

During the dinner meeting, Vice-President A. C. Stevens announced the following winners of District prizes for 1936 technical papers, and made awards accordingly: (1) for the best Student Branch paper, William A. Harry of Cornell, now with the Bell Telephone Laboratories; (2) for first paper prize, Edgar A. Harty (A'22,M'36) in charge of design and manufacture of copper oxide rectifiers for the General Electric Company, Lynn, Mass.; (3) for the best paper prize, E. M. Hunter (A'28, M'36) central station engineering department, General Electric Company, Schenectady, N. Y. Details of these awards are covered in the formal report on paper prizes published elsewhere in this issue.

Another interesting demonstration lecture was delivered the evening of the first day by L. W. W. Morrow (A'13, F'25) general manager of the fiber products division of the Corning Glass Works, Corning, N. Y., on the subject of "Fibrous Glass." This is a new product of amazing characteristics. Although glass in every sense of the word manufactured by a secret process, the fibers look and feel not unlike silk, and lend themselves to the manufacture of all manner of fabrics through the use of regular textile manufacturing machines, in addition to having the inherent characteristics of glass, such as fireproofness and nonabsorbence of liquids. This new product is essentially an alloy, as is glass in any form, and has many properties similar to metallic alloys. A temperature of some 1,200 or 1,400 degrees centigrade is required to melt and mix the constituents preparatory to drawing the fibers. The fibers are about 0.0004 inch in diameter, and from 1.5 to 20 inches long, are heat-resistant, nonabsorbent, and strong (reputedly the equivalent of about a million pounds per square inch in the smaller fibers). It is a product of recent research and already is being used in the manufacture of textiles, insulating and other tapes, insulating pipe coverings, and house insulation, and the future seems wide open with possibilities for application in the manufacture of electrical equipment.

Registration is reported and analyzed in the accompanying tabulation.

**Analysis of Registration at Buffalo Meeting**

| | Location | | | |
|---|---|---|---|---|
| Classification | Buffalo | District 1* | Other Districts | Totals |
| Members | 63 | 80 | 44 | 187 |
| Students | 2 | 71 | 5 | 78 |
| Men guests | 22 | 35 | 11 | 68 |
| Women guests | 8 | 9 | 2 | 19 |
| Totals | 95 | 195 | 62 | 352 |

* Outside of Buffalo.

**Refrigerating and Air Conditioning Machinery Manufacturers Meet.** The Refrigerating Machinery Association met on May 12 and 13, 1937, at Hot Springs, Va., and immediately following, on May 14 and 15, the Air Conditioning Manufacturers' Association held its annual meeting.

# Section and Branch Activities

## Annual Report for 1936-37

THE following constitutes the annual report on Institute Section and Branch activities for the fiscal year which ended April 30, 1937. Similar information for 3 preceding fiscal years appeared in ELECTRICAL ENGINEERING for June 1936, pages 752–54; June 1935, pages 674–75; and June 1934, pages 1027–29.

The names of our present members of the Sections committee and the committee on Student Branches, which supervise the 2 important divisions of Institute activities covered by this report, are: Sections—W. H. Timbie, *chairman*, W. M. Dann, Mark Eldredge, O. W. Holden, E. T. Mahood, H. H. Race, I. M. Stein, and, *ex-officio*, the chairmen of all Sections of the Institute. Student Branches—F. Ellis Johnson, *chairman*, Edward Bennett, L. A. Doggett, E. E. Dreese, O. E. Edison, O. W. Eshbach, T. W. Fitzgerald, E. A. Loew, Charles F. Scott, R. W. Sorensen, and, *ex-officio*, all Student Branch counselors.

### SECTION ACTIVITIES

The East Tennessee Section was organized in September and enthusiastically began carrying on a normal amount of activity. This brought the total number of Sections to 62. Three prospective new Sections are being actively discussed.

Practically all the 62 Sections carried on at least normal amounts of activity, and many were unusually active. The total number of meetings reported was 621, or 81 more than the total for the preceding year.

President MacCutcheon visited about 40 Sections prior to April 30, and will visit several others, bringing the total number to about 47. He was enthusiastically welcomed, and his visits contributed much to the success of Section activities.

The outstanding development in Section activities in recent years is the inauguration of special types of meetings designed to meet as fully as possible the desires of the members. Eighteen Sections have adopted plans for holding technical group, technical committee, special technical, or other types of meetings devoted to more highly specialized subjects than those usually presented at regular Section meetings. The types of such activities usually have been chosen after receipt of replies to questionnaires requesting members to express their principal technical interests.

In 3 Sections, Alabama, Montana, and Toronto, local group meetings were held at points in their territories from which few members could attend regular Section meetings.

Table I contains tabular information on the meetings of all Sections and of their technical groups, technical committees, discussion groups, and other subdivisions. Information on many of these special activities has appeared in ELECTRICAL ENGINEERING during the past year. In the following statements, particular attention is given to some of the more recent developments, and especially to those of newer types.

The Toronto Section established a discussion group having as its purpose the development of engineers in the preparation and presentation of 5-minute talks and discussions. Meetings 40 minutes in length were held immediately preceding regular Section meetings and at the same place. Three talks and general discussion constituted the program of each. It is expected that this plan will be continued next year for the purpose mentioned and also to improve the knowledge of the members in economics and human relations in engineering.

The Toronto Section also formed a technical discussion group which met at supper on the evenings of Section meetings, and then held its discussions between 6:05 and 7:45. The general subject was "Control and Protective Practice"; 3 or 4 papers were presented at each meeting.

The Seattle Section sent a questionnaire

**Table I. Section Meetings Held During Year Ending April 30, 1937**

| Section | AIEE Members August 1935 | AIEE Members August 1936 | Meetings During Year Number | Meetings During Year Average Attendance | Avg. Attendance as Per Cent of Membership, August 1936 |
|---|---|---|---|---|---|
| Akron | 64 | 67 | 8 | 90 | 134 |
| Alabama | 38 | 42 | 7 | 270 | 643 |
| Muscle Shoals power subgroup | | | 3 | 66 | |
| Atlanta | 71 | 72 | 5 | 77 | 107 |
| Baltimore | 167 | 174 | 9 | 169 | 97 |
| Boston | 378 | 386 | 8 | 172 | 45 |
| Central Indiana | 94 | 116 | 5 | 82 | 71 |
| Chicago | 614 | 603 | 7 | 212 | 35 |
| Power group | | | 2 | 96 | |
| Industrial group | | | 5 | 131 | |
| Cincinnati | 143 | 159 | 9 | 284 | 178 |
| Cleveland | 220 | 245 | 8 | 134 | 55 |
| Industrial motors and control group | | | 3 | 60 | |
| Electronics | | | 3 | 32 | |
| Columbus | 62 | 63 | 8 | 44 | 70 |
| Technical lectures | | | 13 | 8 | |
| Connecticut | 225 | 267 | 8 | 123 | 46 |
| Dallas | 87 | 89 | 6 | 48 | 54 |
| Denver | 138 | 132 | 10 | 46 | 35 |
| Technical committee | | | 1 | 55 | |
| Detroit-Ann Arbor | 268 | 320 | 10 | 150 | 47 |
| Special Technical Meeting | | | 1 | 25 | |
| East Tennessee* | | 49 | 8 | 44 | 90 |
| Erie | 48 | 52 | 9 | 74 | 142 |
| Florida | 47 | 60 | 2 | 129 | 215 |
| Fort Wayne | 55 | 64 | 12 | 103 | 161 |
| Houston | 65 | 75 | 9 | 50 | 67 |
| Iowa | 50 | 56 | 8 | 100 | 179 |
| Ithaca | 56 | 54 | 10 | 126 | 233 |
| Kansas City | 134 | 148 | 10 | 152 | 103 |
| Lehigh Valley | 185 | 184 | 8 | 114 | 62 |
| Los Angeles | 385 | 440 | 9 | 102 | 23 |
| Special technical meeting | | | 1 | 65 | |
| Louisville | 56 | 50 | 5 | 60 | 120 |
| Lynn | 99 | 120 | 14 | 373 | 311 |
| Technical lectures | | | 3 | 87 | |
| Madison | 51 | 48 | 4 | 46 | 96 |
| Memphis | 31 | 33 | 10 | 48 | 145 |
| Mexico | 66 | 67 | 5 | 40 | 60 |
| Milwaukee | 173 | 208 | 11 | 177 | 85 |
| Minnesota | 74 | 72 | 9 | 45 | 63 |
| Power committee | | | 4 | 22 | |
| Montana | 34 | 38 | 6 | 70 | 18 |
| Fort Peck group | | | 4 | 17 | |
| Nebraska | 51 | 56 | | | |
| New Orleans | 44 | 50 | 5 | 73 | 146 |
| New York | 2,773 | 3,036 | 4 | 632 | 21 |
| Power group | | | 7 | 276 | |
| Transportation group | | | 3 | 143 | |
| Communication group | | | 4 | 381 | |
| Illumination group | | | 3 | 317 | |
| Niagara Frontier | 197 | 208 | 8 | 137 | 66 |
| North Carolina | 78 | 83 | 2 | 108 | 130 |
| Oklahoma City | 110 | 120 | 7 | 121 | 101 |
| Philadelphia | 517 | 550 | 8 | 118 | 21 |
| System characteristics group | | | 1 | | |
| Pittsburgh | 379 | 411 | 8 | 181 | 44 |
| Pittsfield | 107 | 121 | 10 | 765 | 632 |
| Colloquium series | | | 6 | 29 | |
| Portland | 92 | 110 | 9 | 82 | 75 |
| Illumination committee | | | 2 | | |
| Trans. & Dist. committee | | | 3 | 46 | |
| Electrochem. and Electrometallurgy com | | | 2 | | |
| Communication committee | | | 2 | 33 | |
| Providence | 85 | 82 | 7 | 112 | 137 |
| Rochester | 71 | 80 | 14 | 125 | 156 |
| Communication group | | | 3 | 18 | |
| Power group | | | 2 | 30 | |
| St. Louis | 182 | 201 | 8 | 111 | 55 |
| San Antonio | 26 | 29 | 7 | 34 | 117 |
| San Francisco | 373 | 401 | 9 | 200 | 50 |
| Special technical meetings | | | 5 | 56 | |
| Saskatchewan | 24 | 25 | 7 | 27 | 108 |
| Schenectady | 353 | 367 | 12 | 219 | 60 |
| Technical discussion meetings | | | 4 | 50 | |
| Junior discussion group | | | 5 | 25 | |
| Seattle | 117 | 146 | 9 | 52 | 36 |
| Transmission & distribution | | | 6 | 28 | |
| Communications | | | 4 | 13 | |
| Electronics & electron tubes | | | 4 | 20 | |
| Power generation | | | 4 | 20 | |
| Sharon | 55 | 62 | 9 | 99 | 160 |
| Technical discussion meetings | | | 2 | 40 | |
| Spokane | 44 | 48 | 7 | 44 | 92 |
| Springfield, Mass | 65 | 68 | 9 | 60 | 88 |
| Syracuse | 65 | 71 | 4 | 379 | 533 |
| Toledo | 69 | 66 | 11 | 59 | 89 |
| Toronto | 286 | 293 | 13 | 114 | 39 |
| Discussion group | | | 10 | 25 | |
| Technical discussion group | | | 8 | 38 | |
| Hamilton group | | | 2 | 165 | |
| Urbana | 36 | 36 | 6 | 24 | 67 |
| Utah | 39 | 41 | 8 | 49 | 120 |
| Vancouver | 88 | 97 | 10 | 60 | 62 |
| Virginia | 86 | 90 | 2 | 36 | 40 |
| Washington | 229 | 258 | 8 | 144 | 56 |
| Worcester | 62 | 63 | 8 | 94 | 149 |
| Total...62 | 10,881 | 11,822 | | | |
| Total number of meetings | | | | 621 | |
| Total attendance | | | | 74,950 | |

* Organized September 2, 1936.

## Table II. Courses of Instruction Offered by Sections

| Section | Subject | Member Fee | Duration | Enrollment |
|---|---|---|---|---|
| Lynn | Electronics | $10.00 | October-December | 21 |
| New York | | | | |
| Power group | Electrical engineering | 10.00 | 20 weeks—September | 53 |
| | | | (Repeated)—January | 45 |
| | Structural planning and design | 10.00 | 20 weeks—September | 170 |
| | | | (Repeated)—January | 200 |
| | Industrial control lectures | 2.00 | 8 weeks | 120 |
| | Public speaking | 15.00 | 16 weeks—September | 17 |
| | | | (Repeated)—January | 15 |
| Communication group | Electronics lectures | 2.00 | 8 weeks | 300 |
| Niagara Frontier | Applied structural design | | October-January | 50 |
| Philadelphia | Electrical theory review | 15.00 | September-May | 23 |
| | Mathematics review | 15.00 | September-May | 25 |
| | Electronics (repeat) | 12.00 | January-May | 27 |
| | Any 2 courses | 25.00 | | |
| Springfield | Electronics | 10.00 | January-May | 30 |
| Vancouver | Electronics and electron tubes | 7.50 | 20 weeks | 27 |

to its members and to the members of the University of Washington Branch, in October 1936, asking whether they would be interested in taking part in technical group meetings devoted to 6 subjects which were named or to other subjects which they were invited to suggest. After a tabulation of the responses, the executive committee decided to organize technical groups covering the 4 subjects in which the greatest interest had been shown: transmission and distribution, power generation, communication, and electronics and electron tubes. Free discussion was encouraged. Attendance was very good, comparable in many cases with that at regular Section meetings.

The Schenectady Section junior discussion group held dinner meetings to which the younger members of the local Sections of several engineering societies were invited. Opportunities were presented for open discussions on technical and general subjects. It also held a technical discussion series of dinner meetings for members of the Sections. Subjects were chosen by use of a postal card interest finder.

The Columbus Section held a series of lectures on technical subjects of special interest to its members.

The Pittsfield Section held a colloquium series for brief presentations by specialists of published papers of interest to electrical engineers and general discussions of them.

The Philadelphia Section arranged near the end of the year for 2 technical discussion groups: one on system characteristics under fault conditions, the other on industrial applications of electricity.

The Rochester Section organized communication and power groups.

The power group of the Chicago Section continued its work with notable success, and an industrial group was formed.

The Cleveland Section continued its industrial motor and control group, and organized an electronics group.

The Denver Section organized a technical committee, and the Detroit-Ann Arbor

## Table III. Section Meetings Held During Last 3 Fiscal Years

| | Fiscal Year Ending April 30 | | |
|---|---|---|---|
| | 1935 | 1936 | 1937 |
| Number of Sections | 61 | 61 | 62 |
| Number of meetings held | 521 | 540 | 621 |
| Average number of meetings | 8.5 | 8.9 | 10.0 |
| Total attendance | 73,381 | 85,501 | 74,950 |
| Average attendance per meeting | 141 | 158 | 121 |

## Table IV. Branch Meetings Held During Year Ending April 30, 1937

| Branch | Meetings During Year: Number | Average Attendance | Approx. No. of Talks by Students |
|---|---|---|---|
| Akron, University of | 6 | 7 | 7 |
| Alabama Polytechnic Institute | 14 | 34 | 4 |
| Alabama, University of | 19 | 24 | 12 |
| Arizona, University of | 30 | 10 | 15 |
| Arkansas, University of | 20 | 20 | 19 |
| Armour Institute of Technology | 12 | 35 | 2 |
| British Columbia, Univ. of | 8 | 22 | 14 |
| Brooklyn, Polytechnic Inst. of | 8 | 101 | 7 |
| Brown University | 3 | 57 | — |
| Bucknell University | 13 | 23 | 7 |
| California Institute of Technology | 14 | 25 | 1 |
| California, University of | 22 | 62 | 15 |
| Carnegie Institute of Tech | 23 | 35 | 48 |
| Case School of Applied Science | 28 | 54 | 56 |
| Catholic University of America | 1 | 9 | — |
| Cincinnati, University of | 8 | 64 | 3 |
| Clarkson College of Technology | 10 | 20 | — |
| Clemson Agricultural College | 10 | 41 | 13 |
| Colorado State Agri. College | 6 | 7 | 4 |
| Colorado, University of | 11 | 46 | — |
| Columbia University* | 9 | 25 | 3 |
| Cooper Union | | | |
| Day division | 7 | 24 | 5 |
| Evening division | 7 | 17 | 5 |
| Cornell University | 6 | 25 | 4 |
| Denver, University of | 13 | 22 | 2 |
| Detroit, University of | 3 | 80 | — |
| Drexel Institute | 15 | 19 | 10 |
| Duke University | 16 | 45 | 30 |
| Florida, University of | 12 | 28 | 3 |
| George Washington University | 8 | 27 | 10 |
| Georgia School of Technology | 7 | 37 | 4 |
| Harvard University | 3 | 30 | 1 |
| Idaho, University of | 8 | 35 | 7 |
| Illinois, University of | 12 | 75 | 6 |
| Iowa State College | 16 | 60 | 4 |
| Iowa, University of | 26 | 35 | 26 |
| Johns Hopkins University | 22 | 25 | 23 |
| Kansas State College | 15 | 95 | 20 |
| Kansas, University of | 9 | 40 | 10 |
| Kentucky, University of | 24 | 50 | 6 |
| Lafayette College | 6 | 19 | 15 |
| Lehigh University | 7 | 84 | 4 |
| Lewis Institute | 9 | 53 | — |
| Louisiana State University | 13 | 24 | 6 |
| Louisville, University of | 9 | 10 | 4 |
| Maine, University of | 3 | 29 | — |
| Marquette University | 11 | 57 | — |
| Maryland, University of | 10 | 43 | 10 |
| Massachusetts Inst. of Tech | 8 | 84 | 6 |
| Michigan College of Min. & Tech | 9 | 43 | 3 |
| Michigan State College | 10 | 30 | 4 |
| Michigan, University of | 10 | 23 | 2 |
| Milwaukee School of Engineering | 10 | 40 | 1 |
| Minnesota, University of | 7 | 55 | 5 |
| Mississippi State College | 15 | 15 | 10 |
| Missouri School of Mines & Met | 9 | 49 | 5 |
| Missouri, University of | 10 | 48 | 6 |
| Montana State College | 26 | 23 | 69 |
| Nebraska, University of | 14 | 29 | 6 |
| Nevada, University of | 8 | 20 | — |
| Newark College of Engineering | 4 | 35 | 6 |
| New Hampshire, University of | 21 | 20 | 28 |
| New Mexico, University of | 10 | 14 | 5 |
| New York, College of the City of | | | |
| Day division | 32 | 25 | 14 |
| Evening division | 14 | 11 | 3 |
| New York University | | | |
| Day division | 15 | 30 | 35 |
| Evening division | — | — | — |
| North Carolina State College | 12 | 33 | 23 |
| North Carolina, University of | 12 | 18 | 10 |
| North Dakota State College | 6 | 15 | 3 |
| North Dakota, University of | 14 | 14 | 9 |
| Northeastern University | 6 | 40 | — |
| Notre Dame, University of | 8 | 26 | 10 |
| Ohio Northern University | 12 | 14 | 6 |
| Ohio State University | 7 | 36 | 1 |
| Ohio University | 9 | 30 | 2 |
| Oklahoma A. & M. College | 13 | 42 | 6 |
| Oklahoma, University of | 6 | 29 | 2 |
| Oregon State College | 6 | 47 | 3 |
| Pennsylvania State College | 11 | 45 | 11 |
| Pennsylvania, University of | 5 | 21 | 6 |
| Pittsburgh, University of | 23 | 63 | 11 |
| Porto Rico, University of | — | — | — |
| Pratt Institute | 10 | 68 | 1 |
| Princeton University | 2 | 15 | — |
| Purdue University | 12 | 107 | — |
| Rensselaer Polytechnic Institute | 7 | 51 | 18 |
| Rhode Island State College | 6 | 28 | — |
| Rice Institute | 6 | 23 | 2 |
| Rose Polytechnic Institute | 7 | 33 | 12 |
| Rutgers University | 10 | 13 | 5 |
| Santa Clara, University of | 21 | 39 | 2 |
| South Carolina, University of | 8 | 8 | — |
| South Dakota State College | 13 | 17 | 17 |
| South Dakota State School of Mines | 10 | 14 | 1 |
| Southern California, Univ. of | 11 | 25 | 2 |
| Southern Methodist University | 7 | 23 | 4 |
| Stanford University | 11 | 33 | 3 |
| Stevens Institute of Technology | 8 | 82 | — |
| Swarthmore College | 8 | 22 | 15 |
| Syracuse University | 31 | 9 | 40 |
| Tennessee, University of | 9 | 33 | 1 |
| Texas A. & M. College | 8 | 40 | 5 |
| Texas Technological College | 12 | 17 | 17 |
| Texas, University of | 17 | 33 | 7 |
| Tufts College | 8 | 35 | 3 |
| Tulane University* | 4 | 20 | 1 |
| Union College | 4 | 20 | — |
| Utah, University of | 10 | 29 | 2 |
| Vermont, University of | 6 | 29 | — |
| Villanova College | 12 | 13 | 12 |
| Virginia Military Institute | 22 | 34 | 26 |
| Virginia Polytechnic Institute | 25 | 35 | 39 |
| Virginia, University of | 5 | 20 | 5 |
| Washington, State College of | 12 | 23 | 5 |
| Washington, University of | 12 | 36 | 11 |
| Washington University | 13 | 24 | — |
| West Virginia University | 17 | 27 | 101 |
| Wisconsin, University of | 6 | 66 | 1 |
| Worcester Polytechnic Institute | 4 | 42 | 5 |
| Wyoming, University of | 9 | 11 | 8 |
| Yale University | 6 | 23 | 3 |
| Total | 119 | | 1,130 |
| Total number of meetings | | | 1,363 |
| Total attendance | | | 46,121 |

* Authorized by Board of Directors January 26, 1937.

**Table V. Branch Meetings Held During Last 3 Fiscal Years**

| | Fiscal Year Ending April 30 | | |
|---|---|---|---|
| | 1935 | 1936 | 1937 |
| Number of Branches | 117 | 118 | 119 |
| Number of meetings held | 986 | 1,045 | 1,363 |
| Average number of meetings | 8.4 | 8.9 | 11.5 |
| Total attendance | 36,629 | 45,304 | 46,121 |
| Average attendance per meeting | 37 | 43 | 33.8 |
| Number of student talks | 708 | 772 | 1,130 |

**Table VI. Conferences on Student Activities**

| District or Section | Location | Date |
|---|---|---|
| 7 | University of Arkansas, Fayetteville | 5/2/36 |
| 1 | New Haven, Conn. (North Eastern District meeting) | 5/8/36 |
| 8 & 9 | Pasadena, Calif. (Summer convention) | 6/23/36 |
| 7 | Dallas, Texas (South West District mtg.) | 10/27/36 |
| 2 | Ohio State University, Columbus | 11/13–14/36 |
| Pittsburgh Section | Pittsburgh, Pa. | 1/12/37 |
| 4 | Alabama Polytechnic Institute, Auburn | 4/2/37 |
| 6 | South Dakota State College, Brookings | 4/23/37 |

and Los Angeles Sections adopted plans for special technical meetings. The Lynn Section had several technical lectures. The Minnesota Section formed a power committee in the spring of 1936. The communication, illumination, power, and transportation groups of the New York Section continued their highly effective activities. The Portland Section communication, electrochemistry and electrometallurgy, illumination, and transmission and distribution groups were continued with excellent results. The San Francisco and Sharon Sections continued their special technical meetings.

The Lynn Section held a technical paper competition on April 6, 1937, offering 3 prizes of $15, $10, and $5, with the decisions based 1/3 on written papers, 1/3 on oral presentation, and 1/3 on ballot by the audience. The Springfield Section announced, in March 1937, a prize paper contest, opening at that time and closing on September 13, 1937, the subject being "Ways and Means to Improve the Springfield Section of the AIEE." The prizes are $25 and $10. Several Sections continued the prizes offered annually in the past.

The Pittsfield and Schenectady Sections held their annual competition in 2 joint meetings, one in each city, with 3 speakers representing each Section at each of the meetings. Prizes of $15 and $10 were awarded at each meeting.

The Schenectady Section held its fourth annual competition among men in the General Electric Company testing department, having 6 speakers selected from the original group of 21. Prizes of $10 and $5 were presented.

Sections that have been sponsoring student conventions and holding joint meetings with neighboring Branches continued the arrangements. The Baltimore Section sponsored a convention of the Student Branches in the eastern part of District 2 on April 19, 1937.

Table II contains information regarding courses of instruction offered by 6 Sections. In some cases the courses are open to nonmembers at higher fees. The fees were established at amounts that would meet the expenses involved. The Philadelphia Section reported that its courses have been valuable in building up interest in the Section, and have been responsible for obtaining a considerable number of new members and reinstatements. Other Sections reported keen and well-sustained interest in the courses.

Table III contains numerical information on Section meetings held during the past 3 years.

## Branch Activities

Two new Student Branches were organized during the year, one at Columbia University, New York, N. Y., on February 19, and the other at Tulane University, New Orleans, La., on March 1; both have been very active.

Nearly all Branches carried on a normal amount of activity, 87 having held 8 or more meetings each, and only 6 having held fewer than 4 meetings. Comprehensive information on many phases of Branch activities appears in Tables III to VIII, inclusive.

The total number of Branch meetings held during the year, as reported to headquarters, was 1,363, by far the largest number ever held in a fiscal year. The largest previous number was 1,137 for the year 1930–31, and the number for 1935–36 was 1,045.

The number of talks by students was also the largest number ever reported—1,130, as compared with 772 for the preceding year, and the largest previous number, 1,085, for the year 1930–31. However many Branches had few or no student talks, and this phase of the activities should receive more attention in the future.

Students have continued to show very

**Table VII. Student Conventions**

| Sponsored by District or Section | Location | Date | No. of Student Papers |
|---|---|---|---|
| 7 | University of Arkansas, Fayetteville | 5/1/36 | 13 |
| 1 | New Haven, Conn. (North Eastern District mtg.) | 5/8/36 | 9 |
| 8 & 9 | Pasadena, Calif. (Summer convention) | 6/24–26/36 | 10 |
| 7 | Dallas, Texas (South West District mtg.) | 10/27/36 | 9 |
| Pittsburgh Section | Pittsburgh, Pa. | 1/12/37 | 6 |
| 4 | Alabama Polytechnic Institute, Auburn, Ala. | 4/2/37 | 6 |
| Baltimore Section | Johns Hopkins University, Baltimore, Md. | 4/19/37 | 4 |
| New York Section | New York University, New York, N. Y. | 4/28/37 | 5 |

**Table VIII. Section or Joint Section and Branch Meetings With Active Student Participation**

| Sections | Schools | Date | Student Talks | Attendance |
|---|---|---|---|---|
| Minnesota | University of Minnesota | 5/13/36 | 4 | 54 |
| New Orleans | Louisiana State University | 5/15/36 | 2 | 105 |
| St. Louis | Missouri School of Mines and Metallurgy, University of Missouri, Washington University | 5/15/36 | 6 | 93 |
| Portland | Oregon State College | 5/16/36 | 3 | 60 |
| Cincinnati | University of Cincinnati | 5/19/36 | 4 | 100 |
| Utah | University of Utah | 5/25/36 | 4 | 35 |
| Kansas City | Kansas State College, University of Kansas | 12/3/36 | 4 | 100 |
| Vancouver | University of British Columbia | 3/1/37 | 4 | 52 |
| Dallas | Southern Methodist University | 3/1/37 | 3 | 70 |
| Houston | A. & M. College of Texas, Rice Institute | 3/11/37 | 2 | 60 |
| Atlanta | Georgia School of Technology | 3/15/37 | 4 | 40 |
| East Tennessee | University of Tennessee | 3/16/37 | 1 | 30 |
| Florida | University of Florida | 3/19/37 | 1 | 177 |
| Worcester | Worcester Polytechnic Inst. | 4/6/37 | 5 | 51 |
| Seattle | University of Washington | 4/12/37 | 2 | 57 |
| Washington | University of Maryland, George Washington University, Catholic University of America | 4/13/37 | 3 | 140 |
| Los Angeles | University of Southern Calif. Calif. Inst. of Technology | 4/13/37 | 5 | 203 |
| Cleveland | Case School of Applied Science | 4/15/37 | 2 | 117 |
| Minnesota | University of Minnesota | 4/21/37 | 4 | 55 |
| San Francisco | University of California, University of Santa Clara, Stanford University | 4/23/37 | 3 | 152 |
| Spokane | University of Idaho, State College of Washington | 4/30/37 | 2 | 108 |
| Totals—20 Sections, 30 Branches | | | 68 | 1,859 |

keen interest in opportunities to take part in joint Section and Branch meetings and in student conventions. Details regarding such meetings appear in tables VII and VIII.

Students presented 9 papers in one session of the North Eastern District meeting in New Haven, Conn., May 6–9, 1936; 10 papers in 2 sessions of the combined summer and Pacific Coast convention in Pasadena, Calif., June 22–26, 1936; and 9 papers in 2 sessions of the South West District meeting in Dallas, Texas, October 26–28, 1936. They have keenly appreciated these opportunities, and the quality of material and the presentations has inspired numerous favorable comments by Institute members.

About 54% (674) of the Enrolled Students whose terms expired on April 30, 1937 (1,253) applied for admission as Associates, this being the highest percentage during the past several years.

## Engineers' Club Organized at Fort Wayne, Ind.

To provide a medium "for closer co-operation in the engineering profession" in Fort Wayne, Ind., the Fort Wayne Engineers' Club has been organized. Many members of the AIEE Fort Wayne Section have played important parts in formulating the organization plans according to Section Chairman D. H. Hanson who supplied the information for this news item. Although its organization meeting was held in January of this year, the club already has some 350 members representing all branches of the profession and all industries and utilities in the Fort Wayne area.

The primary objects of the club are: "(1) The advancement of the arts and sciences connected with engineering by the presentation and discussion of subjects, and by the participation in matters of interest to the engineering profession; (2) to advance the interest of individual members and to enhance the prestige of the profession within the community; and (3) to promote closer union and co-operation among the members by professional and social intercourse." Civic co-operation is said to be one of its chief purposes.

As temporary officers, the following have been serving:

**President:** H. M. Witherow (A'28, M'36) electrical engineer, General Electric Company, past-chairman (1935–36) of the Fort Wayne Section.

**Vice-President:** W. M. Carroll, mechanical engineer, S. F. Bowser Company.

**Secretary:** P. H. Daily, chemical engineer, International Harvester Company.

**Treasurer:** Otto Gumpper, civil engineer, City of Fort Wayne.

**Temporary Directors:** J. I. Cornell, radio engineer, Magnavox Company; M. H. Merritt, chemical engineer, Kopper's Construction Company; J. Kuttler, automatic engineer, International Harvester Company; E. W. E. Kamm, engineer and patent attorney, S. F. Bowser Company; L. D. Nordstrum (A'04, M'13) electrical engineer, General Electric Company (Section chairman 1914–15); and John McKay, civil engineer, Indiana Service Company.

Regular election will take place at the May meeting of the club.

## Engineering Society Room Constructed at Brown University

TO MEET the need of a social room for engineering students at Brown University, Providence, R. I., a small classroom was remodeled in such manner as to make it an attractive meeting and lounging place. This room, located in the engineering building, is the headquarters of the student engineering societies, and as such forms the natural social center for all engineering students at the university. The following description of the project was supplied by Professor Frederick N. Tompkins, counselor of the AIEE Brown University Branch:

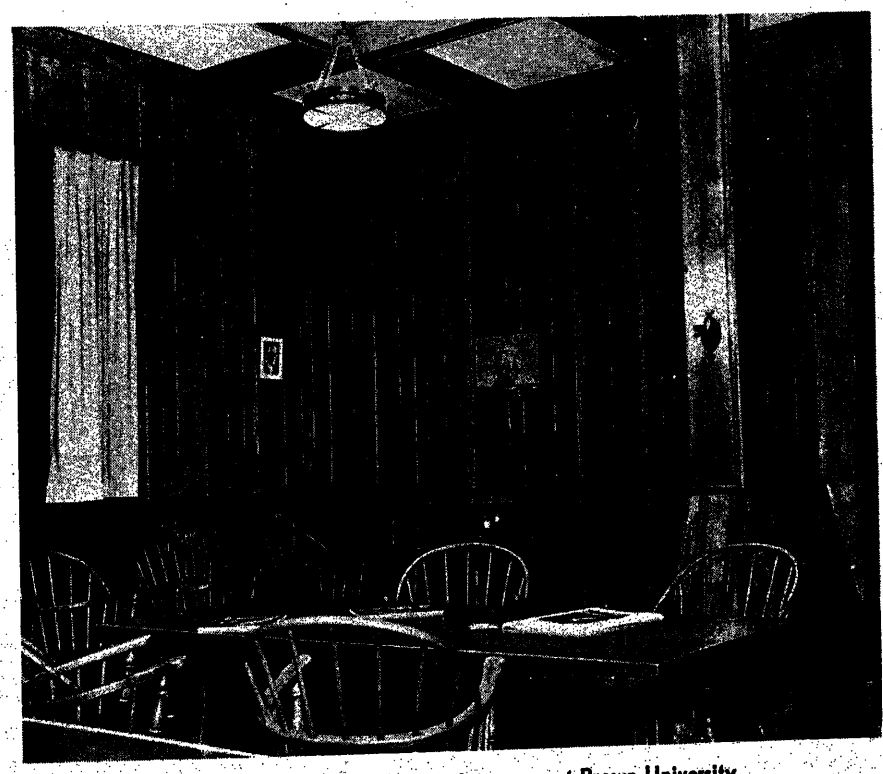
The engineering society organization, as operating at Brown, closely follows that of the Providence Engineering Society. The parent society is the Brown Engineering Society, to which all engineering students are eligible and which serves as a co-ordinating society for the branches of the AIEE, ASME, and ASCE. Practically all the juniors and seniors join one of the branches of the national societies while the freshmen and sophomores seldom do so. Thus, since members of the branches are automatically members of the Brown Engineering Society, membership adapted to all students is provided. Joint meetings are almost always held, small meetings taking place in the society room, larger gatherings in one of the class rooms; and several times each year an evening meeting, including dinner, is held at the University Camp, which is in the country within easy motoring distance of Providence.

As the money for this project was limited, student help was used in the construction under the guidance of members of the staff. An old colonial design was decided upon, and since the room was originally part of a laboratory with a very high ceiling and walls of whitefaced brick, a total reconstruction was necessary. A new beamed and paneled ceiling was hung from the orginal. The panels, which are of Celotex, lift out since the piping and wiring above may need servicing at some time. The walls were sheathed with knotty pine laid vertically, boxes and grills being built around the existing heating coils on two walls. The windows originally were not built to be opened, swinging transoms being provided at the top for ventilation. As the new ceiling was dropped below these, it was necessary to rebuild the windows to the casement type and they were fitted with attractive drapes.

A lally column support for the floor above was boxed in and a leather-covered seat built around its base, thus removing what otherwise would have been an eyesore and detriment to the appearance of the room. The walls were stained with a mixture of oak and walnut stain and finished with a hand-rubbed wax finish. The door did not fit the architecture of the room, so that it was sheathed to correspond and fitted with hand-made antique latches.

Special hand-made ceiling lighting units and antique-type wall brackets were made by a member of the staff who makes a hobby of constructing such material. The question of suitable furniture then arose; it was decided to buy Windsor chairs, but to make the other pieces in so far as possible. Suitable reading and study tables were designed and built, as was a ping-pong table.

A suitable floor covering for the concrete



A view of the engineering society room at Brown University

floor being beyond the budget possibilities at the time, the floor was filled and painted to serve until some future date when a linoleum covering could be purchased.

This room represents one of the finest investments ever made from the standpoint of student morale and usefulness. It is in use nearly all the time and is of particular help to freshmen and sophomores who, since they do not have much work in the laboratories of the engineering division, are apt to feel a lack of contact with their fellow students, particularly with upper classmen.

## Telephone Building for 1939 World's Fair

The American Telephone & Telegraph Company, through its president, Walter S. Gifford (A'16), has contracted with the New York World's Fair Corporation for a building site of more than 3 acres for an exhibit at the fair in 1939. "We plan to erect an imposing structure on the site allocated to us," Mr. Gifford said. "Inspired by the theme of the fair ('building the world of tomorrow'), we intend to construct a building in which we shall give exhibitions of the fascinating forces underlying modern electrical communications. . . . The fair will give our industry the opportunity to tell our story to millions of visitors, and when the fair opens its gates I am sure that the roster of industrial America will be there blazing the trail to a better tomorrow."

The agreement is the first exhibit contract into which the fair corporation has entered; an area of about 75 acres is available for private buildings and is expected to be allocated to exhibitors by similar contracts. Other exhibit space will be available in buildings to be erected by the corporation. The cornerstone of the $900,000 administration building, the first to be erected on the site of the fair at Flushing Meadow in the borough of Queens, was laid April 27, 1937.

## NEMA Welding Section Aids AWS Expansion

The electric welding section of the National Electrical Manufacturers Association, recognizing the important functions of the American Welding Society as a technical spokesman for the welding industry, voted at its January 1937 meeting to furnish financial support to the extent of $10,000 for the expansion program which the AWS recently proposed. A matter of immediate importance is the co-ordination of tests of men, machines, and filler metal, so as to relieve some of the unnecessary burden which a great duplication of test requirements has brought about.

At the March meeting of the NEMA welding section a co-ordinating committee was appointed to work with the management committee of the AWS and to make the fund available as it is required for support of the new activities.

# American Engineering Council

## Report of Patents Committee as Adopted by AEC Assembly

A REPORT of the patents committee of American Engineering Council for the year 1936, as adopted by the assembly of AEC at its annual meeting held January 15, 1937, is presented herewith. In approving the report, the assembly left to action of its executive committee the matter of a budget for financing further studies subject. The personnel of the AEC patents committee for 1936 was: R. S. McBride, *chairman;* David Beecroft, J. H. Critchett, William Grosvenor, F. B. Jewitt (A'03, F'12, past-president) and Warner Seely. Full text of the report follows:

The committee on patents during 1936 considered the 2 major problems assigned to it by action of the assembly in January 1936, and has given brief attention to various legislative hearings and proposed Federal enactments. By correspondence and conference the committee has formulated certain recommendations which it suggests as a basis for action of the staff of the Council during the coming legislative session. It also recommends a somewhat modified plan for future work of the committee.

A number of bills were introduced in the last session of Congress and Congressional hearings held with a view to determining what Congress might do to regulate pooling or cross-licensing of patents. Additional proposals of legislation are contemplated in the next session of Congress. Exploration of this field leads the committee to renew the recommendations of last year and to suggest the adoption of the following resolution by the assembly:

1. American Engineering Council opposes enactment of any forms of legislation thus far introduced into Congress to limit or to regulate pooling or cross-licensing of patents.

The committee feels that the public interest has been much more served than harmed by patent pools and by cross-licensing. Such evils as may have been experienced would not have been corrected by any of the proposed forms of legislation. The committee feels that administration of present laws, including proper and reasonable application of antitrust legislation, would suffice to correct those types of evils of pooling which have been disclosed or charged as bad practice.

Further investigation of this important subject is necessary. It will require considerable work, first in the gathering of information as to past experience of successful pools and cross-licensing plans. The committee believes that such study should be made the major activity of the committee on patents during 1937, and recommends the following resolution:

2. American Engineering Council should provide as a part of the 1937 budget a small allotment of funds in order that specialists and clerical assistance can be secured to make a survey of past experience as the basis of a further study by the patents committee on the subject of pooling and cross-licensing of patents.

At its last annual meeting the assembly of the American Engineering Council expressed its support for the idea of the single Court of Patent Appeals. A definite bill providing for such a court was introduced in the last Congress. Such bill will be reintroduced, probably in several modified forms. The committee believes that Council should give support to the general idea, with such limitations as should be suggested in order to secure the highest standard of technical proficiency in the selection of judges, by the following resolution:

3. American Engineering Council reiterates its approval of the proposed single Court of Patent Appeals to review decisions of the lower courts as applied to facts presented to the lower courts but not for introduction of new evidence. It looks with favor upon the idea of having the judges named to such court selected by the President only after careful review of their special and technical competence with the advice of the engineering and scientific societies as well as advice of the patent bar and the legal profession.

Scientific advisers to the courts have been recommended by a number of agencies, but not all with the same purpose. Most often quoted is the suggestion of a special patents committee of the Science Advisory Board. That committee recommended that scientific advisers be made available to aid *trial* court justices. In this conclusion the committee agrees. The patents committee looks with some favor on such an idea if a suitable method of selecting advisers free from preconceived opinions were fixed and if a sufficiently diversified list of skilled scientific and engineering talent were made available. However, the committee has doubted the wisdom of having such scientific advisers named permanently as a part of a new single Court of Patent Appeals. It feels that the idea of naming 3 such advisers who would serve for all classes of cases would not afford such highly skilled aid in all divisions of science and technology as courts really require. Furthermore, the committee gravely questions whether an appellate court could properly utilize scientific advisers under circumstances that would deny to the litigants all right of examination or cross-examination of such witnesses as to their experience, disinterestedness, reasons for their recommendations, and factual basis for their opinions. The committee recommends the following resolution:

4. American Engineering Council recommends that no provision be made for the naming of scientific advisers to the proposed Court of Patent Appeals.

A wide variety of legislative proposals were before the last Congress intending limitation of life of patents or restriction on freedom of use of patents by owners. Among the varied subjects of legislation were the following: (*a*) taxation during nonuse, and at increasing rates; (*b*) compulsory working; (*c*) compulsory licensing; (*d*) prompt (3-year) final action in the Patent Office;

(*e*) publicity in the Patent Office 3 years from the date of filing; (*f*) expiration of patents 20 years from date of filing; (*g*) free Government use of patents and freedom of Government infringement in times of emergency; (*h*) provision for Government employees patents, with or without free public use; (*i*) validation of patents 5 years after issue, if uncontested.

The committee on patents is unanimously opposed to all these legislative proposals under present circumstances. It believes Council should take some formal action regarding these matters on the following lines:

5. American Engineering Council opposes all the various types of proposals which would restrict the freedom of owners of patents to use them constructively under present laws. It opposes them as not necessary for the public welfare, and prospectively objectionable both from the standpoint of the inventor and the public need for stimulation of progress by inventions. It regards such offenses as are now charged against the patent system as the result of defects in administration of present laws and not as evidence of the need for more legislation.

The committee believes that every effort should be made by industry as well as by the engineering profession to increase the presumption of validity of patents as issued. It feels that engineers generally should assist patent examiners whenever possible to keep abreast of the arts with respect to which they are examining patent applications. The committee has not found any legislation, proposed to date, sufficiently constructive to feel that it deserves support of the American Engineering Council. It does, however, hope that some means may be developed for increasing the standards of competence and experience of the staff of examiners.

Most promising of the proposals for this purpose thus far presented appears to be the suggestion that the number of higher rank and better paid examiners be increased, if necessary at the expense of the number of junior examiners engaged. By this change it is hoped that the more competent and efficient members of the examiner's staff may be advanced in salary and positions more rapidly. It is hoped that there would then be less tendency for the better members of the examiner's staff to resign from the Patent Office early in their career because of unwarranted delay before promotion, such as now often experienced.

The committee does not believe that this matter requires formal action but does suggest that the membership of the engineering profession can well give encouragement to this or any other means found practical for advancing the standards and increasing the technical knowledge of the Patent Office staff.

# Standards

## Railway Motors

A complete revision of AIEE Standard No. 11, "Railway Motors" has been completed by a sectional committee working under the rules of procedure of the American Standards Association and the sponsorship of the Institute. The new American standard is now available in pamphlet form; it is known as No. 11 "Railway Motors and Other Rotating Electrical Machinery for Rail Cars and Locomotives," the new title being indicative of the increased scope of the standard.

A detailed description of the changes that have taken place was covered in an article published in ELECTRICAL ENGINEERING, March 1936, pages 312–13 Copies of the standard are available at 50 cents each with 50 per cent discount to members on single copies. Address AIEE, 33 West 39th Street, New York, N. Y

## Wires and Cables

In the standards for wires and cables 8 new specifications have been added, 5 of these representing entirely new developments and 3 being extensive revisions of former standards. All have the status of American Standard or Tentative Standard. A listing of the 8 follows:

*Nos. C8.5, C8.6, C8.7* (published as one pamphlet superseding former AIEE Nos. 69, 70, and 71) Cotton Covered, Silk Covered, and Enameled Round Copper Magnet Wire, respectively. Price 30 cents per copy with 50 per cent discount to members on single copies. Address AIEE, 33 West 39th Street, New York, N. Y.

*C8.11 Code Rubber Insulation for Wire and Cable for General Purposes* is based on the requirements for the rubber insulation in the Underwriters' Laboratories' Standard for Code Wire. It is in agreement with the 1936 edition of that standard. Price 20 cents each with 50 per cent discount to members on single copies. Address AIEE, 33 West 39th Street, New York, N. Y.

*C8.12 Cotton Braid for Insulated Wire and Cable for General Purposes.* These specifications cover braids as applied to rubber and varnished cloth insulated wires and cables. They do not cover "fancy" or special braids or braids for fixture wire or weather resisting wire and cable. Three classes of braids are covered, namely: heavy, for outdoor or rough service; standard, for indoor or protected service; and code, for installation under the National Electric Code. Price 20 cents each with 50 per cent discount to members on single copies. Address AIEE, 33 West 39th Street, New York, N. Y.

*C8.16 Tree Wire Coverings.* Tree wire is a cable having a solid or stranded conductor insulated with a material such as a rubber compound and having a weather- and abrasion-resistant covering. These specifications provide that the coverings shall be of such quality and characteristics that they will not substantially deteriorate with age and proper usage except for a minimum amount of wear due to rubbing against the branches of trees. Price 20 cents each with 50 per cent discount to members on single copies. Address AIEE, 33 West 39th Street, New York, N. Y.

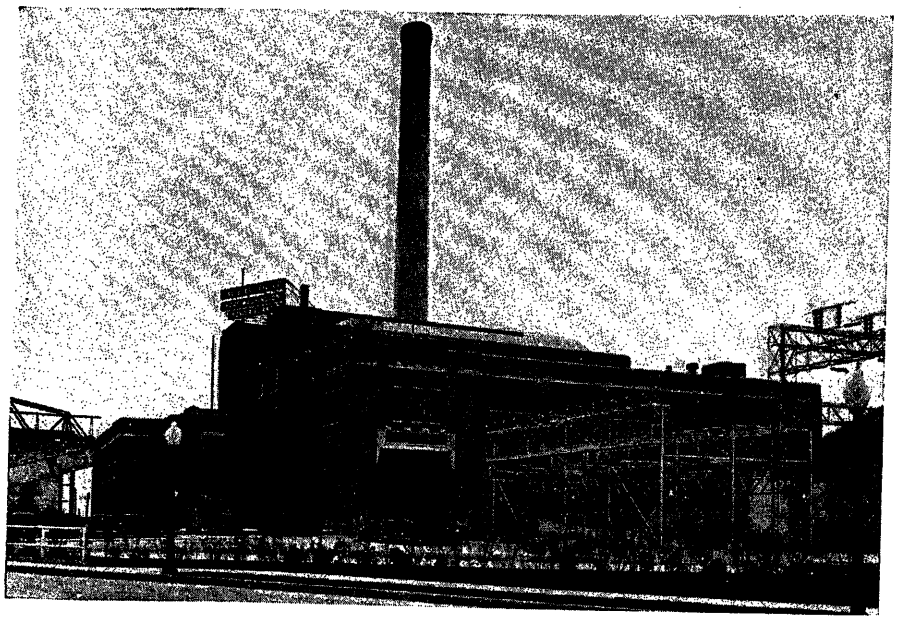
*C8.17 Class OA 30 Per Cent Rubber Insulation for Wire and Cable for General Purposes.* This new standard corresponds to the insulation requirements in ASTM Standard *A27-55T* entitled "Insulated Wire and Cable: Class *OA* 30 Per Cent, Hevea Rubber Compound." The clauses with respect to thickness, chemical requirements, and electrical requirements are identical with those for Class *A* 30 Per Cent Compound (*C8.4*—former AIEE No. 63), but the tensile strength and elongation requirements are somewhat higher. Also, there are 2 additional tests not in the class *A* standard: namely, moisture absorption and accelerated aging. Price 20 cents each with 50 per cent discount to members on single copies. Address AIEE, 33 West 39th Street, New York, N. Y.

*C8.18 Weather Resistant Wire and Cable URC Type.* These specifications cover weather-resistant (weatherproof) wire and cable, the conductors, the materials used for the fibrous coverings, and the saturating and finishing compounds. They are a further development of specifications originally proposed to the industry by the Utilities Research Commission, Inc. Price 20 cents each with 50 per cent discount to members on single copies. Address AIEE, 33 West 39th Street, New York, N. Y.

**Indicating Electrical Measuring Instruments and Instrument Transformers.** This new publication issued by the National Electrical Manufacturers Association contains the material, revised and augmented that was last published in the NEMA apparatus standards. Of particular interest are the new sections devoted to standard dimensions of indicating instruments and the accuracy limits of current and potential transformers. Price 60 cents each. Address National Electrical Manufacturers Association, 155 East 44th St., New York, N. Y.

**Household Electric Refrigerator Standards.** This pamphlet published by the National Electrical Manufacturers Association covers household electric refrigerators and includes such material as the standard method of computing gross volume and food-shelf area, and also the test code for conducting and reporting such tests as "no load" and "ice making." Price 40 cents each. Address National Electrical Manufacturers Association, 155 East 44th Street, New York, N. Y.

**Test Code on Apparatus Noise Measurement.** The standards committee on April 30 authorized the publication of a "Proposed Test Code for Apparatus Noise Measurement." This code has been prepared under the auspices of the subcommittee on sound of the AIEE standards committee, P. L. Alger, chairman. This test code is intended for use as a guide in the measurement of sound levels and the investigation of the various elements that contribute to the total noise produced. It is an aid to the establishment of reasonably uniform methods of conducting and reporting sound-level tests, so that results will be of value for record and will be comparable with tests made at other times and places. As soon as it is possible to complete the work of publication, notice of availability of the code will be made.



**Port Washington plant of the Milwaukee (Wis.) Electric Railway and Light Company, which may be visited by those attending the Institute's 1937 Summer Convention. For the first 10 months of operation, the average fuel consumption was 11,094 Btu per kilowatt-hour of station output**

# Letters to the Editor

CONTRIBUTIONS to these columns are invited from Institute members and subscribers. They should be concise and may deal with technical papers, articles published in previous issues, or other subjects of some general interest and professional importance. ELECTRICAL ENGINEERING will endeavor to publish as many letters as possible, but of necessity reserves the right to publish them in whole or in part, or reject them entirely.

ALL letters submitted for consideration should be the original typewritten copy, double spaced. Any illustrations submitted should be in duplicate, one copy, to be an inked drawing but without lettering, and other to be lettered. Captions should be furnished for all illustrations.

STATEMENTS in these letters are expressly understood to be made by the writers; publication here in no wise constitutes endorsement or recognition by the American Institute of Electrical Engineers.

## Heaviside Calculus and Carson's Integral

*To the Editor:*

The Heaviside operational calculus is finding increasingly widespread application. Accordingly, any device to shorten the work involved in its use would appear of value. In the present note is described a simplification which was found by the writer to greatly facilitate his own computations.

The Heaviside calculus has as its fundamental problem[1] the determination of what is known, in electrical theory, as the "indicial admittance" of a linear physical system. This is simply the response of the system, initially in equilibrium, to a unit disturbance suddenly applied at time zero and maintained constant thereafter. In dynamics, the indicial admittance might correspond to the velocity of a system resulting from a suddenly imparted unit acceleration. In electricity, it is usually the current resulting from a suddenly applied electromotive force of unit magnitude.

Having determined the indicial admittance, the characteristics of a system are then completely determined mathematically, except for a single integration.[1] Adopting electrical terminology, we have the following equation for the current as a function of time, $t$:

$$I(t) = E(0)\,A(t) + \int_0^t A(t-\tau)\,\frac{dE(\tau)}{d\tau}\,d\tau$$

where $I$, $E$, and $A$ represent, respectively, current, electromotive force, and indicial admittance, and $\tau$ is the time variable of integration. In other words, knowing the indicial admittance of a circuit, the response of the circuit at any time, $t$, to an arbitrarily varying electromotive force can be determined (at least formally) by application of the above integral. The integral was independently derived by J. R. Carson, but has long been known in dynamics as Duhamel's integral.

The writer had occasion to use the operational calculus in problems involving fairly arbitrary disturbances. The determination of the unit response of "indicial admittance" was a routine application of the Heaviside expansion formula. (This will not be treated here but can be found in all works on the principles of operational calculus.) However, attempts to apply this in the Carson integral, as given above, proved tedious. Graphical solution was no more economical of time, although it must be employed in some form when the disturbance is given by an arbitrary curve. The writer then noticed that the integral could be made considerably less complex. The step taken was extremely simple and obvious, but does not appear to have been made heretofore. By cancelling the $dt$'s, and correspondingly changing the limits of integration, the integral becomes

$$I(t) = \int_0^{E(t)} A(t-\tau)\,dE(\tau)$$

(The term $E(0)\,A(t)$ is now included by the lower limits of integration.)

To evaluate this graphically it is only necessary to plot $A(t-\tau)$ against corre-

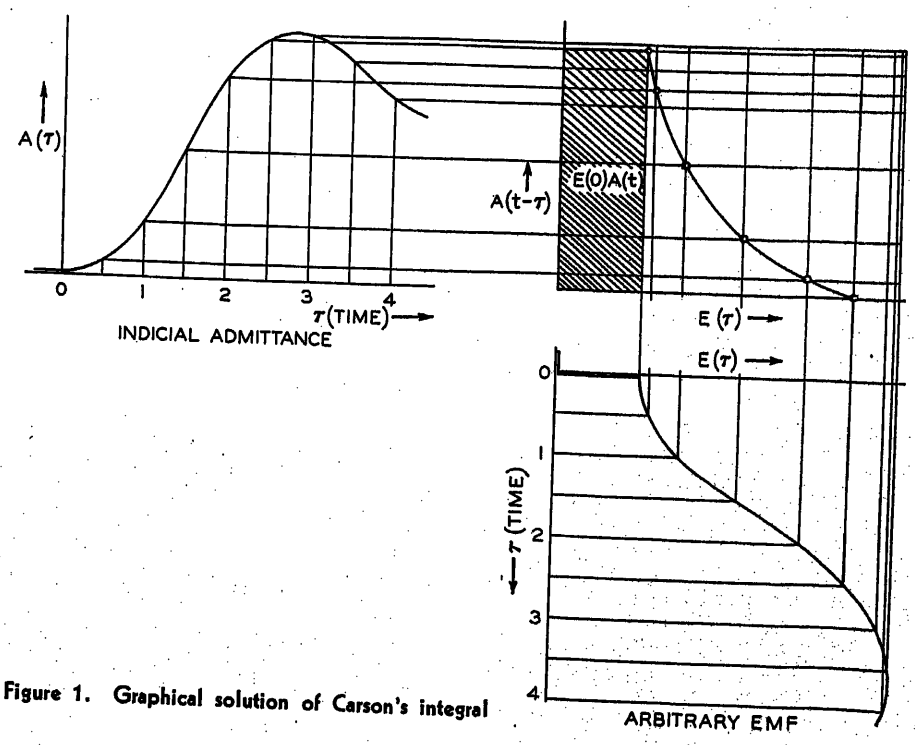



**Figure 1. Graphical solution of Carson's integral**

sponding values of $E(\tau)$ and then measure the area under the curve. A procedure has been developed that makes the work almost mechanical and very rapid. Referring to figure 1, $A(\tau)$ and $E(\tau)$ are plotted so that the $\tau$ axes are perpendicular. Horizontal lines are drawn through points of the $A$ curve corresponding to a series of regularly spaced values of $\tau$. Vertical lines are similarly drawn through points of the $E$ curve corresponding to the same values of $\tau$. Both the vertical and horizontal lines are designated by the corresponding values of $\tau$ and each intersection of a vertical and a horizontal line is designated by the sum of the 2 corresponding values of time, $\tau$. If $I(t)$ is desired for $t = t_1$ a curve is drawn through all intersections designated by the sum $t_1$. The area under this curve is $I(t_1)$. On the diagram, the curve is drawn for $t_1 = 2^1/_2$ seconds. A separate curve evidently results for each instant $t$ at which the value of $I$ is desired. With some care, however, as many as 10 curves can be plotted on a single sheet.

For those interested in the fundamentals of the Heaviside operational calculus, including the application of the above graphical solution of Carson's integral, reference 2 is suggested.

REFERENCES


1. ELECTRIC CIRCUIT THEORY AND THE OPERATIONAL CALCULUS, John R. Carson. McGraw-Hill Book Company, 1926.

2. CALCULATION OF THE MOTION OF AN AIRPLANE UNDER THE INFLUENCE OF IRREGULAR DISTURBANCES, Robert T. Jones, *Journal of the Aeronautical Sciences*, volume 3, 1936, page 419.


Very truly yours,


ALBERT I. NERKEN
Hampton, Va.


## Invention of the Watt-Hour Meter

*To the Editor:*

In the January 1937 issue of ELECTRICAL ENGINEERING, in the paper "Development of a Modern Watt-Hour Meter" by I. F. Kinnard and H. E. Trekell, page 172, lines 6 to 8, the origin of the a-c induction watt-hour meter is ascribed to Shallenberger, in 1894. There is no doubt about Shallenberger's inventing in 1888 (simultaneously with Borel and Paccard in Switzerland) the a-c induction *ampere*-hour meter, but the induction *watt*-hour meter is my invention; see U.S. Patent 423,210, filed October 7, 1889, and issued March 11, 1890. The principle is very clearly explained in lines 88–95 in the first page of specification: ..."the inductive resistance of the shunt winding is very great as compared with its ohmic resistance, its phase of magnetization will be displaced for nearly one quarter of a phase from that of the series magnet..."

To get exact quadrature between the 2 magnetic fields, all modern meters have also a shunt path for part of the magnetic flux produced by the voltage coil. Though this was not expressly put forth in the specification, the numerous figures in the patent show it clearly: large pole surfaces provide a considerable amount of stray fields not acting on the meter disk.

In fact, even the first type of meters manufactured by Ganz & Co., from 1889 onwards, had approximately quadrature

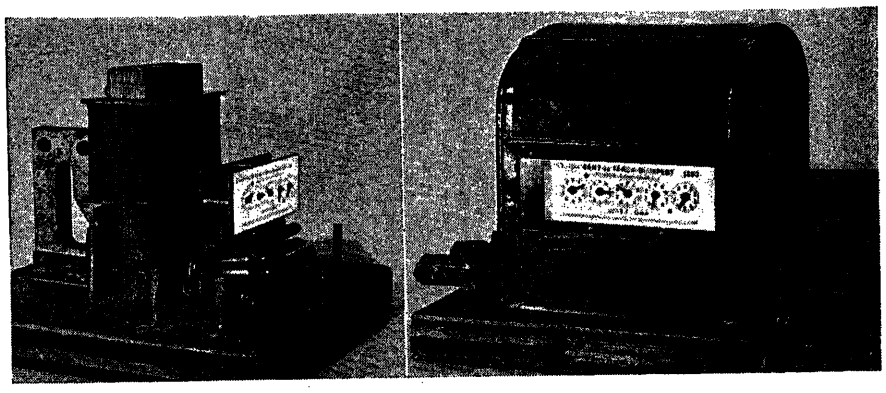


**Figure 1. An a-c induction watt-hour meter manufactured in 1893**

phase difference between current and voltage fields, though at that remote date this was of no great importance, as loads were nearly exclusively glow lamps and even the earliest meters were sufficiently satisfactory in this respect.

Meter number 2,157, made in 1893, came back into our museum after about 25 years of service; retested, without adjustment, and taking the 100 per cent load at $\cos\varphi = 1.0$ as unity, it gave the following indications:

| | | | | | | |
|---|---|---|---|---|---|---|
| $\cos\varphi$ | 1.0 | 0.9 | 0.8 | 0.7 | 0.6 | 0.5 |
| slow, % | 0 | 1.6 | 2.5 | 3.5 | 4.5 | 7.0 |

Meter number 52, made in 1889, but with the air-gap of the current field magnet increased from the original 10 millimeters to 20 millimeters (this was usual about a few years afterward, to straighten out the constant curve), everything else unchanged, came back after about 20 years of service; retested, without adjustment, and taking 100 per cent load at unity power factor as unity, it gave the following readings:

| load, % | 10 | 25 | 50 | 75 | 100 |
|---|---|---|---|---|---|
| $\cos\varphi = 1.0$ | 1.006 | 1.002 | 1.005 | 1.000 | 1.000 |
| $\cos\varphi = 0.5$ | 1.04 | 1.002 | 1.017 | 1.005 | 1.025 |

Meter number 2,157 is shown in figure 1; "watt-ora" means watt-hours. The torque of these early meters was from 60 to 100 centimeter-grams (600 to 1,000 millimeter-grams). Weight of the rotor was about 100 grams.

One of these earliest induction watt-hour meters is in The Edison Institute at Dearborn, Mich.

Very truly yours,


DOCTOR OTTO T. BLÁTHY
Ganz & Co. Ltd.
Budapest, Hungary


## Electronic Tube Nomenclature

*To the Editor:*

I notice on page 284 of the February 1937 issue of ELECTRICAL ENGINEERING a tabulation of electronic tube nomenclature that is being studied by the American Standards Association.

As comments have been invited, I submit the following point of view:

In connection with the names "kenetron" and "pliotron," would it not be wiser to dispose of these terms and adopt simply the terms "diode," "triode," etc.? This would pave the way for tubes with larger numbers of grids and is in conformity with the present-day practice where we have ascended the scale up to the point of pentode.

If we are to adopt certain terms, such as "pliotron" which have arisen in the industry subsequent to the pioneer work, I wonder if we are keeping pace with the early group of experimenters and inventors. I have in mind, for example, the idea or rather term introduced by DeForest, "the audion." The audion was originally applied by DeForest to the 2-electrode tube or diode and later to his triode. Were we to consider giving credit to DeForest for his invention of the 3-electrode tube, then certainly it would seem that it should carry the term "audion" into our present-day nomenclature. On the other hand, this would naturally raise a question as to whether or not Edison should be associated with the triode and perhaps it will raise a question on the part of some whether or not Fleming should be associated with the diode. Edison gave no term to his 2-electrode tube. However, when Fleming used this particular instrumentality, later, it became popularly known as "the Fleming valve." Since the 2-electrode tube used by Fleming and the 2-electrode hard diode of today are so very nearly the same as Edison's original tube, it would seem to me that any type of personal designation would need to reflect proper credit upon Edison.

An endeavor to give individual inventors credit or individual scientists credit certainly leads to difficulty. Nevertheless, out of deference to these pioneers, we should not adopt comparable terms of a commercial character which, it seems to me, have the unfortunate effect either of making the origin of the devices obscure or leading to a gross misunderstanding.

The great contributions of our telephone company, the Westinghouse Company, the General Electric Company, and others to the vacuum tube art are, of course, well recognized. However, I wonder if it is wise to adopt a term originated by one of these companies if that term carries no more significance with it than just the name. It would seem far better in this case to go over to the impersonal terms, diode, triode, tetrode, pentode, etc. which can raise no question in the minds of many contributors to this art.

Very truly yours,


EDWARD L. BOWLES (A'22, F'33)
Associate Professor of Electrical Communications, Massachusetts Institute of Technology, Cambridge.

# Personal Items

J. W. WHITE (A'29) general manager of the Westinghouse Electric International Company, New York, N. Y., has been elected vice-president and general manager of that company. Mr. White was born at Indianapolis, Ind., in 1889, and received his early education at Randolph-Macon Academy; later, while engaged with the Westinghouse company at East Pittsburgh, Pa., he attended Carnegie Institute of Technology. He joined the Westinghouse Electric & Manufacturing Company, East Pittsburgh, in 1905, and continued at the main works until 1912. In 1917 Mr. White filled the position of manager of the central station and transportation divisions of the Detroit, Mich., offices of that company. His first connection with the export business was in 1918, when he was assigned the managership of the Westinghouse offices at Havana, Cuba. In 1925 he was made managing director of the Westinghouse Company of Japan, with his staff offices at Tokyo. In 1931 Mr. White was made managing director of Cia. Westinghouse Electric International in Argentina, which position he held until he was returned to the United States in 1936 to become general manager of the Westinghouse Electric International Company.

F. W. SMITH (A'05, M'12) president, Consolidated Edison Company of New York, Inc., Brooklyn (N. Y.) Edison Company, Inc. and New York and Queens Electric Light and Power Company, has retired. Mr. Smith was born June 16, 1867, at Alden, N. Y., and began his career as an office boy for the United States Illuminating Company in 1880. His service with that company and its successors therefore has spanned a period of almost 57 years; he entered the electrical industry 2 years prior to the opening of the Pearl Street station of the Edison Electric Illuminating Company of New York, and 3 months after the introduction of the incandescent lamp by Thomas A. Edison. In 1883 Mr. Smith became a general clerk and remained in that position until 1889 when he was appointed paymaster for the United Electric Light and Power Company, successor to the United States Illuminating Company. In 1891 he was made assistant auditor of the company, and after remaining in that position for 8 years was elected assistant secretary. A year later he was elected secretary of The Brush Electric Illuminating Company, of which he subsequently became president and a director. In 1905 Mr. Smith was elected secretary of the United Electric Light and Power Company; in 1912 he became vice-president; in 1916, general manager. In 1926 he was elected chairman of the board of directors of the New York and Queens Electric Light and Power Company, and in 1929 became president of The Brush Electric Illuminating Company. Mr. Smith was elected president of The New York Edison Company, Inc., and the United Electric Light and Power Company in 1932; president of the Consolidated Edison Company of New York, Inc., in 1935; and president of the Brooklyn Edison Company, Inc., in 1936. He was active in the affairs of the former National Electric Light Association, and served as vice-president (1919), president (1922), and member and chairman of many of the committees of that organization. He is a member of several technical organizations.

L. B. FULLER (A'03) superintendent of power, Utah Power & Light Company, Salt Lake City, has been appointed chief engineer of the company. Mr. Fuller was born June 14, 1879, at Nelson, Ohio, received a diploma from Hiram College, attended Montana State College, and was graduated from Cornell University in 1906. He had been engaged in engineering work before receiving his formal technical education, and following his graduation was employed as construction superintendent of the Telluride Power Company's Grace, Idaho, hydroelectric plant; upon completion of that plant in 1908 he was transferred to the engineering department of the Telluride Power Company. In 1913 Mr. Fuller was appointed general construction foreman on power house and penstock construction during an extension of the Grace hydroelectric station by the Utah Power & Light Company, successor to the Telluride Company. During 1916–18 he served as construction superintendent on several hydroelectric projects, and in 1919 was appointed general construction superintendent of an extensive hydroelectric and steam-electric project executed by the Phoenix Utility Company for the Utah Power & Light Company. In 1927 Mr. Fuller was appointed assistant superintendent of power of the Utah Power & Light Company; he became superintendent of power in 1929.

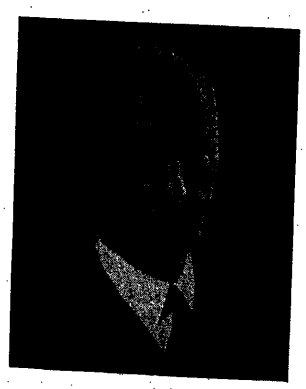
J. A. HALE (M'26) formerly chief engineer of the Utah Power & Light Company, Salt Lake City, recently was appointed vice-president of both the Utah Power & Light Company and the Utah Light & Traction Company. Mr. Hale was born September 18, 1888, at Calloway, Va., and received the degree of bachelor of science in civil engineering at Virginia Polytechnic Institute. In 1911 he was appointed junior engineer in the United States Reclamation Service, remaining in that capacity until 1913, when he became affiliated with the Utah Power & Light Company as an assistant engineer. During 1918–19 he served as cost engineer for the United States Housing Corporation, but late in 1919 returned to the Utah Power & Light Company to continue his service with that company without interruption. Mr. Hale was appointed chief engineer in 1927.

E. G. CONROY (A'32) formerly superintendent of radio, City of San Antonio, Texas, now is associated with the bureau of municipal research at the University of Texas, Austin. Mr. Conroy is a native (1907) of San Antonio, and received the degree of bachelor of science in electrical engineering at the University of Notre Dame in 1930. Following his graduation, he entered the long lines department of the American Telephone and Telegraph Company at South Bend, Ind., as a student engineer, and remained with that company until he was appointed supervisor of radio of the City of San Antonio. Mr. Conroy is chairman of the AIEE San Antonio Section.

W. H. BURLESON (M'31) formerly assistant manager of the power utilities department of the Ohio Brass Company, Mansfield, Ohio, has been appointed manager of that department. Mr. Burleson was graduated from the Texas Agricultural and Mechanical College in 1913, following which he joined the engineering staff of the Texas Power and Light Company and eventually



J. W. WHITE



F. W. SMITH



L. B. FULLER



J. A. HALE

became assistant chief engineer of that company before associating himself with the Ohio Brass Company in 1922. His work with the Ohio Brass Company has required much traveling, and he has visited many utility companies throughout the United States and Canada. Mr. Burleson is chairman of the engineering committee of the high-voltage section of the National Electrical Manufacturers' Association, chairman of the United States Department of Commerce standing committee on simplified practice recommendation 73, covering one-piece insulators, a member of the American Standards Association committee on insulator standardization, and temporary chairman of the ASA subcommittee on suspension-insulator standardization.

L. J. BERBERICH (A'30, M'36) recently resigned his position as research engineer in charge of cable- and capacitor- oil development for the Socony-Vacuum Oil Company, Incorporated, Paulsboro, N. J., to become a research engineer in the insulation division of the research laboratories of the Westinghouse Electric & Manufacturing Company, East Pittsburgh, Pa. Doctor Berberich was born at Petersburgh, Va., in 1906, and received the degrees of bachelor of engineering (1928) and doctor of engineering (1931) at The Johns Hopkins University. In 1931 he was appointed to the faculty of The Johns Hopkins University, and served as a full-time research assistant, but in the following year he joined the research staff of the Socony-Vacuum Oil Company. He was placed in charge of cable- and capacitor-oil development in 1934. Doctor Berberich is a member of the National Research Council's committee on insulation and the American Society of Testing Materials committee D-9 on electrical insulating materials. He is a member of the American Association for the Advancement of Science and Sigma Xi.

A. J. JOHNSTON (A'32) engineer for the American Totalisator Company, Baltimore, Md., has been transferred to San Mateo, Calif., as manager of the Pacific coast division of that company. Mr. Johnston is a native (1897) of Milwaukie, Ore., and an electrical engineering graduate of Oregon State College. He spent several yeaas in design and application engineering of supervisory control and telemetering equipment for the General Electric Company before becoming affiliated with the American Totalisator Company, and is the author of a paper "The Torque Balance Telemeter," presented at the 1932 AIEE summer convention.

O. L. RIGGS (A'21, M'29) formerly superintendent of electric distribution, Lynn (Mass.) Gas and Electric Co., recently was appointed sales manager for the American Electric Service and Maintenance Company, Springfield, Mass. Mr. Riggs entered the employ of the United Electric Light and Power Company, New York, N. Y., as an inspector in 1920, where he remained until 1925 before becoming affiliated with the Lynn Gas and Electric Company.

PAUL NARBUTOVSKIH (A'32) teaching assistant in electrical engineering, Stanford University, Calif., has been appointed to the faculty of the mathematics department of San Jose State College, San Jose, Calif. Mr. Narbutovskih was born at Tiumen, Russia, in 1902, and received the degree of bachelor of arts at Stanford University in 1929, following which he remained at that institution as a graduate student and teaching assistant. He is the author of a paper, "Tooth-Frequency Eddy-Current Loss," published in the February 1937 issue of ELECTRICAL ENGINEERING, pages 253–6.

R. B. CAPRON (A'30, M'30) assistant distribution engineer, Utica (N. Y.) Gas and Electric Company, has been appointed distribution engineer for the St. Lawrence area of the Niagara Hudson Power Corporation, with headquarters at Potsdam, N. Y. Mr. Capron received the degrees of bachelor of arts (1926) and electrical engineer (1928) from Columbia University, following which he entered the employ of the Utica Gas and Electric Company as a cadet engineer. He became assistant distribution engineer in 1934.

H. R. ANDERSON (A'27, M'36) formerly assistant electrical engineer for United States Engineers, Fort Peck, Mont., now is employed as transmission engineer for the Loup River Public Power District, Columbus, Nebr. Mr. Anderson, a native (1900) of Huron, S. D., and an electrical engineering graduate of Iowa State College, has had experience in engineering and construction work with several public utility companies.

ALEXANDER WILSON (A'15) assistant to the vice-president in charge of operations Philadelphia (Pa.) Electric Company, has been made operating manager of the company. Mr. Wilson was born at Philadelphia in 1887 and received the degree of mechanical engineer at Cornell University in 1910. Almost immediately following his graduation, he entered the employ of the Philadelphia Electric Company and has since served that company as construction engineer (1918–27), assistant chief engineer (1928–30), and assistant to the vice-president in charge of operations since 1930.

E. H. COLPITTS (A'11, F'12) retired vice-president of the Bell Telephone Laboratories, Incorporated, New York, N. Y., recently was awarded the Japanese Fourth Order of Merit of the Sacred Treasure, in recognition of his promotion of electrical engineering in Japan and his furthering of good relations between Japan and the United States. A biographical sketch of Doctor Colpitts appeared in the April 1937 issue of ELECTRICAL ENGINEERING at the time of his retirement.

C. C. LONG (A'14, M'30) mechanical and electrical construction engineer, Riegos y Fuerza del Ebro, Barcelona, Spain, has returned to the United States. Mr. Long has been in Spain since early in 1930, during which time he has had complete charge of the planning, design, purchase of materials, and construction of a series of hydroelectric stations featuring completely automatic control.

H. H. KRUEGER (A'21) who has been assistant superintendent of power of the Utah Power & Light Company, Salt Lake City, has been appointed superintendent of power. Mr. Krueger entered the employ of the Utah Power & Light Company in 1914 and in the following 2 years served as operator or maintenance engineer of many of the generating stations and major substations of the interconnected system of that company. After serving as chief dispatcher and as a member of the production and transmission department, he became assistant superintendent of power in 1930.

WILLIAM KELLY (F'25) president of the Buffalo, Niagara, and Eastern Power Corporation, Buffalo, N. Y., has been elected a vice-president and director of the newly formed Buffalo Niagara Electric Corporation. A biographical sketch of Colonel Kelly appeared in the February 1937 issue of ELECTRICAL ENGINEERING, page 290.

N. I. KORMAN (Enrolled Student) North Attleboro, Mass., who is enrolled at Worcester Polytechnic Institute, Worcester, Mass., has been awarded a Charles A. Coffin fellowship. Mr. Korman, a native (1916) of Providence, R. I., will pursue research in ultrahigh-frequency measurements at Massachusetts Institute of Technology.

N. R. GIBSON (M'32) vice-president of the Buffalo, Niagara, and Eastern Power Corporation, Buffalo, N. Y., has been elected a vice-president and director of the recently organized Buffalo Niagara Electric Corporation. A biographical sketch of Mr. Gibson appeared in the February 1937 issue of Electrical Engineering, page 290.

D. L. HERR (Enrolled Student) University of Pennsylvania, Philadelphia, has been awarded a Charles A. Coffin fellowship. Mr. Herr is a native (1916) of Ephrata, Pa. He will remain at the University of Pennsylvania to study oscillation in nonlinear circuits.

J. F. BRINER, JR. (A'36) has resigned his position as an under clerk in the Electric Rate Survey, Federal Power Commission, New York, N. Y., to become affiliated with the engineering department of the Niagara, Lockport, and Ontario Power Company, Buffalo, N. Y.

S. M. ZUBAIR (A'27, M'34) formerly an assistant electrical engineer for the Buffalo, Niagara, and Eastern Power Corporation, Buffalo, N. Y., now is employed by The Tata Hydro-Electric Power Supply Co., Ltd., Bombay, India.

W. T. ELSTON, JR. (A'36) has resigned his position as a field engineer for the Central Hudson Gas and Electric Corporation, Kingston, N. Y., to join the research engineering department of the Speer Carbon Company, St. Marys, Pa.

G. S. ONORY (A'33) formerly an electrical engineer for the consulting engineering firm of Ford, Bacon, and Davis, New York, N. Y., now is an assistant valuation engineer for the New York State Public Service Commission, with headquarters at Rochester.

R. R. MCGEE (A'28) formerly employed in the switchgear engineering department of the General Electric Company, Philadelphia, Pa., now is associated with the Trumbull Electric Manufacturing Company, Plainville, Conn.

ROBERT LOEWE (A'32) who has been a surveyor for the Works Progress Administration, Chicago, Ill., now is employed as a transformer design engineer for the Westinghouse Electric & Manufacturing Company, Sharon, Pa.

R. V. CREASY (A'36) who has been an electrical draftsman for the Newport News Shipbuilding and Dry Dock Company, Newport News, Va., now is an equipment engineer for the Western Electric Company, Chicago, Ill.

H. E. STAFFORD (A'13, M'25) formerly electrical superintendent of the Canadian International Paper Company, Nipigon, Ont., now is employed in the consulting engineering firm of John Stafford, Toronto, Ont.

E. A. ROTHFUS (A'35) formerly an electrician, United States Engineers, Fort Peck, Mont., now is employed as an electrical tester for the Westinghouse Electric & Manufacturing Company, East Pittsburgh, Pa.

F. P. Rosso (A'36) city electrical engineer, Cherokee, Okla., Municipal Light and Water Department, now is associated with the Public Service Company of Oklahoma, McAlester, in the commercial lighting department.

J. L. BLACKBURN (A'36) graduate student, Westinghouse Electric & Manufacturing Company, East Pittsburgh, Pa., recently was transferred to the Newark, N. J., offices of that company.

C. T. GOHN (A'35) clerk, Westinghouse Electric & Manufacturing Company, Philadelphia, Pa., has been transferred to the test engineering department of the East Pittsburgh, Pa., works of that company.

# Obituary

ARTHUR WILLIAMS (A'97, M'08, F'13, member for life) former vice-president of The New York (N. Y.) Edison Company, Inc., died April 14, 1937. Mr. Williams was born August 14, 1868, at Norfolk, Va., and was educated in private schools at New York. He served The New York Edison Company for 42 years, starting as a repair boy in 1885 and retiring in 1928 as vice-president in charge of commercial relations. He became general commercial manager of the company in 1915 and held that position until 1924, when he was made vice-president in charge of commercial relations. In 1917 Mr. Williams was appointed to the post of food administrator for the city of New York; he served in that capacity for 2 1/2 years before resigning in 1920. During the Spanish-American War he served as commanding officer of the New York Volunteer Forces, mining New York Harbor. In 1912 he was decorated by the King of Spain, receiving the rank of knight in the Royal Order of Isabel the Catholic, and in 1926 was made a chevalier of the French Legion of Honor. Mr. Williams was a past-president of the American Association for the Advancement of Science, Association of Edison Illuminating Companies, and the National Electric Light Association; he was also a member of the American Academy of Political and Social Sciences, American Electrochemical Society, American Association for Labor Legislation, International Industrial Relations Association, and Society of American Military Engineers.

EDDY CLIFFORD JERMAN (A'20) director of the educational department, General Electric X-Ray Corporation, Chicago Ill., died September 13, 1936, according to word just received at Institute headquarters. Mr. Jerman was born in Ripley County, Indiana, November 21, 1865, and attended Franklin College and Central Business College (Austin, Texas), following which he became associated with the Physicians and Surgeons Supply Company and Jones Brothers Electric Company, both of Cincinnati, Ohio, as an electrician. In 1891 he established his own business at Indianapolis, Ind., at first selling medical and dental electrical supplies; however, in 1896 he began to manufacture X-ray machines. Until 1903 Mr. Jerman acted as an instructor in medical electricity at the Physiomedical College of Indiana and the Central College of Physicians and Surgeons of Indiana; at that time he moved his offices to Topeka, Kans., where he continued the manufacture of electromedical equipment until in 1917 he joined the staff of the Victor X-Ray Corporation, which later became the General Electric X-Ray Corporation, to organize its educational department. Mr. Jerman's service as director of that department covered a period of almost 20 years.

GUY S. TURNER (A'18) president, Turner and Turner, Inc., Memphis, Tenn., died in March 1937. Mr. Turner was born April 2, 1876, at Water Valley, Miss. From 1896 to 1898 he served as a machinist for several companies in Texas and in Mexico, and following a year's service with the United States Army Signal Corps during the Spanish-American War, entered the employ of the Memphis Power and Light Company in 1899. He was first a machinist, but became successively electrical foreman, chief electrician, superintendent and mechanical engineer, and engineer in charge of manufacture, remaining with that company until 1920. At that time he established the firm of Turner and Turner, and served as its president for 16 years.

PHILIP A. LANG (A'88, M'88, member for life) retired engineer, London, England, died February 25, 1937. Mr. Lang was born in October 1856, in Mecklenburg, Germany, and started his technical career as an electrician for Siemens Brothers and Company, Woolwich, England, in 1880. In 1882 Mr. Lang came to the United States and secured a position as head of the testing department of Bergmann and Company, New York, N. Y., where he remained for 4 years before becoming associated with the Westinghouse Electric & Manufacturing Company, East Pittsburgh, Pa., first as an electrician and later as superintendent of the detail department. He was subsequently sent to England as a representative of the Westinghouse company, and eventually became managing director of the British Westinghouse Electric & Manufacturing Company, Trafford Park.

# Membership

## Recommended for Transfer

The board of examiners, at its meeting on May 12, 1937, recommended the following members for transfer to the grade of membership indicated. Any objection to these transfers should be filed at once with the national secretary.

**To Grade of Fellow**

Pratt, Haraden, vice-president and chief engr., Mackay Radio and Telegraph Co., New York.

1 to Grade of Fellow

**To Grade of Member**

Bewley, L. V., electrical engineer, General Electric Company, Pittsfield, Mass.
Dyer, L. L., superintendent of substations, Southern California Edison Company, Los Angeles.
Garin, A. N., electrical engineer, General Electric Company, Pittsfield, Mass.
Goodwin, V. E., managing engineer, lightning arrester, cutout and capacitor department, General Electric Company, Pittsfield, Mass.
Jackson, E. S., electrical distribution engineer, Consumers Power Company, Jackson, Mich.
Pettee, A. D., district engineer, General Cable Corporation, Chicago, Ill.
Pinder, K., electrical engineer, E. I. du Pont de Nemours and Co., Wilmington, Del.
Rey, W. J., electrical engineer, United States Department of the Interior, Washington, D. C.
Roser, J. O. K., assistant to manager, transformer division, General Electric Company, Pittsfield, Mass.
Schott, J. T., telephone engineer, Bell Telephone Laboratories, Incorporated, New York, N. Y.
Underwood, R. J., assistant engineer, New England Power Service Company, Providence, R. I.

11 to Grade of Member

## Applications for Election

Applications have been received at headquarters from the following candidates for election to membership in the Institute. If the applicant has applied for direct admission to a grade higher than Associate, the grade follows immediately after the name. Any member objecting to the election of any of these candidates should so inform the national secretary before June 30, 1937, or August 31, 1937, if the applicant resides outside of the United States or Canada.

Adams, E. V., British Columbia Electric Railway Company, Ltd., Vancouver, B. C., Canada.
Alexieff, V. M., Pacific Gas and Electric Company, San Rafael, Calif.
Anspacher, W. B., Union Electric Power and Light Company, St. Louis, Mo.
Arvidson, C. E., Commonwealth and Southern Corporation, Jackson, Mich.
Ballou, R. P. (Member) Allen Bradley Company, Milwaukee, Wis.
Beller, C. J. (Member) Cleveland Electric Illuminating Company, Cleveland, Ohio.

Benkesser, G. E. (Member), Bureau of Power and Light, Los Angeles, Calif.
Bragunier, C. E., Phoenix Engineering Corporation, New York, N. Y.
Brown, G. C. (Member), Cutler-Hammer, Inc., Milwaukee, Wis.
Brown, M. J., Westinghouse Electric & Manufacturing Company, East Pittsburgh, Pa.
Buswell, M. P., Westinghouse Electric & Manufacturing Company, Seattle, Wash.
Cameron, D. G., General Electric Company, Lynn, Mass.
Campbell, J. F., Consolidated Edison Company, New York, N. Y.
Clay, L. J., Public Service Supply Company, Inc., Cleveland, O.
Cluff, T. W. (Member), Ottawa Electric Company and Ottawa Electric Railway Company, Ottawa, Ont., Canada.
Coburn, W. N., Green Mountain Power Corporation, Bellows Falls, Vt.
Coggeshall, I. S. (Member), Western Union Telegraph Company, New York, N. Y.
Condit, P. A., Pure Oil Company, Chicago, Ill.
Critchley, W. A. (Member), 1730 Ocean Avenue Brooklyn, N. Y.
Crosby, F. A., Otis Elevator Company, San Francisco, Calif.
Crosby, T. H. (Member), Canadian Westinghouse Company, Ltd., Vancouver, B. C., Canada.
Dailey, J. A. (Member), General Electric Company, Kansas City, Mo.
Dickinson, W. E., 7*D* Godfrey Court, Fort Riley, Kans.
Diemond, C. C., Bureau of Reclamation, Ephrata, Wash.
Ellerbeck, K. H., Pacific Telephone and Telegraph Company, Seattle, Wash.
Ennis, B. J., Burns and McDonnell Engineering Company, Kansas City, Mo.
Fisken, J. B. (Member), Water Division, City of Spokane, Wash.
Fleischer, F. H., General Electric Company, Fort Wayne, Ind.
Fuller, A. G., Phelps Dodge Corporation, Ajo, Ariz.
Gilman, B. E., L. E. Myers Company, Caro, Mich.
Gosal, G. S., 1731 Allston Way, Berkeley, Calif.
Graham, A. M., Western Union Telegraph Company, Washington, D. C.
Gratz, D. W., Glendale Public Service, Glendale, Calif.
Gronauer, C., Milwaukee Electric Railway and Light Company, Milwaukee, Wis.
Harrison, R. (Member), Scarborough Public Utilities Commission, Toronto, Ont., Canada.
Heiman, H. O. (Member), city engineer's office, Milwaukee, Wis.
Hiers, J. B., Jr. (Member), General Electric Company, Miami, Fla.
Hopwood, J. M., Globe Union, Inc., Milwaukee, Wis.
Howery, H. A. (Member), Kansas City Power and Light Company, Kansas City, Mo.
Hranac, F. V., Unites States Navy Department, Washington, D. C.
Huehnel, A. L., Square D Company, Milwaukee, Wis.
Hughes, M. McC., General Electric Company, Louisville, Ky.
Jones, R. L., Southwestern Bell Telephone Company, Oklahoma City, Okla.
Kalbach, J. F., General Electric Company, Fort Wayne, Ind.
Karg, W. R., Diehl Manufacturing Company, Elizabeth, N. J.
Kinser, J. H., Houston Lighting and Power Company, Houston, Texas.
Kokesh, F. P., Minneapolis-St. Paul Sanitary District, St. Paul, Minn.
Kunz, A. F., Ohio Bell Telephone Company, Cleveland, O.
Lauder, A., Phillips Electrical Works, Ltd., Brockville, Ont., Canada.
Mallett, M. B. (Member), General Electric Company, Pittsfield, Mass.
McCall, R. L. (Member), substations and water department, Jacksonville, Fla.
Meichel, C. B. (Member), Department of Public Utilities, St. Louis, Mo.
Mergenthaler, A. H. (Member), Alabama Power Company, Birmingham.
Merkel, N. M., Metropolitan Edison Company, Reading, Pa.
Meyers, W. N., Federal Shipbuilding and Drydock Company, New York, N. Y.
Miller, G. R., Metropolitan Water District of Southern California, Rice, Calif.
Myers, H. C., Government Printing Office, Washington, D. C.
Osborne, H. R., Ferranti Electric, Ltd., Toronto, Ont., Canada.
Osgood, D. T., Bell Telephone Laboratories, Incorporated, New York, N. Y.
Osterhout, E. W., New Jersey Zinc Company, Franklin, N. J.
Pacanins, A., Hilicrest Hotel, Toledo, O.
Penn, L., Travelers Insurance Company, New York, N. Y.
Pennington, C. C., Tennessee Valley Authority, Chattanooga, Tenn.
Perkins, W. S., General Electric Company, Bridgeport, Conn.
Pickles, S. B., Gardner Electric Manufacturing Company, Emeryville, Calif.
Ramadanoff, D. (Member), Cornell University, Ithaca, N. Y.
Ramien, C. H., Jr., Globe Union, Inc., Milwaukee, Wis.
Reeves, G. A., Jr., Oklahoma Gas and Electric Company, Oklahoma City, Okla.
Robbins, C. F., Cutler-Hammer, Inc., Milwaukee, Wis.
Rohlfsen, A. G., Johns-Manville Products Corporation, Lompoc, Calif.
Schmidt, I. F., Milwaukee Electric Railway and Light Company, Milwaukee, Wis.
Schnabel, J. F. (Member), Euclid Electric an Manufacturing Company, Euclid, Ohio.
Schoen, A. M., Commonwealth and Southern Corporation, Jackson, Mich.
Shuman, U. S., Philadelphia Electric Company, Philadelphia, Pa.
Smith, C., New York and Queens Electric Light and Power Company, Flushing, N. Y.
Smith, C. G., Smith Milligan Electric Company, Tulsa, Okla.
Spitler, C. H., Brown-Brockmeyer Company, Inc., Dayton, O.
Stark, O. P., Jr., Hoosier Engineering Company, Columbus, Ohio.
Steel, H. D., Herman D. Steel Company, Philadelphia, Pa.
Stevenson, R. B., Dollar Steamship Company, San Francisco, Calif.
Stodola, F. J., Milwaukee Electric Railway and Light Company, Milwaukee, Wis.
Thwaites, J. T., Canadian Westinghouse Company, Hamilton, Ont., Canada.
Tibbals, L., Colonial Radio Corporation, Buffalo, N. Y.
Tracy, J. B., Jr., Radio Experimental Laboratories, Taunton, Mass.
Ullman, F. (Member), Westinghouse Electric & Manufacturing Company, New York, N. Y.
Vialet, F. C., 2257—7th Avenue, New York, N. Y.
Wedge, R. E., General Electric Company, Fort Wayne, Indiana.
Wells, C. A., Southern California Telephone Company, Los Angeles, Calif.
Younger, D., American Telephone and Telegraph Company, Buffalo, N. Y.
Zigler, M. O., Federal Power Commission, Denver, Colo.

91 Domestic

**Foreign**

Channa, B. N., Public Works Department, Jogindernager, Mandi State, India.
Drake, H. H., Indian Iron and Steel Company, Ltd., Burnpur, India.
Gademann, O. M., Allgemeine Elektricitäts-Gesellschaft, Berlin, Germany.
Koo, C. T., Shanghai Power Company, Shanghai, China
Martinez G. R., La Consolidada, S. A., Calzada de la Ronda, Mexico, D. F., Mexico.
Russell, A. J. G., 256 St. Asaph Street, Christch .rch, New Zealand.
Smyth, L C., Cerro de Pasco Copper Corporation, Or ya, Peru.
Shima, R., Toden Electric Supplies Company. To yo, Japan.
Warbu on, J. H., Edison Swan Cables, Ltd., I don, England.

9 For.ign

# Engineering Literature

## New Books in the Societies Library

Among the new books received at the Engineering Societies Library, New York, recently, are the following which have been selected because of their possible interest to the electrical engineer. Unless otherwise specified, books listed have been presented gratis by the publishers. The Institute assumes no responsibility for statements made in the following outlines, information for which is taken from the preface of the book in question.

MUNICIPAL YEAR BOOK. 1937. Edited by C. E. Ridley and O. F. Nolting. Chicago, International City Managers' Association, 1937. 599 pages, illustrated, 10x7 inches, cloth, $5.00. Contains articles on developments in various fields of municipal administration and gives statistics on cities over 10,000. Lists educational institutions giving courses in public administration and includes a directory of city officials in all cities over 10,000.

MEN of MATHEMATICS. By E. T. Bell. New York, Simon and Schuster, 1937. 592 pages, illustrated, 10x6 inches, cloth, $5.00. Biographical and critical information about the important men in the mathematical field, from the Greeks to the present time.


**Engineering Societies Library**
29 West 39th Street, New York, N. Y.

MAINTAINED as a public reference library of engineering and the allied sciences, this library is a co-operative activity of the national societies of civil, electrical, mechanical, and mining engineers.

Resources of the library are available also to those unable to visit it in person. Lists of references, copies or translation of articles, and similar assistance may be obtained upon written application, subject only to charges sufficient to cover the cost of the work required.

A collection of modern technical books is available to any member residing in North America at a rental rate of five cents per day per volume, plus transportation charges.

Many other services are obtainable and an inquiry to the director of the library will bring information concerning them.


FIRST ELEVATED RAILROADS in MANHATTAN and the BRONX of the CITY of NEW YORK. By W. F. Reeves. New York, New York Historical Society, 1936. 137 pages, illustrated, 10x7 inches, cloth, $3.00. Description of the development and progress of the early elevated railroads in Manhattan and the Bronx, including the various schemes proposed from 1825 up to the first actual construction in 1867.

JOURNAL of the ROYAL TECHNICAL COLLEGE, volume 4, part 1, January, 1937. Glasgow, Royal Technical College. 212 pages, illustrated, 10x7 inches, paper, 10s. 6d. Contains several papers of interest to electrical engineers, including a discussion of the sensitivity of the Schering bridge network and the commutation period in grid-controlled mercury-arc rectifiers.

THEORIE der WECHSELSTROMMASCHINEN in Vektorieller Darstellung. By W. Michael. Leipzig und Berlin, B. G. Teubner, 1937. 272 pages, illustrated 10x6 inches, paper, 16.50 rm.; bound, 18 rm. (in U.S.A.). Develops the theory of a-c machines by means of "space diagrams" and "space vector diagrams." Includes chapters on transformers, induction machines, commutator motors, auxiliary machines, and cascade connections between induction and commutator machines.

OBJECTIVE RATE PLAN for Reducing the Price of Residential Electricity. By W. F. Kennedy. New York, Columbia University Press, 1937. 83 pages, charts, tables, 9x6 inches, cloth, $1.25. Relates the history of the plan, the reasons for its adoption and the results obtained.

COMPENSATING INDUSTRIAL EFFORT. By Z. C. Dickinson. New York, Ronald Press Company, 1937. 479 pages, illustrated, 9x6 inches, cloth, $4.50. A study of the problem of work incentives. Covers the causes determining the amount of wages of occupations and individuals, the relative efficacy of various stimuli and factors in increasing production, and the social consequences of various work-and-pay situations.

ALTERNATING CURRENTS in RADIO RECEIVERS. By J. F. Rider. Published by author, 1440 Broadway, New York, N. Y., 1937. 94 pages, illustrated, 9x6 inches, paper, $0.60. A discussion of basic facts about alternating currents in radio receivers.

AMERICAN SOCIETY for TESTING MATERIALS. INDEX to PROCEEDINGS, volumes 31–35 (1931–35). Philadelphia, American Society for Testing Materials, 1937. 194 pages, 9x6 inches, cloth, $2.25; half leather, $3.00. Contains author and subject indexes for the *Proceedings* of 1931–1935 and of the symposiums presented at regional, local, and annual meetings, and not published in the *Proceedings*.

APPLICATIONS of the METHOD of SYMMETRICAL COMPONENTS. (Electrical Engineering Texts.) By W. V. Lyon. New York and London, McGraw-Hill Book Company, 1937. 579 pages, illustrated, 9x6 inches, cloth, $6.00. Designed to demonstrate the use of symmetrical components in the solution of problems in unsymmetrical polyphase circuits. The reader is expected to have a thorough grounding in single-phase and symmetrical polyphase circuits, transformers, and symmetrical operation of 3-phase induction and synchronous machines.

GÉNÉRATRICES et MOTEURS à courant continu. By E. Roth and J. Bardin. Paris, Librairie Armand Colin, 1937. 223 pages, illustrated, 7x5 inches, paper, 13 frs.; bound, 15.50 frs. Presents the principles of d-c machines, written in easily understood language and intended for students and designers.

# Industrial Notes

**Building Construction Still Upward.**—Not since May 1930 has residential building been undertaken in such heavy volume as was reported in April this year, according to F. W. Dodge Corp. The value of such operations started during April in the 37 states east of the Rocky Mountains amounted to $108,204,400, a gain of 20 per cent over the March figure and an increase of 61 per cent over April 1936. Besides residential building, the April 1937 figures show $96,179,300 for non-residential building and $65,741,500 for heavy engineering projects, i. e., public works and public utilities.

**U. S. Rubber Appoints Dr. Sturdevant.**—According to a recent announcement United States Rubber Products, Inc., has appointed Dr. Earl G. Sturdevant as consulting engineer of its electrical wire and cable dept. Dr. Sturdevant joined the company in 1929, being previously connected with the Western Electric Co. In 1931 he was appointed development manager of the electrical wire and cable department, where he contributed to the successful development of Laytex, the new dielectric.

**New Branch Manager for Weston.**—H. E. Held has recently been appointed to succeed the late C. F. Henderson as manager of the San Francisco agency of the Weston Electrical Instrument Corporation, with offices at 420 Market St. Mr. Held was previously assistant to Mr. Henderson for a number of years.

**Resistance Wire Division Sold.**—The C. O. Jelliff Mfg. Corp., Southport, Conn., has recently purchased the resistance wire division of George W. Prentiss and Co., of Holyoke, Mass.

**Century Electric Moves New York Office.**—The New York office of the Century Electric Co. has been moved from 50 Church St. into larger quarters in the Underwood Building, 30 Vesey St. James Larkin is district sales manager.

**Frigidaire Plants Enlarged.**—The erection of 2 new factory buildings, together with enlargement and rearrangement of the Moraine City, O., manufacturing facilities of Frigidaire Div., General Motors Corp., will be started shortly. The construction and plant layout program will involve an expenditure in excess of $4,000,000.

**New Oil Blast Circuit Breaker.**—A new oil blast circuit breaker, type FK-45, with 75,000 kv-a interrupting rating has been announced by the General Electric Co. The FK-45 unit is a non-oil-throwing breaker with plate steel rectangular tank with separating chamber, internal mechanism, silver-to-silver main contacts, easily renewable arcing contacts, oil blast baffles, and Herkolite bushings. It is available in three current sizes, 600, 1200 and 2000 amperes. A feature of the new breaker is its sturdy tank construction which makes it especially applicable where heavy duty and small space requirements are indicated.

**New Type Motor Starter.**—The Allis-Chalmers Manufacturing Co., Condit Works Boston, Mass., announces a new type of across-the-line air motor-starter, equipped with "Ruptors," known as type AP-7. The Ruptors are enclosing chambers which confine and depotentiate the arc formed by circuit interruption. These "arc-depotentiating chambers" greatly increase the interrupting ability of the contacts and form an isolating barrier between contacts of opposite polarity. The starter is furnished for $7\frac{1}{2}$ hp at 440 and 550 volts, 5 hp at 220 volts, and 3 hp at 110 volts.

**New G-E Building in Los Angeles.**—Contracts were recently awarded for the construction of a new $700,000 General Electric building at Los Angeles. The new building is designed to contain 6 stories and basement, 3 stories of which are planned to be completed for occupancy by September. The new structure will occupy approximately a city block in the downtown section of Los Angeles and will contain 250,000 square feet of floor space.

# Trade Literature

**Capacitors.**—Catalog 139A. Describes new pole-type capacitors for power correction of distribution systems. Cornell-Dubilier Corp., South Plainfield, N. J.

**Fire Alarm Systems.**—Bulletin 102, 16 pp. Describes Samson fire alarm systems for institutions, factories, etc. S. H. Couch Co., Inc., North Quincy, Mass.

**Watthour Meters.**—Bulletin GEA-2404A, 16 pp. Describes 2-element, single-disk watthour meters, their mountings, connection diagrams, etc. General Electric Co., Schenectady, N. Y.

**Underground Conduit.**—Bulletin 3751, 16 pp. Describes fibre conduit, standard and thin wall, together with fittings. Line Material Co., So. Milwaukee, Wis.

**Heating Units.**—Bulletin GED-650, 60 pp. Describes numerous small heating units and devices of all kinds for a wide variety of applications. General Electric Co., Schenectady, N. Y.

**Flexible Metal Tubing.**—Bulletin SS-3, 16 pp. Describes seamless flexible metal tubing, one of the 4 major styles of flexible metal hose made by this company. Illustrates a wide variety of installations where absolute tightness in conveying liquids or gases is essential. The American Brass Co., American Metal Hose Branch, Waterbury, Conn.

**Pulleys and Couplings.**—Bulletin, 4 pp. Describes a complete line of "V" grooved pulleys, variable speed and step-cone pulleys; flexible couplings. Congress Tool & Die Co., Inc., 9030 Lumpkin Ave., Detroit, Mich.

**Flow Meters.**—Catalog, 40 pp. Describes electrical and mechanical flow meters for recording, integrating, controlling and indicating the flow of steam, liquids, or gases. Details of the new electric flow meter and its operation, using Bristol's metameter principle of telemetering, are included. The Bristol Co., Waterbury, Conn.

**Service Cables.**—Bulletin C-31, 20 pp. Describes various types of service cables, illustrating uses and installations permitted by the National Electric Code. Typical applications and specifications are included. Anaconda Cable and Wire Co., 25 Broadway, New York City.

**Lightning Protective Equipment.**—Bulletin GEA-1743B, 12 pp. Describes lightning protective equipment for a-c rotating machines insuring protection against traveling-wave voltages due to lightning. The protective arrangement covers the combined use of arresters and capacitors. General Electric Co., Schenectady, N. Y.

**Motors.**—Bulletin 305. Describes Reliance disc-brake motors,—combined units for power applications requiring quick, accurate, automatic stops or the holding of a load. Typical applications are small cranes, hoists, and auxiliary movements on machine tools. They frequently eliminate the need for clutches and permit direct connection of motors. Reliance Electric & Engineering Co., 1086 Ivanhoe Rd., Cleveland, O.

**Arc Welders.**—Bulletin "The Arc-Welding of Tomorrow." Describes the advantages gained by the use of the internally stabilized arc of the "Smootharc Welder." Photographs illustrate the applications of many of the models, from the vertical 75- and 100-ampere types to the 200-, 300-, 400- and 600-ampere horizontal types. Stationary and portable-trailer models are also shown. Harnischfeger Corp., 4200 W. National Ave., Milwaukee, Wis.

**Transformers.**—Bulletin 340, 8 pp. Describes power and distribution transformers, illustrating various types of large equipment, single phase and three phase, used for power transmission, electric arc furnaces, railway systems, or other industrial purposes. Brief mention is made of a few of the important developments and improvements, such as uni-row radiators, straight line tap-changers, circular coils, etc. Pennsylvania Transformer Co., 1701 Island Ave., N. S., Pittsburgh, Pa.

**Voltage Regulators.**—Bulletin 5601, 8 pp., Electronic Automatic Alternator Voltage Regulator, Type EF. Describes and illustrates this type of regulator which can be used with any known method of excitation. It explains in detail the operation of this comparatively new method of automatic voltage regulation. Bulletin 5602, 8 pp. Describes a similar regulator designed for only one scheme of excitation, i. e., one regulator for each exciter. Ward Leonard Electric Co., Mt. Vernon, N. Y.

# Electrical Engineering

Registered U. S. Patent Office

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### The Cover

**Construction view of Coulee Dam, feature item of the inspection trip program of the AIEE 1937 Pacific Coast convention (see news section)**



# High Lights

**Pacific Coast Convention.** An all-day inspection trip to the Grand Coulee project on the Columbia River is one feature that has been included on the program of the Institute's 1937 Pacific Coast convention to be held in Spokane, Wash., August 30–September 3, in the heart of the Pacific Northwest. Other attractions include a high-class technical program, a joint session with the Institute of Radio Engineers, the usual sports competitions, and special entertainment (*pages 910–12*).

**Huge Telescope Being Welded.** Framework for the 200-inch telescope now being built in a new observatory on Mt. Palomar, Calif., will consist of electric-arc-welded units bolted together at the site. Astronomers estimate that this new instrument will penetrate the universe to a distance of a billion light-years (*pages 783–6*).

**Charles Le Geyt Fortescue.** An appreciation of this noted electric-power-transmission engineer (who died December 4, 1936), prepared by one who was associated with him for many years, outlines his many contributions to the electrical industry (*pages 781–3*).

**Electrical Computer.** A search for a simple computing device to simplify and expedite the calculations involved in the design of the overhead catenary for an extensive railroad electrification led to the development of an electrical computer, the circuit of which represents an exact analogy of the mechanical system embodied in the messenger cable of a catenary span (*pages 787–90*).

**Summer Convention.** As this issue goes to press, the Institute's 1937 summer convention is being held in Milwaukee, Wis. At the opening session, election of 2 noted engineers as AIEE Honorary Members was announced, and new officers to serve the Institute during the ensuing year were named (*pages 913–14*).

**Letters to the Editor.** Readers of ELECTRICAL ENGINEERING continue to express themselves informally on a variety of subjects through the "Letters To The Editor" columns (*pages 917–18*).

**Saturated Synchronous Machines.** Effects of saturation in salient-pole and cylindrical-rotor synchronous machines operating under steady load may be analyzed by a method based upon the 2-reaction theory, with good agreement between calculated and test results; torque angle is obtained by using saturated quadrature synchronous reactance rather than unsaturated reactance (*pages 858–63*).

**Ignitors.** A rod of high-resistivity material is used in ignitron tubes to initiate the discharge by the formation of an arc between the rod and the mercury-pool cathode in which the rod is immersed. Current required by the ignitor should be as small as possible; shaping the rod to a point and slotting it greatly increase its effectiveness (*pages 810–12*).

**Distance Relays.** Distance-measuring and directional elements are used in various relay combinations to provide fault protection in power systems; the performance of distance relays may be determined from the effective impedance presented to the element, which may be expressed in terms of certain fundamental quantities and thus reduce to a minimum the labor involved in the calculations for any specific situation (*pages 833–44*).

**Photoelectric Hysteresigraph.** Initial magnetization curves or any desired symmetrical or unsymmetrical hysteresis loops may be recorded graphically on the fluorescent screen of a d-c instrument which depends for its operation on a photoelectric fluxmeter (*pages 805–09*).

**Directors' Report.** The annual report to the membership of the Institute's board of directors summarizes activities and the work of national committees during the year. Membership statistics and financial statements are included (*pages 791–804*).

**Potier Reactance.** Calculation of Potier reactance, which is a combination of reactance, change of saturation, and change of flux form, is possible by means of 3 approximate empirical methods given in this issue. The probable accuracy of the methods for typical machines is shown (*pages 813–18*).

**Oil-Impregnated Paper.** Extended tests indicate that there is no correlation between dielectric loss and electrical life of oil-impregnated paper insulation, and that gas-free specimens are superior to any specimens saturated with gas at pressures up to 200 pounds per square inch (*pages 845–9*).

**Relay Operation.** When synchronous machines hunt or fall out of step with one another an oscillating interchange of power may cause relays to operate unnecessarily. Some remedies for such incorrect relay operation have been suggested (*pages 823–32*).

**The Perfect Reading Page.** Is ELECTRICAL ENGINEERING's "easy reading" page really easier to read? This question is answered in part by a writer thoroughly qualified to draw conclusions on the subject (*pages 779–81*).

**Distortion of Traveling Waves.** The shape of a lightning wave traveling on a transmission line is altered by corona at normal operating frequency. How to predict the distortion is described in a paper in this issue (*pages 850–6*).

**Lightning Arresters.** A new station type of autovalve lightning arrester is described in a paper in this issue (*pages 819–22*).

# DISCUSSIONS

Appearing in this issue are discussions of the following papers:

## Communication


Currents and Potentials Along Leaky Ground-Return Conductors—Sunde 887
Inductive Co-ordination of Common-Neutral Power-Distribution Systems and Telephone Circuits—Coleman and Davis 889
Calorimetric Measurement of Dielectric Losses in Solids—Race and Leonard 890


## Electric Welding


The Resistance Welding Circuit—Pfeiffer . . . 864


## Electrical Machinery


Proposed Transformer Standards—Clem . . . . 868
A New Electrostatic Precipitator—Penney . . . 869
Negative-Sequence Reactance of Synchronous Machines—Thomas 903
Two-Reaction Theory of Synchronous Machines—Crary 905
Synchronous Machine With Solid Cylindrical Rotor—Concordia and Poritsky 906
Contributions to Synchronous-Machine Theory—Langsdorf 907


## Electronics


Electronic Transient Visualizers—Reich . . . . 873
An Electronic Regulator for D-C Generators—Gulliksen 875
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Amplification Loci of Resistance-Capacitance Coupled Amplifiers—Seletzky 877


## Instruments and Measurements


Watt-Hour Meter Bearings—Kinnard and Goss 871
Development of a Modern Watt-Hour Meter—Kinnard and Trekell 879
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Short-Time Spark-Over of Gaps—Hagenguth . . 882


## Power Transmission and Distribution


Studies of Stability of Cable Insulation—Halperin and Betzer 871
Automatic Boosters on Distribution Circuits—Olmsted 893
Trends in Distribution Overcurrent Protection—Lincks and Benner 895
Pole Flexibility as a Factor in Line Design—Seelye and Zucker 900
A Review of Overhead Secondary Distribution—Holben 902



Statements and opinions given in articles and papers appearing in ELECTRICAL ENGINEERING are the expressions of contributors, for which the Institute assumes no responsibility. Correspondence is invited on all controversial matters. ¶ Subscriptions—$12 per year to United States, Mexico, Cuba, Porto Rico, Hawaii, Philippine Islands, Central and South America, Haiti, Spain, Spanish Colonies; $13 to Canada; $14 elsewhere. Single copy $1.50. ¶ Address changes must be received by the fifteenth of the month to be effective with the succeeding issue. Copies undelivered because of incorrect address cannot be replaced without charge. ¶ ELECTRICAL ENGINEERING is indexed annually by the Institute, weekly and monthly by *Engineering Index*, and monthly by *Industrial Arts Index*; abstracted monthly by *Science Abstracts* (London). ¶ Copyright 1937 by the American Institute of Electrical Engineers. Number of copies this issue—19,800

# Electrical Engineering

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## Branch Activity—*A Message From the President*

ON August 1, 1936, there was no phase of the Institute work of which I knew so little as I did about the work of the Student Branches. Today there is no phase in which I am more interested, or which I feel is better conducted. A successful Branch must overcome some natural handicaps. If limited to the 2 upper classes, the membership must be completely replaced every 2 years. There are many claims on the students' time. The potential members have had little experience in organization affairs. Active membership is of such short duration that there is little opportunity for the development of leaders. In a Section the average chairman comes to office with several years' experience in Section and committee work, but the Branch chairman seldom has more than one year's training in Branch activity. In the Sections, past-chairmen are a source of inspiration, counsel, and guidance, while in the Branches, the past-chairmen are lost through graduation.

Why, then, is the Branch movement so successful? From my observation, it is because of 3 factors: the enthusiasm of youth; the desire to make use of every agency in acquiring an engineering training; the advice and guidance from the counselors.

From my visits to Branches and Branch conventions come several ideas as to how Branch activity is being successfully carried on. I believe that these ideas are worthy of record, and hope that the future will see many additions to the record. The Student Branch should be organized on the following fundamental principles.

It is an honor and a duty to be a member; a privilege to attend the meetings. The officers should be selected from the most capable and distinguished members, for certainly capable, enthusiastic officers are essential for a successful Branch. The meetings must be worth while. At the close of the meeting, each one attending must feel that he has gained professionally by being present. Discussion of the subject presented should be stimulated and encouraged, for often it is the most valuable part of the meeting. It should be understood that the meetings are closed to nonmembers, excepting on specific invitation. The Branch officers should be responsible for, and carry on, the Branch activities, depending upon the counselor only for advice and guidance.

The program should be planned in advance and as a co-ordinated whole, for it is the most important of the Branch activities. Although programs should be broadened beyond the highly theoretical and basically technical, the Branch should always remember that it is an integral part of a national technical society. A meeting where engineering results are demonstrated with the aid of equipment is extremely interesting and very popular. Speakers should be sought from 3 sources: graduate engineers in industry; faculty members from the home and other colleges; and from the membership of the Branch. Exchange of faculty speakers between neighboring Branches produces good results.

The year may be divided into 2 periods, providing 4 periods within a cycle of membership. Officers would then be elected twice each year, resulting in more opportunities for service and less time required from each officer. Rotation in office, with its advantages, is then possible. In one school where such a plan is followed, an observer from each of the freshman and sophomore classes is invited to attend the executive committee meetings, as well as the Branch meetings. These observers do not pay dues, are carefully selected by the Branch, and the selection is considered an honor. In this school, regular membership is open only to juniors and seniors. As each sophomore class becomes junior, there are 4 men who know something of the purposes, conduct, and activities of the Branch, and these men almost invariably join and take an active part in the Branch affairs.

Where several Branches are geographically close, joint activities are inspiring to each. During the last year, I saw 2 illustrations of the effectiveness of such a plan: at Pittsburgh in a joint afternoon session of the Branches from Carnegie Institute of Technology, the University of Pittsburgh, and the University of West Virginia; in North Carolina between Duke University, the University of North Carolina, and the North Carolina State College. Such joint activities provide training in co-operation, and offer the stimulation of competition.

Co-operation from a neighboring Section is of great assistance. Although the primary responsibility rests on the Section, the Branch should be very receptive. Many Sections offer a reduced price to Branch members if they attend a Section dinner. In the West, each of a group of interested Section members has pledged himself to entertain once each year a Branch member as his guest at a Section dinner.

Light refreshments following a Branch meeting offer the opportunity for, and stimulate, sociability—a good quality which many engineers lack. The cost may be kept so low as not to be a burden on the treasury, and yet the purpose accomplished.

At one university I visited, an Engineer's Lounging Room was provided and furnished through the co-operation of the university authorities and the other engineering society branches.

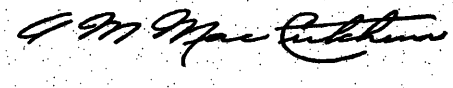
One of the most interesting and stimulating functions at the District meeting held in Dallas was the luncheon of the Branch chairmen, secretaries, and counselors. The counselor participated only by introducing the Branch chairman, who told of the plans for the future and the accomplishments of the past. Each of the 13 Branches was represented, and the 13 chairmen limited their remarks to a total of 45 minutes, each one telling something of interest to all.

In one of the schools, I found an engineering society to which all upper classmen were eligible. No junior or senior was denied the advantage and opportunity of an organized technical activity. This university engineering society was divided into groups, corresponding to the national professional engineering societies. Within the general society was developed the professional consciousness so desirable, and joint meetings were held treating economic and social responsibilities of the engineer. Once each year a purely social meeting was held. At this university, one evening a month was designated as Engineers' Night, and the other student organizations studiously avoided any conflicting activities. On Engineers' Night there was held either a joint meeting with all members of the engineering society free to participate, or simultaneous group meetings, with each devoted to a subject peculiarly interesting to that group. Contact with the national engineering society was maintained through the corresponding branch. With such an organization, possibly 4 evenings a year might be devoted to joint meetings and the presentation of general subjects, and 5 evenings devoted to parallel group meetings, featuring the presentation of specialized technical subjects. A joint meeting, with its consequently larger audience, is particularly suitable for an address by an outside engineer, or by a professor from the same or another technical school. Under this type of organization, I suggest the following as a typical Branch program.

| *No.* | *Class* | *Speaker* | *Type of Subject* |
|---|---|---|---|
| 1. | Joint | Professor | "The Problems of a Student Engineer" |
| 2. | Branch | Outside Engineer | "What My Company Expects of a Young Engineer" |
| 3. | Joint | Social | "Skits of the Anvil or Gridiron Variety" |
| 4. | Branch | Student | "Description of an Interesting Engineering Test or Problem" |
| 5. | Branch | Student | "Paper on Some Phase of Electronics" |
| 6. | Joint | Outside Engineer | "The Engineer's Opportunities and Responsibilities" |
| 7. | Branch | Graduate Student | "Presentation of a Research Problem" |
| 8. | Branch | Outside Engineer | "Description of Interesting Installation, Application or Research Problem" |
| 9. | Joint | Students | "Several Demonstrations" |

As you study this program, you will note that no student is asked to prepare a paper before the fourth meeting, by which time the interst in the engineering society and Branch activities would have been stimulated by 2 good lectures and one social meeting. The closing meeting would be devoted to several technical demonstrations presented by the various divisions. To this unusually interesting meeting all of the sophomores and freshmen might be invited. The program would have been built up to a fine climax, and the enthusiasm and interest of this last meeting would assure a successful following year for each division.

In the training of the young engineer, the American Institute of Electrical Engineers and the other professional societies are privileged to play an important part. Of this they should be deeply conscious and should meet fully their obligations and embrace their opportunities. The student engineer, in relation to his group and his college, is quite analogous to the graduate engineer in his relation to society. There is a growing feeling that the graduate engineer has not always fully met his responsibilities and risen to his opportunities; that he has not always recognized his social and economic responsibilities. Many engineers have failed to realize that the best idea is of little value unless it is so convincingly presented to others that they accept it and assist in its execution. A compromise plan which is accepted and produces results is far better than the most brilliant individual plan which is neither accepted nor adopted. All engineers need training in the convincing expression of their thought. They should listen to the ideas of others and endeavor to see their viewpoints; should judicially weigh all expressed thoughts as evidence, and select that which is sound for combination with their own views; and should be able to express convincingly a logical conclusion. The development of a unified professional consciousness is of great importance, for then the profession may better serve humanity. Contact between older and younger engineers is stimulating to both. Each has much of value to the other—knowledge, experience, professional standing, and resources on the one side; youth, eagerness, enthusiasm, and a fresh viewpoint on the other. The branch of a national engineering society is a medium through which these needs of a student engineer should be met.



# The Perfect Reading Page

By MATTHEW LUCKIESH
MEMBER AIEE

**With the January 1937 issue, ELECTRICAL ENGINEERING presented to its readers the "easy reading" page. This article presents a discussion of the factors that would influence the production of a perfect reading page, and an opinion, founded upon scientific research, concerning this "easy reading" page as an approximation of the theoretical ideal.**

DIFFERENCES of opinion cease to exist when adequate knowledge is available. Although this ideal stage has not been reached for the perfect reading page, great advancement has been made recently in the science of seeing. So long as opinions are based merely upon the science of vision, they must remain opinions because the basis is inadequate. Seeing is an activity of human beings; vision is merely an ability of eyes and the visual sense. Seeing involves the end products of human efficiency, behavior, and welfare.* It considers human beings as seeing machines and relegates eyes or the visual sense to the status of a part of the machine. Abuse of eyes is one of the consequences of unnaturally close and prolonged visual tasks imposed by civilization; however, much control can be exercised over certain factors, such as printing and lighting, to reduce the severity of visual tasks and the unnecessary waste of human resources.

The visibility of objects depends primarily upon

1. Size of the critical details.
2. Contrast between the object and background.
3. Brightness of the object and background, which depends upon the reflection factor and intensity of illumination.
4. Time available for recognizing the object.

In general, the theoretically ideal printed page results from

1. Large type of the most legible style.
2. Paper of high reflection factor and dull surface. If it is tinted, it should be optically and aesthetically satisfactory.
3. High level of illumination comparable to that in the shade of a tree or porch.
4. Time usually is not of great importance, if other factors are satisfactory.

Before considering the ideal printed page from a practical viewpoint, the process of reading should be considered. The focus of the eyes passes along the printed line in a series of leaps. Inasmuch as the movement of the eyes does not produce any apparent blurring, the eyes are assumed to be in some manner anesthetized during rapid motion. If one sees only when the eyes are at rest, the duration of the fixational pause is important. This has been found to vary chiefly between 0.07 and 0.30 second. These values are of importance in considering cases in which split seconds are important, but are merely of passing interest for the present.

Reading is done by swallows, as in drinking water. Words, or even groups of them, are seen at each pause. The number of stops made in reading a line depends upon visibility, familiarity, practice, and intelligence; consequently, the distinguishing of a critical detail, such as the space between the dot and the body of the letter *i*, may appear to be of little or no importance. Details remain of utmost fundamental importance, however, as typographical errors adequately testify. These details seem to dwindle in importance only through extensive practice in reading; in fact, seeing is very largely learning. Human beings learned to see things out in space before thinking became a conscious act.

## Components of the Perfect Reading Page

A scientific analysis of visibility and the results of seeing show that the fundamental factors already listed are the basis of ease of seeing and, therefore, of the perfect reading page.

By omitting some of the tedious steps in considering type size, 12-point type may be concluded to be quite satisfactory for continued reading. Newspapers commonly are set in 8-point type, with parts of them in 6-point type. These small sizes, combined with paper of poor quality and generally meager intensities of illumination, make newspaper reading a severe visual task. The effect of type style on legibility is a complex matter, but long experience has evolved satisfactory styles devoid of needless details and with an openness necessary for good legibility. Obviously, the size of type determines the amount of matter that can be printed upon a page. This is an important consideration for publications such as newspapers, but such economy in space should not be carried too far in journals, and particularly in books.

The contrast between the print and the page depends upon the blackness of the ink and the reflection factor of the paper. Perfect black on perfect white does not exist. This would be 100 per cent contrast as computed on the basis of the ratio

$$100 \times \frac{\text{Background brightness—Object brightness}}{\text{Background brightness}}$$

An article written especially for ELECTRICAL ENGINEERING.

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* SEEING—A PARTNERSHIP OF LIGHTING AND VISION (a book), M. Luckiesh and Frank K. Moss. Williams and Wilkins Company, Baltimore, Md., 1931.

Usually the nearest approach is a contrast of about 97 per cent. For a telephone directory the contrast between the print and paper commonly is about 80 per cent, and for the better examples of newsprint about 85 per cent.

Any color, even a light tint, added to white paper decreases the contrast slightly; however, the extent to which this decrease causes a decrease in visibility should be considered in weighing this against other considerations. There can be no justification for the use of highly colored paper for pages that must be read for extended periods; furthermore, from purely the optics of the eye, blue, violet, purple, and pink papers are inadvisable. Normal eyes cannot focus blue light at the usual reading distance. Adequate experiments have shown that elimination of the blue and violet components of light does not decrease visibility appreciably, because the resultant loss of light is compensated by increased definition of the image. For this reason alone, a yellowish tint is better than any other.

The loss in contrast is very slight in a white paper tinted yellow, and is less in ordinary artificial light than in daylight. Although contrast is very important in the visibility of objects, it is of only slight importance in the range of high contrasts; therefore, any other small advantage gained by the use of a paper of yellowish tint overcomes the loss caused by the slight decrease in contrast.

The reflection factor of a paper having a slight yellowish tint is a few per cent less than it would be if the tint were eliminated, thus reducing the brightness of the paper under a given intensity of illumination by an amount exactly proportional to the reduction in reflection factor. An appreciable change in visibility requires such a large change in brightness, however, that the reduction caused by a slightly lowered reflection factor is negligible, particularly when the intensity of illumination is sufficient for ease of seeing.

The perfect reading page, so far as the reader is concerned, depends upon lighting as well as upon the paper or printing. Glossy paper may reflect bright, imperfect images into the eye; dull paper is ideal, but if half tones must be considered, the practical ideal may be different. Dull papers nevertheless have been developed for halftone printing without too much compromise between the reader, printer, and paper manufacturer.

Ease of reading printed matter depends upon visibility, but manifests itself remotely from this. The writer and his colleague, Frank K. Moss, have measured successfully the nervous muscular tension indicated by the finger tips for a large number of subjects over a range of illumination intensities of from one to 100 foot-candles. One foot-candle, which is the illumination one foot from a candle, is a common illumination indoors. The general average in the indoor world is less than 5 foot-candles where reading is done. Near a window in the daytime there is commonly an illumination of several hundred foot-candles.

Experiments have indicated that while the subjects read a book printed in 12-point type on excellent dull, white paper, the ease of reading continues to increase up to at least 1,000 foot-candles. No one is conscious of this nervous muscular tension, except in special cases of difficult visual work; but it results from all visual work and represents waste of human resources. The 12-point type could be read at one foot-candle.

This and many other researches prove that ease of reading cannot be judged by visibility, and the mere possibility of seeing provides no reason for believing that further improvement in seeing is of no value. This new knowledge arose directly from an expansion of the concept of vision into one of seeing, and from a consideration of human seeing machines, instead of merely eyes.

Whether refinements of this new technique could show appreciable difference in the ease of seeing objects against a yellowish tint, as compared with a white one, is at present unknown; however, some other reasons for using a slightly yellowish paper seem to be adequate. It does not decrease visibility appreciably because of its slightly lower reflection factor and the consequent slightly lower contrast; moreover, its color is in the right direction from the viewpoint of chromatic aberration of the eye.

Aside from the foregoing considerations, the aesthetic or, more broadly, psychological effects are important. From an aesthetic point of view the author prefers a slightly yellowish tint, and many other persons have expressed a similar preference. Psychologically, the subtle warmth of the yellowish tint has something in its favor. White has much virtue in its place and, in fact, is symbolic of virtue; but white has disappeared from many places in which it dominated until a few years ago. Modern hospitals have eliminated it to a great extent, and modern kitchens and bathrooms have little of it. The decorative schemes of hospitals, kitchens, and bathrooms consequently have reverted to their proper function—to please aesthetically and psychologically.

## Electrical Engineering's "Easy Reading" Page

The reflection factors of the paper formerly used in ELECTRICAL ENGINEERING and of the present sepia-tinted paper are 76 and 73 per cent, respectively, for ordinary tungsten-filament light. The difference is slightly greater for daylight. Assuming the same quality of ink and printing, this difference is not sufficient to produce an appreciable difference in contrast. In fact, measurements made with the Luckiesh-Moss visibility meter of the visibility of print of the same size of type on the former and present papers revealed no significant difference; therefore, the change has been made with no appreciable sacrifice in measurable factors. In other words, whatever the gain (or loss) may be in the aesthetic comfort and possibly in physical comfort is achieved without other sacrifices. The appraisal of the factors that cannot be measured at present must be left to the readers. Their present, or initial, reactions will be interesting to compare with their reactions a few months hence. Certainly there is a striking difference in the appearance of the 2 papers, considering the slight difference in brightness or reflection factor. Many white papers have reflection

factors of from 80 to 85 per cent, and there would be an appreciable difference in the visibility of a given black print on them and on this sepia-tinted paper, which has a reflection factor of 73 per cent. The present discussion, however, refers to the paper formerly used and not to any other so-called white paper. Incidentally, all these measurements were made with papers backed up by several thicknesses, thus simulating actual reading conditions for a book or magazine.

Regardless of initial reactions to a yellowish-tinted paper, one should first give consideration to the general reaction against white. As to the influence of aesthetic and psychological effects upon the efficiency and behavior of human beings there can be no doubt on the part of those who understand that human beings are seeing machines. Feelings are just as real as any reality, and one can be just as unconscious of them as of other results of seeing, such as nervous muscular tension. To recapitulate, there is some scientific evidence, however slight, in favor of a paper of yellowish tint, and from the aesthetic and psychological viewpoints also it may have something in its favor. At any rate, knowledge springs both from controlled researches and mass experience. The present attempt to produce a perfect reading page provides opportunities for demonstrating or acquiring knowledge along these 2 general lines.

# Charles Le Geyt Fortescue

## and His Contributions to the Electrical Industry

By C. A. POWEL
MEMBER AIEE



CHARLES LE GEYT FORTESCUE will long be remembered as an engineer well-known for his technical achievements and well-loved for his qualities as a man. Some of his accomplishments have been so outstanding that it seems worth while calling attention to their value and to the extent to which they have been useful in extending human knowledge and lightening the labor of other engineers in his own and succeeding generations.

In the appreciation of the present generation of electrical engineers, Doctor Fortescue will be known for 3 principal fields of work. These probably would be his development of the method of symmetrical co-ordinates used for the solution of unbalanced polyphase circuits; his analysis of the factors affecting stability of transmission systems; and his philosophy of lightning protection and his contribution to the theory of direct strokes. A group of engineers a little earlier in time probably would credit him with his work in rationalizing the design of transformers; with his studies of dielectric phenomena which led to the adoption of the sphere gap as a standard of high voltage measurement; and with his work on the development of line insulators on the so-called "faradoid" principle.

These and many similar accomplishments indicate that his interests lay principally in the transmission of power and its related problems, a field which has expanded enormously since he entered the profession.

Fortescue was born at York Factory, Manitoba, Canada, November 11, 1876, where his father was chief factor of the Hudson Bay Company. He came of an old Devonshire family that as far back as the fifteenth century became prominent in literature. Educated at Dawlish, Devon, England, and at Queens University, Kingston, Ontario, Canada, he was Queens' first graduate in electrical engineering, and it used to be remarked that "they started with a good one." In recognition of his outstanding contributions to electrical engineering, his alma mater awarded him, in 1929, an honorary degree of doctor of laws. On graduation in 1898 he joined the Westinghouse Electric & Manufacturing Company at East Pittsburgh, Pa., where he remained throughout his professional career.

Doctor Fortescue became an Associate member of the AIEE in 1903 and was transferred to the grade of Fellow in 1921. He served on the following Institute committees: power transmission and distribution, 1925–29 and 1932–36; telegraphy and telephony (now communication) 1914–17; electrophysics, 1916–17, 1920, 1922–24, 1927–31. He was the author or co-author of 23 technical papers and numerous discussions published in the AIEE TRANSACTIONS over a period of 27 years.

Starting as an apprentice in the Westinghouse shop, he

Written especially for ELECTRICAL ENGINEERING.

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was quickly noticed by B. G. Lamme, who happened to be in need of a young assistant to devise new designs and new methods of building armature coils. The problem of meshing together the ends of armature coils—primarily a problem in 3-dimension geometry—was a fertile field in which the mathematically minded young engineer had full scope for imagination and for adapting theoretical schemes to practical necessities. His success in working out original short-cut methods of designing coils with short ends, requiring very little clearance, marked him as having ingenuity to an unusual degree, and he was transferred to the transformer department to see what could be done to rationalize the design of transformers, which at that time, as Fortescue himself used to say, "was more of an art than a science." His success in this work perhaps is best demonstrated by the section prepared by him for the "Standard Handbook for Electrical Engineers" which follows closely the principles developed by him in the years spent on this work.

About 1909 Fortescue became imbued with the importance of the dielectric field in transformers. He claimed that the so-called creepage effect was not a characteristic of the insulation surface itself but of the dielectric field in which the surface lay. Assisted by S. W. Farnsworth, development work was undertaken to prove or disprove this idea and to lay out a high-voltage transformer design in which the dielectric field was taken into account. This resulted in 2 very noteworthy papers published in the AIEE TRANSACTIONS of 1913:

AIR AS AN INSULATOR WHEN IN THE PRESENCE OF INSULATING BODIES OF HIGHER SPECIFIC INDUCTIVE CAPACITY by C. L. Fortescue and S. W. Farnsworth, pages 893–906.

THE APPLICATION OF A THEOREM OF ELECTROSTATICS TO INSULATION PROBLEMS by C. L. Fortescue, pages 907–25.

An important result of this research was the proposal that the sphere gap should be used as a standard for measuring high voltages. This was done in 2 papers, also published in 1913 in the AIEE TRANSACTIONS:

THE SPHERE SPARK GAP by S. W. Farnsworth and C. L. Fortescue, pages 733–7.

CALIBRATION OF THE SPHERE GAP VOLTMETER by L. W. Chubb and C. L. Fortescue, pages 739–48.

This proposal was accepted and today has become standard practice throughout the world.

About this time Fortescue turned his attention to railway electrification and the related power-supply problems. For heavy traction, the transmission lines and the trolley-rail circuits with their interconnecting transformers constituted a network of considerable complexity; and since there was then practically no literature on networks, he applied himself to their solution and formulated a number of network theorems. One of these was the theorem of equivalent loads by which a load at any point on a railroad could be replaced by 2 loads at adjacent substations inversely proportional to the impedance of the trolley-track circuit from the 2 substations to the actual load point. Another was that of superimposed solutions, which permits the determination of voltage drop to a given point by adding the separately computed voltage drops to that point due to loads at each of many load points. In the same way, the current in any branch of the network may be determined by adding the separately determined currents in that branch due to each particular load. These theorems are rigorously correct; they serve to reduce a complicated network to a very simple one, thus permitting one to make calculations in a very few hours that formerly would have required days.

Fortescue was active on the various a-c railway electrifications, including particularly those of the New York, New Haven and Hartford, Norfolk and Western, and Pennsylvania railroads, and did much to rationalize the design of railway power-supply systems and to set the reactance proportions which obtain at the present time. He gave attention to the problems of inductive co-ordination with communication and railway-signal circuits, and in connection with the latter he contributed the resonant impedance bond. He proposed several new schemes of phase balancing and phase conversion, and among others the series type of phase balancer which was the first scheme to provide balancing action without automatic devices such as voltage regulators.

It was while working on these unbalanced railway-supply circuits that Fortescue conceived the possibility of a mathematical analysis that led to the invention of symmetrical co-ordinates. In simple mathematical terms it consists of a system of generalized Lagrangian co-ordinates especially suitable to all types of polyphase problems. His paper

METHOD OF SYMMETRICAL CO-ORDINATES APPLIED TO THE SOLUTION OF POLYPHASE NETWORKS, AIEE TRANSACTIONS, volume 37, 1918, pages 1027–1115

is one of the milestones of the industry. This mathematical tool is now established in all countries as the only effective method of analyzing general polyphase network problems. For his development of this theory Doctor Fortescue received the Elliott Cresson Gold Medal of the Franklin Institute.

With the advent of the interconnection of power systems during and following the World War, Fortescue began to interest himself in the problems of the maintenance of synchronism over long transmission lines. Here again in his search for methods of simplifying the calculations he and his associates broke new ground by bringing out the so-called power-angle diagram which today is the form generally used for expressing stability.

Following the establishment of these interconnecting transmission lines, their principal drawback was found to be their susceptibility to outage due to lightning. This led Fortescue to turn his attention to the problem of methods of protection against lightning. In 1923, J. F. Peters, now consulting engineer of the Westinghouse company, brought out the klydonograph which was the first instrument suitable for field studies of lightning surges. With this device studies were made under the direction of Doctor Fortescue in co-operation with power companies, and the results of these gave a great deal of information regarding lightning surges which previously had been unsuspected. Thus encouraged, Fortescue undertook a further series of tests using the Norinder type of oscillograph,

the results of which confirmed the ideas Fortescue had been building up, and in a paper

THEORETICAL AND FIELD INVESTIGATIONS OF LIGHTNING, AIEE TRANSACTIONS, volume 48, 1929, pages 449–68

he promulgated his idea that induced strokes of lightning were not in general harmful to transmission lines and that protection against direct strokes was quite feasible.

Doctor Fortescue was a prolific inventor, the recipient of some 185 patents. Perhaps his outstanding characteristic as an inventor was his fondness for generalized theorization, which led him away from beaten paths and produced many inventions of fundamental and outstanding character, leaving to others the task of perfecting details as to methods for carrying them out. Among the important Fortescue patents might be mentioned those on the design of transformer windings to distribute properly the electrostatic stress through the insulation; thermoelectric protection of distribution transformers against burnouts and secondary short circuits; the high-voltage condenser-type bushing; shunt and series phase-balancers for railway systems; high-speed d-c circuit breakers with impulse tripping for d-c railways; the application of the "faradoid" principle to porcelain insulator design whereby the insulator surfaces were shaped to conform to the electrostatic field about the insulator; control grids for vapor-filled converters; and interphase transformers for vapor-filled converters.

His technical achievements, great as they were, did not account for his great popularity. He was human, sometimes beautifully inconsistent in little things. On a fishing trip he was complaining about lack of regulation in the United States which permitted any number of fishermen on a given stream. "Now in England," he said, "a stream like this would be fished by but one man who had bought the fishing rights on the stream." "Of course," rejoined another of the party, "you assume that you would be that one man."

He often worked on "hunches," but with the unerring instinct of genius. He had a feeling of what the answer to a problem should be and backed his "hunches" with logic. It is sometimes much easier to solve a problem backwards by assuming an answer.

His company always was sought. Aside from his wide technical interests, his reading and contemplations covered the arts and social sciences. An interesting conversationalist, "Forty," as he was familiarly known, always had a fresh and original point of view. He thoroughly enjoyed a story, both in the hearing and the telling. A favorite with old and young, his association with young engineers seemed to affect him as Ponce's waters and accounted for the enthusiasm that was so characteristically "Forty," even during the debility occasioned by his last illness.

His influence was felt in every group with which he worked. Doctor Joseph Slepian, now consulting research engineer of the Westinghouse company, has said that he received more inspiration from his contact with Fortescue than with any other man in the company. Working with a group, his personality was impressed both upon his work and upon his associates, frequently to the extent that a group's labor came to be associated only with the name of Fortescue. Outside engineers also sought his advice and counsel. His integrity and honest judgment enhanced still further his technical recommendations.

# 200-Inch Telescope Being Welded Electrically

## Mounting structure for the 200-inch telescope being built on Mt. Palomar, in Southern California, will consist of electric-arc-welded units

A BILLION light-years is the distance to which scientists and astronomers estimate that they will be able to explore the universe when the new 200-inch reflecting-type telescope, largest in the world, is completed on Mt. Palomar, Calif. This is twice the range of the next largest telescope in existence, the 100-inch instrument at Mt. Wilson, Calif. (A light-year is the distance traversed by light in a year and is approximately $6\times10^{12}$ miles.) Mt. Palomar, which is about 90 miles from Los Angeles, was selected because of its ideal weather conditions and its isolation. In addition to a new observatory to house the huge telescope, the project includes construction of a new 20-mile road, a new community for the operating staff, several smaller domes, power plant, radio station, million-gallon water reservoir, and an airplane landing field. Headquarters of the observatory will be on the campus of the California Institute of Technology, Pasadena, which institution will supervise its operation.

Originally conceived by Doctor George Ellery Hale in 1918, immediately following completion of the 100-inch Mt. Wilson telescope, actual work on the project began in 1928 when a grant of $6,000,000 was made by the Rockefeller Foundation. It is expected to be completed by 1940. The structure for supporting the telescope is being built in the South Philadelphia Works of the Westinghouse Electric and Manufacturing Company. It consists of

Prepared especially for ELECTRICAL ENGINEERING from information supplied by the Westinghouse Electric & Manufacturing Company, South Philadelphia (Pa.) Works, and particularly that compiled by J. Ormondroyd, experimental division engineer (now with University of Michigan, Ann Arbor) and Norman L. Mochel, metallurgical engineer.

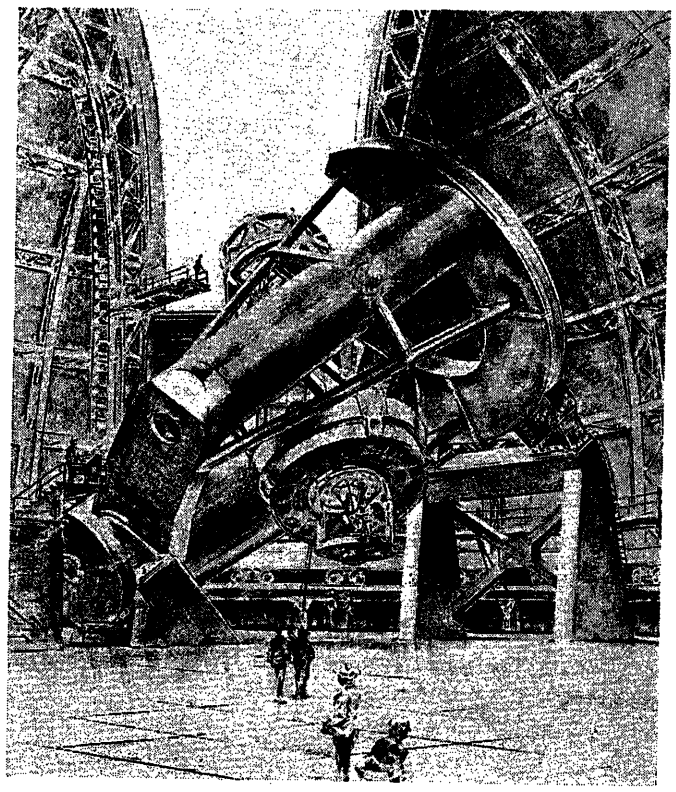


**Figure 1. Artist's conception of the 200-inch Mt. Palomar telescope as it will appear when completed**

several electric-arc-welded units which will be shipped by water to the Pacific Coast and thence by special trucks to the Mt. Palomar site, and which will be bolted together there. The 200-inch glass mirror, which will be the last unit to be installed in the telescope, is now being ground in the optical shop of the California Institute of Technology.

The magnitude of the 200-inch telescope perhaps can be understood best by comparing it with the 100-inch Mt. Wilson telescope (see table I). Its over-all height will be approximately 75 feet. The method of controlling the instrument has not been determined but, undoubtedly it will be electrical. Some conception of the control problem may be gained when it is realized that most of the observations to be made by the telescope will be upon photographic plates and that some exposures will require many hours each. The control mechanism must keep the telescope focused accurately throughout the entire period of exposure.

## Mounting Will Consist of 2 Main Parts

The mounting for the telescope will consist of 2 parts: a tube, and a cradle or yoke which will carry the tube (see figures 1 and 2). The tube, which will serve as the supporting structure for the principal optical elements, will rotate about 2 ball-bearing trunnions supported in the horseshoe-shaped yoke. Its range of rotation will be from the southern horizon to the north celestial pole. The axis around which it will rotate relative to the supporting cradle is known as the declination axis.

The yoke will turn about an axis that is perpendicular to the declination axis. This axis, lying in the meridian (north-south) plane, will be placed at an angle to the horizontal equal to the latitude of the observatory, which will make the axis parallel to the polar axis of the earth, and will point it toward the celestial pole. For this reason, this axis is called the polar axis of the telescope. The yoke will rotate 105 degrees to either side of the meridian plane.

These 2 rotations around the polar and declination axes will permit the telescope to be held on any celestial object within its range. Continuous rotation about the polar axis at the rotational speed of the earth, but in the opposite direction, will keep the tube oriented at a fixed angle relative to the "fixed stars."

The polar-axis bearings, which support the yoke, will be unique in telescope design. To insure smoothness of rotation, the whole million-pound telescope will be floated on oil under high pressure, at both the north and south ends. At the north end the "horseshoe" will be supported on 4 pads. In the surface of each pad will be 4 symmetrically spaced recesses with central oil inlets. Oil flowing through these inlets at a pressure of from 250 to 300 pounds per square inch will support the telescope. Oil will flow continuously through a gap of from 0.003 to 0.005 inch between the pad surface and the outer periphery of the "horseshoe." At the south end, the single bearing will be a ball and socket 8 feet in diameter with oil inlets so spaced that the radial and thrust loads of the telescope will be supported with the ball held about 0.005 inch away from the socket.

The total viscous friction torque of these 2 bearings at the operating speed of one revolution per day will be of the order of 50 foot-pounds. This figure becomes remarkable only when it is realized that conventional roller and ball bearing supports would lead to a friction torque of 30,000 foot-pounds, 600 times the oil-pad friction torque. The smallness of this friction is emphasized by the fact the telescope can be kept rotating at one revolution per day by the amazingly small output of about 1/160,000 horsepower. For quick setting, however, a driving motor of at least $^1/_2$ horsepower will be required.

**Table I. Comparison of 200-Inch Mt. Palomar and 100-Inch Mt. Wilson Telescopes**

| Item | Mt. Palomar | Mt. Wilson |
|---|---|---|
| Type of telescope | Reflecting | Reflecting |
| Diameter of mirror, inches | 200 | 100 |
| Approximate weight, pounds | 1,000,000 | 125,000 |
| Approximate cost, dollars | 6,000,000 | Less than 1,000,000 |
| Fabrication of structure | Welded | Riveted |
| Focal length of mirror, inches | 666 | 500 |
| Relative aperture | 3.33 | 5 |
| Yoke bearings | Oil pad | Mercury float |
| Maximum range, light-years | *1,000,000,000 | 500,000,000 |

*Estimated.

## Arc Welding Being Employed Throughout

The decision to employ arc welding so extensively in the construction of the tube and mounting of the 200-inch telescope is another outstanding example of the engineer's confidence in the welding art. There is nothing of an experimental nature, however, in the adoption of welded construction for the various members of the telescope. Other structures of comparable size and complexity, and of like value and importance, have been fabricated successfully by this method.

Steel plates, bars, structural shapes, and a few steel forgings are being welded together to form the member parts of the telescope. The size and shape of these member parts naturally reflect the general design, but have also been influenced by such practical considerations as the availability of material, machining facilities, transportation, and the necessity for minimizing internal stresses and resulting distortions.

It must be understood that the various member parts are being prepared by machining for bolting together at Mt. Palomar. Frequent references to all-welded construction may have given the erroneous impression that member parts were to be joined on location by welding. It is true that in many large structures, member parts have been and are being joined by welding on location. In such structures, however, the construction and intended service invariably are such as to tolerate distortions that may take place during welding or during the useful life of the structures, or in which the presence of variable and unknown degrees of internal stress are of little concern. Obviously such conditions could not be tolerated in the 200-inch telescope.

In any discussion of welding, one is naturally interested in the materials that must submit to welding. Again one encounters an erroneous impression—that a telescope must be constructed largely of special alloys that have low expansivity. Although it is true that some materials of this type are being used in connection with the mirror and other optical parts, most of the material being used for the tube and mounting is quite ordinary mild carbon steel. All the materials being welded are of standard commercial grades—an important practical consideration.

All plates, bars, and structural shapes have been rolled by one supplier from specially selected heats, to give the greatest possible uniformity of composition. Plates less than $1^1/_2$ inches thick were made of the usual flange quality of steel plate, similar to that covered by ASTM Specification *A*-70. All such steel for the tube was made from a single heat, specially melted for the purpose. Plates $1^1/_2$ inches thick and more were rolled from silicon-killed steel poured into hot-top ingots, to guarantee soundness of section. This steel is similar to grade *A*, ASTM Specification *A*-150. Two carbon-molybdenum steel forgings are being

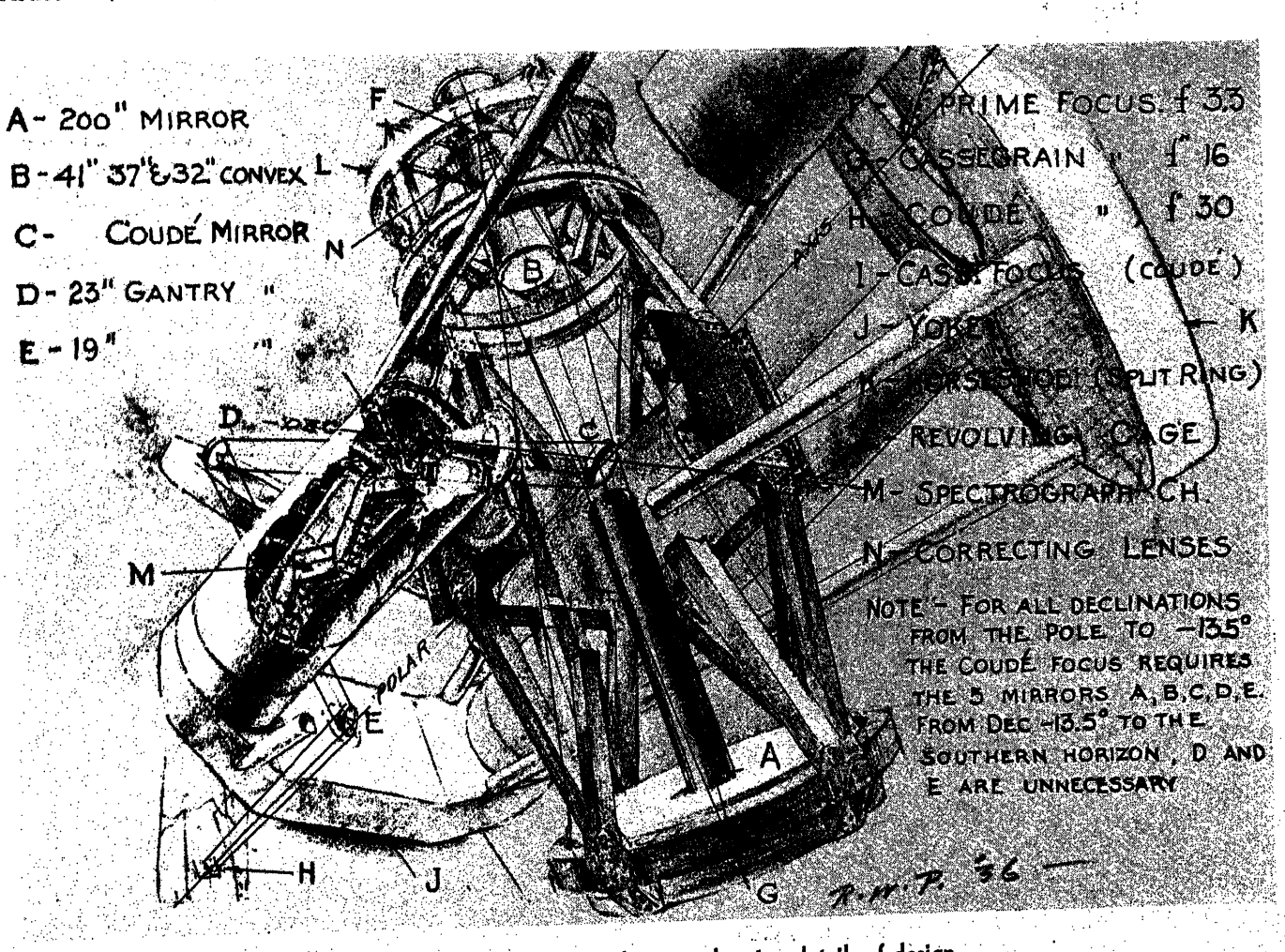



Figure 2. Diagram of telescope showing details of design

used in fabricating the declination bearing housing.

Arc welding only is being employed, and heavily coated electrodes of the mineral-coating or slag-producing type are being used. These are of but 2 makes, both of the highest quality available. It is well recognized today that electrodes can be devised that will meet best some given condition of deposition. Full advantage of this has been taken and 3 kinds of electrodes, as regards position of deposition, have been used. One was used for all down-hand butt welds; another for all down-hand or horizontal fillet welds; and yet another for welds that of necessity had to be made in a vertical position. Overhead welding has been avoided. The electrodes are of such nature that they are equally satisfactory with either d-c or a-c welding apparatus. Both are being used throughout; a-c welding was found to be especially useful for welding into corners.

All welding on the tube parts and to date on the "horseshoe" has been manual welding. The 2 declination-bearing housings were produced using automatic welding for the longitudinal and external circumferential welds.

Figure 3 shows a stage in the fabrication of the prime-focus cage. The lower main ring of the cage was formed on the floor plate and the uprights, formed elsewhere as detail parts, were assembled as shown. The ring is approximately 22 feet in outside diameter and the cage is roughly 12 feet long with the top ring in place. The gauge for controlling the proper radius and for accurately locating the pieces of tubing that are in evidence, may be noted. The simple method for supporting and clamping the ring both inside and out is shown. The use of intermittent welding may be noted in most of the parts.

Figure 4 shows work in progress in the fabrication of one of the end sections of the "horseshoe." This "horseshoe" has an outside diameter of approximately 46 feet. The plates used to form the inner and outer bands were preformed, and are $4^1/_2$ inches thick and 60 inches wide. One side plate was formed first. This plate was then clamped down and the inner and outer bands moved into position and clamped around the outside. Clamping blocks were welded to the bands as shown. The internal plates and reinforcing members were fitted in place and secured by tack welding. After properly fitting the cellular or box-like structures that fasten to the outer band and fixing the various component parts by welding a bar across them, they were removed from the main part and welded under the most ideal conditions on the floor. This had a double advantage: It permitted turning them in any position to get the best welding, and it avoided undue heating and stressing of the main members by the considerable amount of welding necessary. There are 5 of these sub-assemblies, 2 of which are shown in place in figure 4.

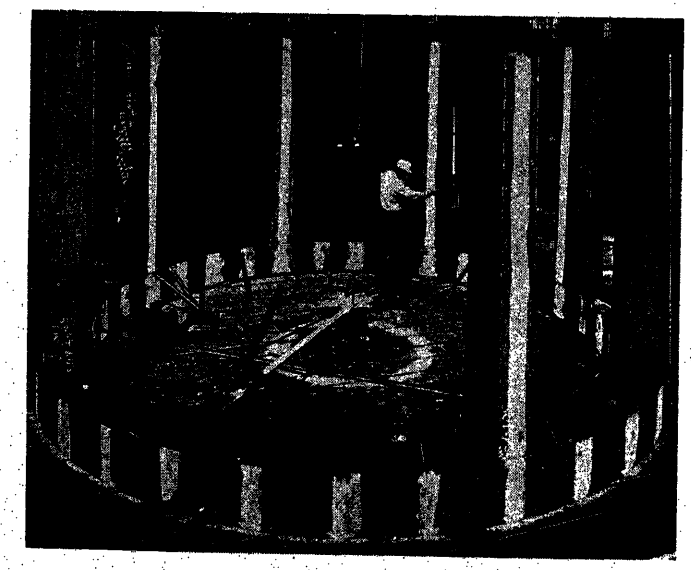


**Figure 3. Fabrication of bottom ring and uprights of prime-focus cage. Note that clamping blocks, struts, and stays are attached exactly where wanted by welding; they are readily removed later**

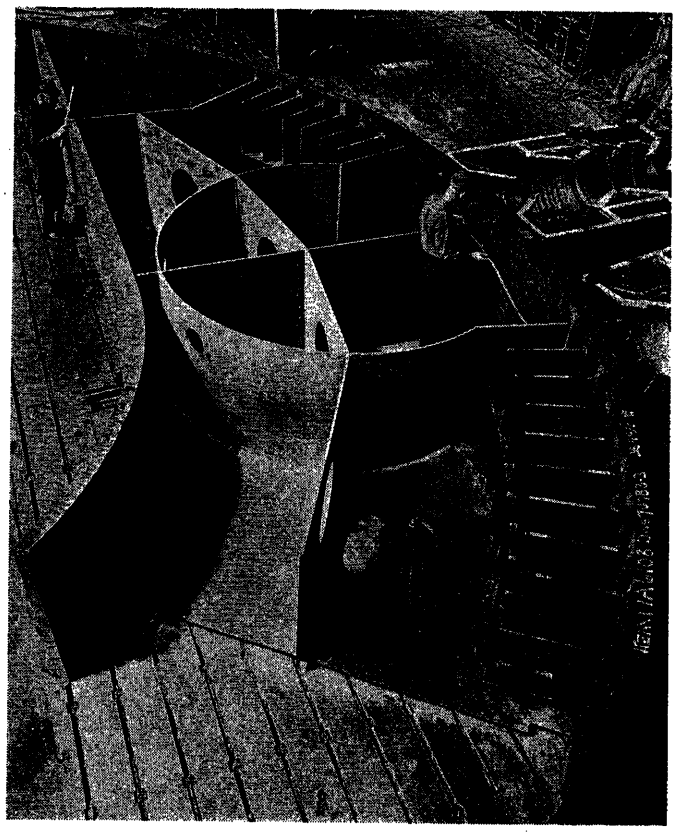


**Figure 4. Early stage in fabrication of one section of the yoke "horseshoe"**

All the telescope parts are being carefully annealed to relieve internal stresses. A double annealing cycle is being used: first heating to from 1,150 to 1,200 degrees Fahrenheit, holding for a period of 3 hours for the first one inch of thickness or fraction thereof, followed by a slow cooling in the furnace until the temperature has fallen below 600 degrees Fahrenheit; and then repeating this cycle in its entirety and cooling below 300 degrees Fahrenheit before the furnace doors are opened.

As an example of the accuracy with which the parts were held to size throughout welding and annealing, when the prime-focus cage was placed on the boring mill to face the lower end where it bolts to the top ring of the tube, the departure from roundness was not greater than $^1/_{16}$ inch.

# Electrical Computer Eliminates Calculations

**Based upon an exact electrical analogy of a mechanical system, a specially constructed electrical computer eliminated many laborious calculations in designing the overhead catenary system for an extensive railroad electrification**

By FRED H. HEDIN
ASSOCIATE AIEE

MANY engineering applications involve the solution of numerous laborious and repeated calculations of a similar nature. The design of the overhead catenary for an extensive railroad electrification, which is typical of such applications, involves the determination of the shape of a messenger cable for thousands of spans that differ only in length and in the location and values of the supported loads. During the design of a recent railroad electrification, a squad of from 15 to 20 men were continuously employed by the engineers on such calculations for a period of about 2 years. Both the volume and required accuracy of these calculations led to a search for some simple computing device whereby the most monotonous part of the calculations might be eliminated and the progress of the work expedited. The purpose of this article is to describe the computer which was developed for this purpose.

## The Problem

As is well known, the contact wire of a catenary system is supported directly or indirectly by means of hangers from a messenger cable, which in turn is supported at intervals of from 200 to 300 feet on structures transverse to the tracks. For the modern high-speed electrification, where heavy currents are collected at speeds of the order of 90 miles per hour by means of the sliding contact of a pantagraph, it is of paramount importance that the riding contact wire be in nearly a horizontal plane, or if a change in elevation is necessary, that the change be smooth and gradual.

On tangent track, with no special work such as crossovers or turnouts, the computation of the shape of the loaded messenger, for the purpose of selecting hanger lengths to give a smooth-riding contact wire, is comparatively simple. Tables or templates are used, as the load is distributed uniformly and there is practically no error in the assumption that the messenger takes a parabolic shape.

However, at interlocking points and yards, the problem is much more difficult. The intersection of the catenary from different tracks, as well as the design of air breaks for sectionalizing purposes, requires that the contact wire be raised or lowered with respect to its normal riding datum, with resultant changes in messenger loading (since the contact wire is itself under high tension). Also the concentrated loads of sectionalizing insulators, which may amount to several hundred pounds, must be carried. The resultant shape of the messenger, under the various concentrated and distributed loads that may exist in a span, is no longer a smooth and simple mathematical curve and must be calculated by the laborious step-by-step moment method. The various spans usually have different loadings because of physical obstructions in locating structures and variations in existing track layout.

Not only are the computations laborious and monotonous, but they consume much time because of the added necessity for checking. It is difficult and very expensive to make field correction, because of the flexible nature of the catenary and because the installation may be made under an extreme temperature condition, which affects the messenger shape.

A typical span, selected from thousands of similar ones, is shown in figure 1(*a*). The messenger loading and shear diagrams also are shown in figure 1(*b* and *c*).

The problem therefore was essentially this: Given a flexible cable, strung at known tension, over a known span, between fixed supports, and subject to known vertical loads, at known points in the span; to develop a simple and accurate device to determine, quickly and automatically, the reactions at the supports and the complete shape of the cable. Further, the device must be equipped to handle variations in the given factors of tension and span length, as well as direction, location, and number of vertical loads.

## Evolution of the Circuit

During the course of the search for a fundamental basis for such a computing device, the following analogy was visualized, more or less accidentally: First, referring to figure 2 (*a*), consider the simple case of a messenger of span $L$ and given horizontal tension $T$, subjected to a single concentrated load $W$ at any point in the span. Then the part of the load $W$ carried at each messenger support (reactions), and the shear in the messenger is as shown. Then, consider the electrical analogy as shown in the simple circuit figure 2 (*b*). A resistor of any length, and of any uniform resistance per unit of length, has a current $I$ supplied to it at the same relative point in its length as the mechanical load is in the messenger span.

Written especially for ELECTRICAL ENGINEERING.

FRED H. HEDIN is with Municipal Civil Service Commission, New York, N. Y., as examiner, electric railroad.

If the 2 ends of the resistor (or current divider) are tied together to a common return circuit, then the division of the current is as shown.

By comparison of (*a*) and (*b*) of figure 2, it is at once apparent that a useful analogy exists. The mechanical load $W$ seems to divide and "flow" to each messenger support, exactly as though the messenger were a uniform resistance connected as shown in (*b*). Therefore, it can readily be seen that if a constant value of pounds per ampere is assumed, and if an ammeter is calibrated directly in pounds on that basis and connected as $A_3$ in figure 2 (*c*) and 2 similarly calibrated ammeters are inserted in the circuit as $A_1$ and $A_2$, and if the input (or "load") current is regulated by resistance $R$ so that $A_3$ reads $W$ pounds; then $A_1$ and $A_2$ will read, directly in pounds, the reactions $R_1$ and $R_2$.

This analogy was based upon the simplest kind of a span with only one concentrated load. The question that now naturally arises is whether the division will be made correctly should additional currents be supplied simultaneously to other points of the resistance divider, to represent other concentrated loads on the messenger. The messenger itself acts to distribute the various concentrated loads to each support exactly as though each load were acting alone on the messenger, the summation of each individual load's reaction being the total reaction at that support. It can be demonstrated by rigid proof that the electrical circuit as shown acts in an identical manner. This proof is somewhat involved for the purpose of this article, but it can be visualized partially by noting that, although there are various $IR$ drops in various parts of the resistance divider due to the application of several "loads," nevertheless, if any point in the divider is considered as a point of application for still another "load," the total potential drop from the proposed point of application to either end of the divider tube is the same. Thus the existence of other "loads" on the resistance divider does not affect the correct distribution of a proposed additional "load" and only serves to require a little more "push" to get the load into the divider. This extra "push" is provided by cutting out a slight amount of additional resistance in the load-applying circuit. Since this resistance always is regulated to produce the correct "load" reading on the ammeter in its circuit, the final position of this uncalibrated load-regulating resistance is not important.

Another interesting fact revealed by comparing (*a*) and (*b*) of figure 2 is that the current distribution in the divider is identical with the shear diagram for the messenger. The current even reverses its direction at the same point as the shear passes through zero. This analogy is true for any number of applied loads on the messenger if corresponding "load" currents are supplied to the resistance divider.

From the foregoing facts, one more step now is possible. In a messenger span under given tension, the sag at various points is proportional to the total moment at these points. The moment involves load and length (moment arm). Similarly, the voltage drop from any point on the resistance divider to either end is dependent on the current (load) and resistance (length) of the section. Therefore it might be surmised that a definite relation exists between the sag at a given point on the messenger and the voltage drop from the end of the properly loaded resistance divider to a corresponding point on the divider. If this is investigated mathematically, the following formula results:

$$V = wpkT \times \text{sag in feet}$$

where

$p$ is the relation between the length of the span and the length of the resistance divider in feet.
$k$ is the amperes per pound used to calibrate the load and reaction meters.
$w$ is the ohms per foot of the resistance divider.
$T$ is the messenger tension.

The constants $w$ and $k$ may be incorporated in the calibration of the volmteter; the factors $p$ and $T$, which are constant for a given problem but may vary in different problems, are calibrated into the voltmeter for the maximum span length and minimum tension (i.e., maximum sag) that are likely to occur. Then the voltmeter reading is reduced by a variable series resistor, calibrated in the ratio of tension to span length, for computing other problems involving greater messenger tension or shorter span, or both. Thus, the voltmeter will read the sag directly in feet if one end is permanently connected to the ends of the resistance divider and the other end arranged to contact the divider at any point where the corresponding messenger sag is desired.

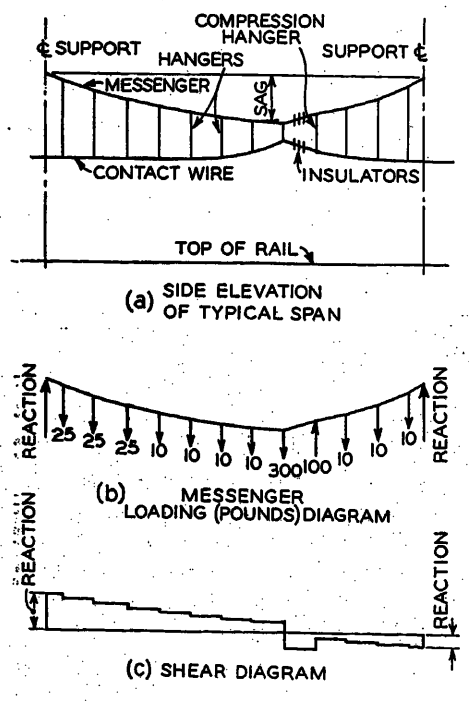



**Figure 1. Typical catenary span to be solved on computer, showing construction, messenger loading, and shear diagrams**

## Construction of Computer

A computer was designed and constructed according to the described electromechanical analogy. The complete wiring diagram is shown in figure 3, and the completed computer is shown in figures 4 and 5.

A choice of design constants was available, and the

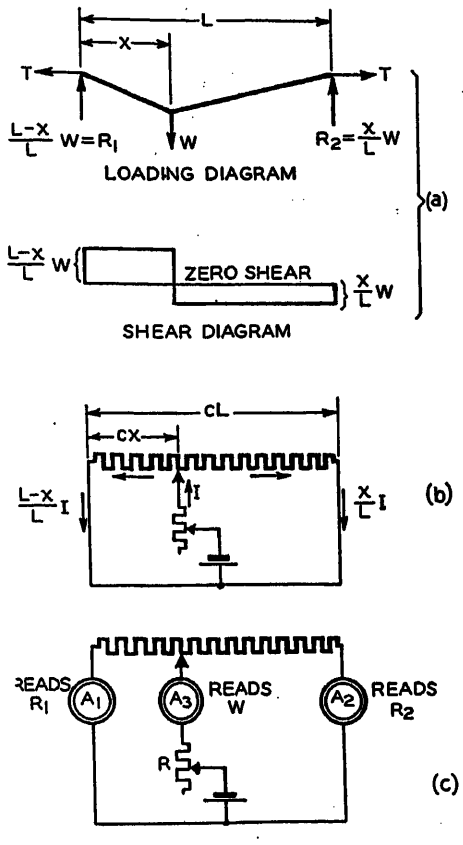



**Figure 2. Elementary analogy between a loaded cable and the simple electrical circuit shown**

design was evolved from the usual balance of one against the other. A special effort was made to locate controls and meters so as to give a visual picture of the loaded messenger, for ease in manipulation.

The main problem was to secure extremely sensitive meters. The voltmeter must have unusually high resistance because its current requirement acts as a "load" on the divider. Any resistance in the reaction ammeters causes, in effect, an extension of the length of the divider resistance. The divider scale is extended beyond the actual ends of the divider to eliminate any such error, but any appreciable extension of this scale would result in a "blind spot" for the application of "loads" that are close to the messenger supports. Also the load current and divider resistance had to be kept as low as possible to avoid heating and to keep the size of the computer within reasonable bounds. Special meters having cobalt steel magnets to give very high sensitivity were needed to obtain close accuracy in the solution of this problem.

As shown in figure 3, sliding contacts were used for applying the "load" currents to the divider. Although in general sliding connections are not satisfactory for good contact, it should be noted that, because of the inherent features of the circuit, no error is produced if the contact resistance varies slightly from day to day as the correct current still is supplied by the "load" circuit since it is read directly on the ammeter.

It should be noted also that, although the computer could be designed so that the divider scale is calibrated directly in feet of span, this would require that the connection to one end of the divider be a sliding connection. As any change in contact resistance of this slider would materially affect the proper division of current and would not be readily apparent, it was decided to incorporate the span length factor into the voltmeter multiplier circuit.

## Operation and Results

A systematic method of operating the computer was developed. Standard data forms were printed and given to the men laying out the catenary design. This form was provided with a tabular arrangement for listing in order: (1) the value and direction (up or down) of the messenger loads, starting from the left support; (2) the respective distances of these loads from the left support in per cent of the total span; (3) the total load carried by the messenger; and (4) the ratio of tension to span length. For use of the computing-machine operator, space was provided for listing: (1) the sag at each load point, and (2) and (3) the reactions $R_1$ and $R_2$. A separate sheet was used for each span and labeled with the numbers assigned

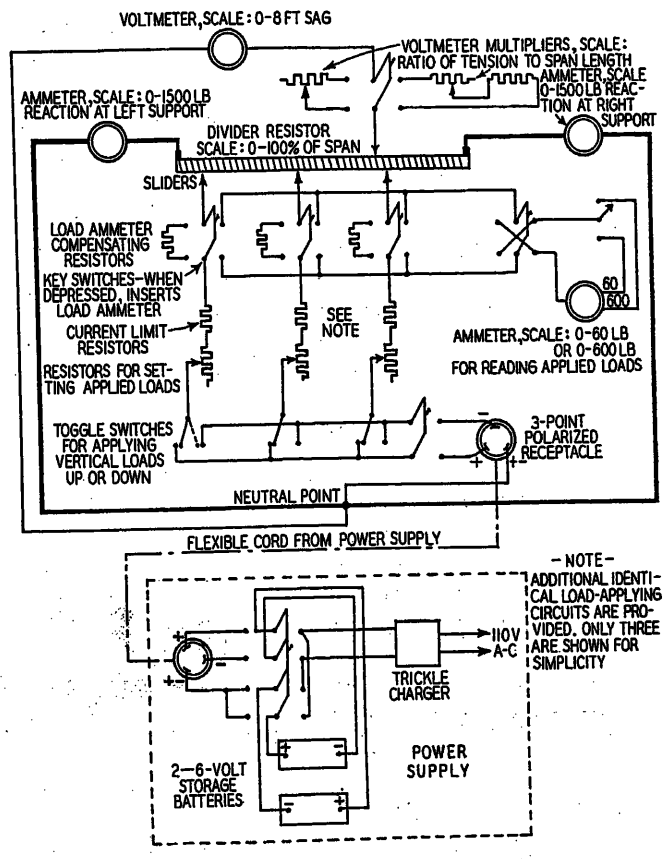



**Figure 3. Wiring diagram for the computer as built, showing the added arrangements for ease in operation**

to the particular messenger and structures involved. At various times, these sheets were collected from all the designers and given to the computing machine operator. He then set up the problems on the machine and completed the data sheets from the meter readings. The completed sheets were returned to the designers and the data used to calculate hangers.

The computing-machine operator's procedure, for a

given span, is as follows (see figures 3 and 4): With the data sheet as a guide, the operator sets the load sliders, in order from left to right at their given percentage locations on the divider scale. Then the toggle switches for the directions of the various loads are set, starting from left to right, from the data sheet (the loads are usually downward). The extreme left load ammeter key then is depressed, inserting the load ammeter in the extreme left slider circuit, and the corresponding load regulating resistor is adjusted until the load ammeter reads the given messenger load nearest the left support. The load ammeter key then is released and returns to its normal position, leaving the first load set and the ammeter available for setting the next load. The load is set for the next slider location in the same way, and the procedure is repeated for all the required load circuits. The divider now is completely "loaded."

Without further manipulation, the reactions may be read, immediately, on their respective meters and noted on the data sheet. The 2 reactions as read on the meters are added, and their sum should exactly equal the total messenger load given on the data sheet. This is practical proof that no mistake has been made in setting the various loads. Although it is possible that compensating errors may give the same result, the chance of such errors is so remote that results may be considered entirely satisfactory.

Without changing the load setup, the next step is to set the voltmeter multiplier scale on the tension-to-span ratio given on the data sheet. Then the sags, which determine the shape of the messenger, are read directly (in feet) from the sag voltmeter by successively moving its slider to the load locations on the divider scale. The sag at any other point in the span may be read by moving the voltmeter slider to the corresponding point on the divider scale. The controls then are brought to zero, and the computer is ready for another problem.

The computer requires very little intelligence to operate and no mechanical or electrical knowledge. It is practically foolproof, and the operator can use it continuously for long periods without going "stale" as he may with continuous mathematical calculations.

Results obtained with the computer have been very satisfactory. Accuracy has been of the order of $1/4$ per cent, which is equal or better than that obtained by slide rule.

The most important gain has been in saving time. A careful check has shown that the computations for a span are completed in an average time of 5 minutes on the computer and are self-checking; the same computation, done "by hand" requires approximately 40 minutes including checking time by a higher-salaried designer. One computer and one operator can handle these computations for a large squad of designers.

## Other Problems Can Be Solved

The most common practice at present is to use stranded cables between guyed columns as supporting structures for the catenary, instead of beams or trusses. The only difference between the solution for the shape of these messengers and the longitudinal messengers, is that the former is designed for constant sag for different spans rather than constant tension. The shape of these cross-span messengers also is solved on this computer as built, with only a slightly different manipulation of the tension-to-span ratio multiplier.

Many other mechanical problems may be solved on slightly different computers involving essentially the same circuit and analogy. It illustrates one more surprisingly exact analogy between electrical and mechanical laws.

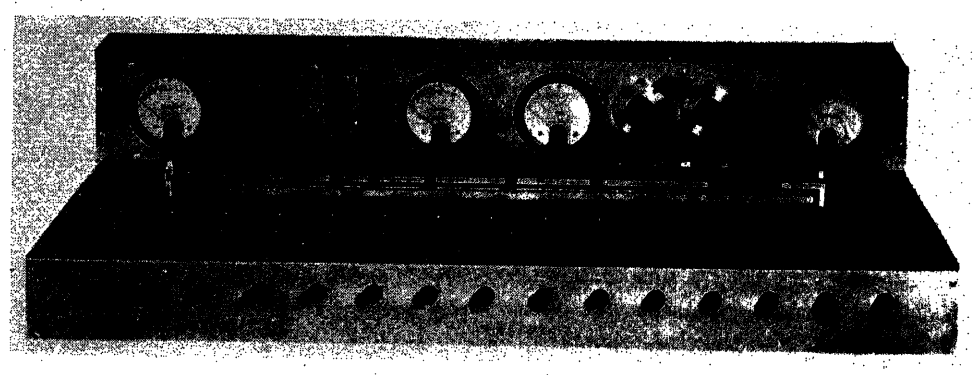


Figure 4 (above). Front and top view of the computer as built, showing compactness and logical location of apparatus for ease in visualizing problem

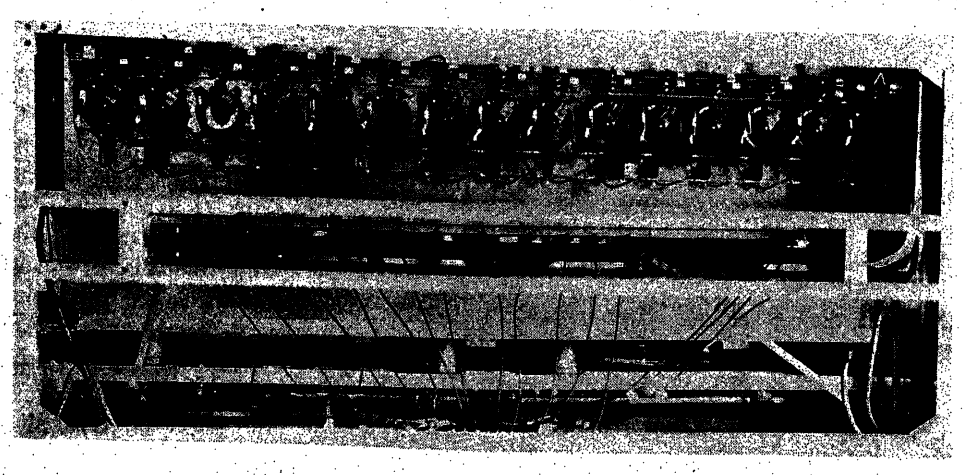


Figure 5 (left). Bottom view of finished computer, showing compact arrangement of wiring and equipment

# Report of the Board of Directors

THE BOARD OF DIRECTORS of the American Institute of Electrical Engineers presents herewith to the membership its fifty-third annual report, for the fiscal year ending April 30, 1937. A general balance sheet showing the condition of the Institute's finances on April 30, 1937, together with other detailed financial statements, is included herein. This report contains a brief summary of the principal activities of the Institute during the year, more detailed information having been published from month to month in ELECTRICAL ENGINEERING.

## Board of Directors' Meetings

During the year, the board of directors held 5 meetings, 4 in New York City, and 1 at Pasadena, Calif. The executive committee meetings in December and March were held in place of regular meetings of the board. Information regarding many of the more important activities of the Institute which have been under consideration by the board of directors and the committees is published each month in the section of ELECTRICAL ENGINEERING devoted to "News of Institute and Related Activities."

## President's Visits

President MacCutcheon attended the winter convention and the South West District meeting. He also visited many Sections, and a considerable number of educational institutions in their vicinities. In several cases, he addressed assemblies of engineering students, while in other cases he spoke at meetings of the AIEE Student Branches.

The places visited are listed below:

**Alabama**
- Alabama Section, Birmingham
- Alabama Polytechnic Institute, Auburn
- University of Alabama, Tuscaloosa

**California**
- Los Angeles Section
- San Francisco Section
- University of California, Berkeley

**Colorado**
- Denver Section
- University of Colorado, Boulder

**Connecticut**
- Connecticut Section and Yale University, New Haven

**District of Columbia**
- American Engineering Council, Washington

**Florida**
- Florida Section, Jacksonville, Gainesville, and Miami
- University of Florida, Gainesville

**Georgia**
- Atlanta Section
- Georgia School of Technology, Atlanta

**Idaho**
- University of Idaho, Moscow

**Illinois**
- Chicago Section

**Maryland**
- Baltimore Section and student convention

**Massachusetts**
- Boston Section
- Lynn Section
- Springfield Section
- Worcester Section
- Worcester Polytechnic Institute, Worcester

**Michigan**
- Detroit-Ann Arbor Section

**Minnesota**
- Minnesota Section, Minneapolis

**Missouri**
- Kansas City Section
- St. Louis Section

**Montana**
- Montana Section
- Montana State College, Bozeman

**New York**
- New York Section
- Winter Convention, New York City
- Board of Directors Meetings, etc.

**North Carolina**
- North Carolina Section, Raleigh
- Duke University, Durham
- North Carolina State College, Raleigh

**Ohio**
- Akron Section
- Columbus Section

**Oklahoma**
- Oklahoma City Section

**Oregon**
- Portland Section

**Pennsylvania**
- Erie Section
- Philadelphia Section
- Pittsburgh Section
- Sharon Section

**Rhode Island**
- Providence Section and Brown University

**South Carolina**
- Columbia
- Clemson Agricultural College, Clemson

**South Dakota**
- District No. 6 Conference on Student Activities, Brookings

**Tennessee**
- East Tennessee Section, Knoxville and Chattanooga

**Texas**
- South West District meeting, Dallas
- Houston Section and Rice Institute

**Utah**
- Utah Section, Salt Lake City
- University of Utah

**Virginia**
- Virginia Section, Richmond

**Washington**
- Seattle Section
- Spokane Section
- State College of Washington, Pullman

**Wisconsin**
- Madison and Milwaukee Sections in Milwaukee
- Summer convention committee, Milwaukee

**Canada**
- Toronto (Ont.) Section
- Vancouver (B. C.) Section

During May and June, President MacCutcheon will visit the Cincinnati, Ithaca, Lehigh Valley, Cleveland, and Rochester Sections, and Massachusetts Institute of Technology Branch, and will attend the North Eastern District meeting, Buffalo, N. Y., and the summer convention, Milwaukee, Wis.

## National Conventions

Two national conventions were held during the year, and a brief report on each follows:

*Summer Convention.* The fifty-second summer convention was held at Pasadena, Calif., June 22–26, 1936, combined with the twenty-fourth Pacific Coast convention. Forty-two technical papers were presented at 9 sessions, and 10 student papers at 2 additional sessions. Six technical conferences were held. Other parts of the convention were the annual business meeting of the Institute, conference of officers, delegates, and members, an address by Doctor R. A. Millikan, golf and tennis tournaments, president's reception and dance, banquet, and ladies' events. The Lamme Medal for 1935 was presented to Doctor Vannevar Bush, of Cambridge, Mass. The registration was 715.

*Annual Meeting.* The annual business meeting of the Institute was held on Monday morning June 22, as part of the opening session of the summer convention. The annual report of the board of directors for the fiscal year ending April 30, 1936, was presented in abstract, the committee of tellers reported upon the election of officers for the administrative year beginning August 1, 1936, and a financial report was presented by National Treasurer W. I. Slichter. President-Elect MacCutcheon responded to the announcement of his election with a brief address.

*Winter Convention.* The twenty-fifth winter convention, held in New York City, January 25–29, 1937, was

opened by a brief general session including an address of welcome by C. R. Beardsley, chairman of the winter convention committee, an address by President MacCutcheon, and a brief announcement regarding the technical sessions by H. S. Osborne, chairman of the technical program committee. President MacCutcheon announced the award of the Alfred Noble Prize for 1936 to Abe Tilles, instructor in electrical engineering at the University of California. During the 13 sessions held, 56 papers were presented. At an evening session, the Edison Medal was presented to Doctor Alex Dow, and John C. Parker, vice-president, Consolidated Edison Company of New York, Inc., gave a lecture on "Power and People." Numerous inspection trips aroused keen interest. The registration was 1,165.

## District Meetings

Two District meetings were held during the year and brief reports follow.

*North Eastern District Meeting.* Held in New Haven, Conn., May 6–9, 1936, with a registration of more than 300 members, students, and guests. The program consisted of 11 technical papers, 4 special addresses, 9 student papers, inspection trips, and entertainment events.

*South West District Meeting.* The sixth South West District meeting was held in Dallas, Texas, October 26–28, 1936. Thirteen technical papers and several special addresses were presented at 5 technical sessions, and 9 student papers at 2 student sessions. A special address was given by Doctor Matthew Luckiesh at a luncheon meeting held jointly with the Dallas Electric Club. There were also numerous inspection trips and entertainment events. The total registration was 533, including 179 students.

## Sections

The activities of the Sections during the past year were outstanding in several respects, particularly with respect to the unusually large total number of meetings held, and the extensive efforts to determine and arrange for meetings of types of special interest to the members.

Seven or more meetings were held by each of 46 Sections, and only 4 Sections held fewer than 4 meetings. There was a great increase in interest in technical groups, special technical meetings, technical lectures, technical committees, discussion groups, and other arrangements desired by Section members. Twenty Sections conducted meetings of these special types in addition to the regular Section meetings. Six Sections offered courses of instruction on engineering subjects. Several Sections held local group meetings at points distant from regular meeting places.

Interest of the Sections in student activities was shown by the holding of the usual joint meetings with Branches, the sponsoring of student conventions, etc.

The East Tennessee Section was organized on September 2, 1936, under authority granted by the board of directors on May 25, 1936, including as its territory approximately the eastern half of the state. Dinner meetings were held in Knoxville and Chattanooga on September 18 and 19, respectively, with excellent attendance and much enthusiasm.

The final report of the special committee to revise Section territories, appointed by action of the board of directors in 1935 to develop plans for extending Section territories and the formation of new Sections to include in so far as practicable all parts of the United States, was presented at the meeting of the board of directors held on January 27, 1937, and the actions recommended were approved, the changes in territories to become effective August 1, 1937. The changes will bring within Section territories nearly one-half of the few hundred members now outside.

Detailed information on these activities may be found in the annual report on Section and Branch activities in the June issue of ELECTRICAL ENGINEERING, pages 762–5.

## Student Activities

Under authority granted by the board of directors at its meeting held on January 26, 1937, the Columbia University Branch was organized on February 19, and the Tulane University Branch was organized on March 1, bringing the total number to 119.

The total number of meetings reported exceeds that for any previous year, and the total number of talks by students is practically equal to the largest number previously reported. However, a considerable number of Branches reported less than a normal number of meetings and no talks by students.

Students have shown an increasing interest in the opportunities to take active parts in the technical programs of national conventions and District meetings. One student technical session was included as part of the North Eastern District meeting in New Haven, 2 such sessions were held during the combined summer and Pacific Coast conventions in Pasadena, and 2 such sessions were held as parts of the South West District meeting in Dallas. The quality of the content and the presentation of the student papers inspired many favorable comments by Institute members.

The terms of enrollment of 1,253 students expired on April 30, 1937, and 674, or about 54 per cent, applied for admission as Associates. The percentage during the past few years has been approximately 50.

**Table I. Section and Branch Statistics**

| | For Fiscal Year Ending | | | |
|---|---|---|---|---|
| | April 30, 1931 | April 30, 1933 | April 30, 1935 | April 30, 1937 |
| **Sections** | | | | |
| Number of Sections | 59 | 60 | 61 | 62 |
| Number of Section meetings held | 491 | 498 | 521 | 621 |
| Total attendance | 108,523 | 73,806 | 73,381 | 74,950 |
| **Branches** | | | | |
| Number of Branches | 109 | 111 | 117 | 119 |
| Number of Branch meetings held | 1,137 | 1,026 | 986 | 1,363 |
| Total attendance | 51,807 | 59,439 | 36,629 | 46,121 |

More detailed information on these activities appears in the annual report on Section and Branch activities in the June issue of ELECTRICAL ENGINEERING, pages 762–5.

## Section and Branch Statistics

Data on the Sections and Branches are given in table I.

## Technical Program Committee

The work of the technical program committee may be considered under 3 general topics: arranging for technical programs under the present established procedures; studying alternative arrangements as to program building and publication of papers to determine whether any constructive recommendations can be made; and in co-operation with other committees making arrangements for general meetings at Institute conventions.

### ARRANGEMENTS FOR TECHNICAL SESSIONS

Under the present unified publication policy, all papers for national conventions (except special addresses) and all approved discussions are published in ELECTRICAL ENGINEERING. The space allotted to the technical program committee for the current year (1,115 pages) is approximately $^2/_3$ the space used by the committee 6 years ago. Under these conditions it is naturally impossible to meet all of the desires of the technical committees for sessions and for presentation of papers. For the summer convention, 18 technical sessions were proposed, 10 scheduled, and 8 postponed or rejected. Twenty-eight per cent of the papers submitted are rejected or withdrawn because of abbreviation or other modifications required for acceptance. Other papers, the number of which, of course, is not known, are not offered to the Institute because of these conditions.

During the past 12 months, there have been 2 national conventions (the summer convention and Pacific Coast convention being consolidated into one) and 2 District meetings. At these 4 meetings, 122 papers have been presented. Every effort has been made by the technical program committee to have the meetings at the national conventions and, in co-operation with the District committees, the District meetings as well, cover the wide range of interests of the Institute membership. In general, the papers have been of high grade, upholding the tradition of the Institute as to the high quality of the material presented at its meetings. The committee has continued to encourage the conference type of session at which papers and discussions are presented without publication. Ten such conference sessions were held during the 2 national conventions.

### ALTERNATIVE ARRANGEMENTS FOR TECHNICAL PROGRAMS

The field of Institute activities, namely, "the advancement of the theory and practice of electrical engineering and of the allied arts and sciences" is diverse and rapidly expanding. In spite of the very considerable provision made by the Institute for the publication and presentation of papers, it is natural that the programs should still be possible of improvement. Some members of the Institute feel that more time and space should be given in Institute programs to subjects of broad general interest including questions in which engineering and social science are jointly involved. On the other hand, many members would like more opportunity for a discussion at Institute meetings of specialized technical subjects on the frontier of immediate technological advance.

It may be questioned whether a mere extension of the program with present procedures as to publication and presentation is the best way to take care of this constant trend toward expansion. Furthermore, the unified publication policy which has served the Institute admirably during the period of depression has certain disadvantages both from the standpoint of program making and of publication. It requires relatively long intervals between the preparation and presentation of papers and involves the distribution in printed form to all members of the Institute of all technical papers, many of which are of interest to only a small proportion of the members.

With these facts in mind, the technical program committee has appointed a subcommittee which is actively studying the whole problem of procedures relating to Institute meetings. It is hoped that based upon these studies the technical program committee will, before the expiration of its term, be able to make specific recommendations for the consideration of next year's committee.

### GENERAL MEETINGS

In response to may suggestions regarding the desirability of having as a part of Institute conventions meetings of broad general interest, arrangements have been made for such a meeting at the summer convention in Milwaukee. The first part of the meeting will consist of an address on the subject "The Engineer in a Changing World," by Doctor Ralph E. Flanders, who is an authoritative speaker on the relations between engineering and economic problems. The second part of the meeting will include a general discussion by the members of the Institute on the subject "How Can Institute Programs Be Made of Greatest Value to the Membership?"

Arrangements for this general session have been made by a special committee consisting of the chairmen of many of the principal committees of the Institute. Based upon the results of this meeting, the special committee will make recommendations to the board of directors regarding the advisability of having similar meetings at future Institute conventions.

## Publication Committee

Throughout the year effort has been made to improve the usefulness of ELECTRICAL ENGINEERING to the membership by including more articles of a general interest type.

The initial budget included an extra appropriation specifically for this purpose, so that the publication of highly technical papers would not have to be curtailed to permit the publication of general interest articles. At the January meeting of the board of directors, a further

specific appropriation was granted to cover the publication of general interest articles.

In requesting this latter appropriation, the publication committee defined the scope of general interest articles as follows:

Timely review articles on various phases of electrical engineering, feature articles by men prominent in the Institute or in other fields of scientific and engineering endeavor, reprints of important electrical engineering papers originally published in English abroad, reprints of important papers published in this country in other fields of engineering, and appropriate general articles on economics and the status of the engineer written by outstanding men; also at times interpretive abstracts of important and highly technical papers published in full elsewhere in ELECTRICAL ENGINEERING; possibly also some English translations of important electrical engineering papers published originally in a foreign language.

Starting with the January issue ELECTRICAL ENGINEERING acquired "The Easy-Reading Page." Based on scientific studies and in the interests of reader comfort, the typography, the paper, and the ink have been selected to provide a nonglare easy-reading page. Many letters have been received commenting favorably on this change.

In general, the unified publication plan adopted by the board of directors in August 1933 has been followed.

## Membership Committee

The work of the membership committee has followed along much the same lines as it has for the past 2 or 3 years. Probably the most important change has been the increased responsibility given to the District vice-chairmen of the committee in connection with the Section membership committees in each District. The vice-chairmen have done an excellent job, and together with the very good co-operation given them by the Section committees, have made possible a report that shows marked improvement in the Institute's membership analysis. The entire membership has again given the committees much assistance this year by suggesting that certain nonmembers be approached. A new pamphlet was prepared, published, and, though written for membership work mainly, it was placed in the hands of every member of the Institute. It is titled, "Membership in the American Institute of Electrical Engineers."

The changes that have occurred in the Institute's membership totals during the year are given in table II. The most interesting figures are those that give the change in total enrollment. There is shown a gain of 708 which is more than twice the gain reported a year ago, the first year of increase since the business depression. There was a good increase in the number of "new members qualified," and the decrease of the members "dropped" column is encouraging. The number dropped this year is 526 compared with 797 last year.

The number of applications received increased again, as shown in table III, by about 11 per cent. The increase of some 13 per cent in Student applications for transfer, and the increase in applications for Student membership, as well as in the total Student enrollment (see table IV) are all very encouraging.

Table V shows a steady decrease in delinquent reinstatements for the past 2 years. This is as it should be since the total number of delinquents has been reduced considerably over the past 2 years. There are 1,869 owing dues on April 30, 1937, as recorded in table VI. The same figure last year was 2,154. The figure of 460

**Table II. Membership Statistics for the Fiscal Year Ending April 30, 1937**

| | Honorary | Fellow | 6-Year Member | Associate | Associate | Total |
|---|---|---|---|---|---|---|
| Membership on April 30, 1936 | 11 | 699 | 3,912 | 5,679 | 4,299 | 14,600 |
| **Additions** | | | | | | |
| Transferred | 1 | 27 | 182 | 571 | | |
| New members qualified | | 6 | 150 | 40 | 1,285 | |
| Former members reinstated | | 2 | 17 | 37 | 42 | |
| | 12 | 734 | 4,261 | 6,327 | 5,626 | 16,960 |
| **Deductions** | | | | | | |
| Died | 2 | 19 | 26 | 32 | 4 | |
| Resigned | | 2 | 34 | 135 | 91 | |
| Transferred | | 1 | 24 | 165 | 591 | |
| Dropped | | 3 | 59 | 204 | 260 | |
| Membership on April 30, 1937 | 10 | 709 | 4,118 | 5,791 | 4,680 | 15,308 |

**Table III. Number of Applications Received From Enrolled Students and From All Others**

| Year Ending | From Students | From All Others | Total |
|---|---|---|---|
| April 30, 1937 | 716 | 1,040 | 1,756 |
| April 30, 1936 | 631 | 946 | 1,577 |
| April 30, 1935 | 575 | 715 | 1,290 |
| April 30, 1934 | 467 | 496 | 963 |
| April 30, 1933 | 674 | 305 | 979 |

**Table IV. Number of Enrolled Students**

| | |
|---|---|
| April 30, 1937 | 4,503 (2,249) |
| April 30, 1936 | 4,049 (1,991) |
| April 30, 1935 | 3,806 (1,983) |
| April 30, 1934 | 3,186 (1,548) |
| April 30, 1933 | 3,260 (1,494) |

Following the number of Students reported for April 30 of each year is indicated within parentheses the number of new applications received during that year; the difference between this number and the reported total, of course, reflects the number of renewals of Student enrollment for the corresponding period.

**Table V. Number of Members in Section Territory Reinstated**

| | |
|---|---|
| August 1, 1936, to April 30, 1937 | 460 |
| Year beginning August 1, 1935 | 663 |
| Year beginning August 1, 1934 | 831 |
| Year beginning August 1, 1933 | 741 |
| Year beginning August 1, 1932 | 277 |

**Table VI. Membership of the Institute, April 30, 1937**

Of the 15,308 members reported for April 30, 1937, 13,439 are fully paid to April 30, 1937. The balance of 1,869 are divided into the following groups:

| | |
|---|---|
| 1. Members owing dues to April 30, 1936. Total number of members who have not acted upon resolution of board of directors adopted in January 1937 providing an extension of time for payment of these dues | 505 |
| 2. Members owing dues to April 30, 1937 | 1,364 |

(During the period May 1 to 25, 1937, 311 members have paid dues to April 30, 1937, reducing the total to 1,053).

### Table VII. Memberships Fully Paid

| | Membership as of April 30 | Number of Members Fully Paid as of April 30 | Per Cent Fully Paid |
|---|---|---|---|
| 1937 | 15,308 | 13,439 | 87.8 |
| 1936 | 14,600 | 12,446 | 85.2 |
| 1935 | 14,260 | 11,512 | 80.5 |
| 1927 (year of maximum membership) | 18,344 | 16,247 | 88.5 |

### Table VIII. Record of AIEE Membership

| Total Membership May 1 | | Total Membership May 1 | | Total Membership May 1 | | Total Membership May 1 | |
|---|---|---|---|---|---|---|---|
| 1884 | 71 | 1899 | 1,133 | 1913 | 7,654 | 1927 | 18,344 |
| 1885 | 209 | 1900 | 1,183 | 1914 | 7,876 | 1928 | 18,265 |
| 1886 | 250 | 1901 | 1,260 | 1915 | 8,054 | 1929 | 18,133 |
| 1887 | 314 | 1902 | 1,540 | 1916 | 8,202 | 1930 | 18,003 |
| 1889 | 333 | 1903 | 2,229 | 1917 | 8,710 | 1931 | 18,334 |
| 1890 | 427 | 1904 | 3,027 | 1918 | 9,282 | 1932 | 17,550 |
| 1891 | 541 | 1905 | 3,460 | 1919 | 10,352 | 1933 | 17,019 |
| 1892 | 615 | 1906 | 3,870 | 1920 | 11,345 | 1934 | 15,200 |
| 1893 | 673 | 1907 | 4,521 | 1921 | 13,215 | 1935 | 14,269 |
| 1894 | 800 | 1908 | 5,674 | 1922 | 14,263 | 1936 | 14,600 |
| 1895 | 944 | 1909 | 6,400 | 1923 | 15,208 | 1937 | 15,308 |
| 1896 | 1,035 | 1910 | 6,681 | 1924 | 16,455 | | |
| 1897 | 1,073 | 1911 | 7,117 | 1925 | 17,319 | | |
| 1898 | 1,098 | 1912 | 7,459 | 1926 | 18,158 | | |

in table V is not directly comparable with the others since it represents only a 9-month period, but the same figure for the same period last year was 608, which indicates a definite trend.

Table VII shows the percentage of fully paid membership to be within less than 1 per cent of the highest figure ever recorded. An increase of 2.6 per cent over last year should give additional encouragement to the members.

Table VIII gives an interesting record of the Institute's growth since its founding in 1884.

## Deaths

The following deaths occurred during the year:

*Honorary Members:* Elihu Thomson, Edward Weston.

*Fellows:* James R. C. Armstrong, Charles L. Fortescue, William D. Gherky, Stephen Q. Hayes, Halbert P. Hill, William B. Jackson, Samuel M. Kintner, Frank A. Laws, Edward B. Meyer, D. McFarlan Moore, George R. Murphy, Louis C. Nichols, Louis F. Reinhard, Albert S. Richey, Robert A. Ross, Frederick A. Scheffler, George C. Shaad, Arthur Williams, Fremont Wilson.

*Members:* Clinton J. Axtell, Allan Cunningham, Frederick S. Cutting, William A. E. Doying, Albert G. T. Goodwin, William K. Hale, Charles E. Hebbert, William A. Hillebrand, Joseph D. Israel, Hamilton McR. Jones, Philip A. Lang, Adolf J. Lobeck, Meldon H. Merrill, Elam Miller, Henry A. Morss, Robert E. Orr, Hugh Pattison, Albert T. Perkins, Arthur J. Ralph, Crandall Z. Rosencrans, Lester R. Sailer, John A. Sirnit, Guy S. Turner, William S. Twining, William F. White, Russell A. Yerxa.

*Associates:* Eugene L. Alexander, Alfred Alsaker, James D. Andrew, Walter E. Bare, Frederick H. Barrington, Irving F. Day, Burton L. Delack, William H. Dieringer, John C. Dolph, Francis E. Donohoe, William G. Ely, Paul Engleheart, William H. R. Fraser, Harry W. Fuller, Nicholas S. Hill, John Jenkinson, Ed. C. Jerman, David H. Kelly, Edgar Knowlton, Edward F. Lawton, Robert Lundell, Frank G. McRae, Julius Meyer, Jesse B. Millard, Thomas E. Penard, John W. Purcell, John A. Rockwood, A. W. Russell, Charles J. Russell, Thomas Spencer, Harry B. Thayer, Carroll Thomas, Earle Lamar Tyler, Hugo Vecera, Francis R. Welles, Charles V. Woodward.

## Board of Examiners

The board of examiners held 10 meetings during the past year, averaging about $2^1/_2$ hours each, and considered 3,787 cases, divided as shown in table IX.

## Standards Committee

The activities of the standards committee for the past year reflect the general upturn in the engineering field with increased interest in standardization activities. The AIEE committees, as well as the sectional committees under the American Standards Association, have been extremely active. Much of this activity has had to do with needed revisions and suggested further development of existing standards.

For instance, the AIEE committee on applications to marine work is preparing an extensive revision of Standard No. 45, "Recommended Practise for Electrical Installations on Shipboard" (Marine Rules). These rules have been in general use without change since 1930. The committee on protective devices submitted to the standards committee 2 reports, one dealing with a proposed revision of "Oil Circuit Breaker Standards," No. 19, now before a sectional committee working under ASA procedure, and the other a new project, "Fuses Above 600 Volts." Both were ordered printed and circulated in report form.

The AIEE committee on instruments and measurements presented a report giving latest revised data on sphere-gap spark-over voltages. This was published by order of the standards committee in ELECTRICAL ENGINEERING so that it might become generally available. Eventually, these data will be included in a general revision, now being developed by the same committee, of Standard No. 4, "Measurement of Test Voltages in Dielectric Tests."

Renewed activities in the development of the test code

### Table IX. Applications for Admission and Transfer

| | | |
|---|---|---|
| **Applications for Admission** | | |
| Recommended for grade of Associate | 1,077 | |
| Re-elected to the grade of Associate | 112 | |
| Not recommended | 3 | 1,192 |
| Recommended for grade of Member | 113 | |
| Re-elected to the grade of Member | 20 | |
| Not recommended | 38 | 171 |
| Recommended for grade of Fellow | 3 | |
| Re-elected to the grade of Fellow | 1 | |
| Not recommended | | 4 |
| **Applications for Transfer** | | |
| Recommended for grade of Member | 167 | |
| Not recommended | 27 | 194 |
| Recommended for grade of Fellow | 24 | |
| Not recommended | 2 | 26 |
| **Students** | | |
| Recommended for enrollment as Students | | 2,200 |
| Total | | 3,787 |

series have also taken place during the past year. An informal session was held during last winter's convention for the discussion of the codes. As a result a revised edition of both the synchronous and the induction machines codes will be issued, and a new code added to the series on d-c machines. The standards committee delegated to the committee on instruments and measurements the development of a code for measurements. Likewise the subcommittee on sound has offered for approval a "Code for Apparatus Noise Measurement."

Many of the ASA sectional committees on which the Institute has representation have been similarly increasingly active. The sectional committee on transformers is about to issue a very complete report on transformers. This will embody not only the revised and enlarged standards themselves, but will include as appendices, the test code and guides for operation of transformers. The sectional committee covering graphical symbols, letter symbols, and abbreviations, has been completely reorganized and is now revising the standards developed by its predecessor. The sectional committee on insulated wires and cables is about ready to issue a series of both revised standards and new ones. These represent only a few of the active sectional committees.

The Institute's co-operation through the standards committee was sought in several general fields. An appointment was made of a representative on a research committee on grounding to study the whole situation. Representation was also had on a committee on radio-electrical co-ordination, a field whose scope and possibilities will require much careful co-operative study and co-ordination work. The most recent development was the committee on international standardization of photometric units to which appointment was made on invitation of the National Bureau of Standards.

It might be well to point out in closing that there seems to be a general tendency under ASA procedure for sectional committees to issue reports in which are combined not only standards, but much related material. This is of particular interest from a historical viewpoint. When development was proposed by the Institute of codes and operating recommendations in particular much opposition was incurred and argument offered opposing such activity. Finally, approval was obtained on the basis that such reports when issued must be entirely distinct from the accepted standards. Evidently, a better understanding of the subject matter has eliminated opposition to such projects.

## U.S. National Committee of the IEC

The past year has been an active one for the International Electrotechnical Commission for a year in which no plenary meeting has been held. The commission has been saddened by the deaths of two of its honorary presidents, Professor Elihu Thomson and Professor Paul Janet of France. The loss sustained by these 2 deaths will not be easily forgotten.

Meetings of advisory committees as follows were held during the year: storage batteries—number 21, aluminum—number 7, radio communication—number 12, electrical installations on shipboard—number 18, and international electrotechnical vocabulary—number 1. In addition, the international special committee on radio interference held a meeting.

President Burke has continued to devote his attention to the financial affairs of the commission, so that the commission ended its fiscal year on January 1 in the most favorable financial position which it has enjoyed for a number of years.

Meetings of the following advisory committees will be held in Paris June 17–23, 1937:

Rating of electrical machinery, transformer section only—number 2

Standard voltages and currents and high voltage insulators—number 8

Electric traction equipment—number 9

Electrical measuring instruments—number 13

It is expected that the U.S. national committee will be represented at these meetings by a good delegation, which will be headed by President Sharp. In addition, there will be held in Paris, June 30 to July 3, an international conference on acoustics. The purpose of this meeting will be to make plans as to the handling of a comprehensive program of standardization in the acoustic field. The conference will be held under the auspices of the IEC, but it is not yet certain as to how the international acoustical work will be set up. The work originally was proposed to the IEC by the international consultative committee on telephony (CCIF), and it is now contemplated that the work will include definitions, units, notations, graphical symbols, methods of measurement and measuring apparatus, including noise meters, electrotechnical acoustics, recording transmission and reproduction of sound (except telephony), architectural acoustics, noise abatement, etc. Acoustical work in the United States is well advanced, 3 important standards in the field having been approved as American standards. The sectional committee in charge of the work is a most authoritative and representative body. The U.S. national committee is accordingly in an excellent position to take care of this work on behalf of American industry. The U.S. national committee will be represented at the meetings by President Sharp, Doctor Harvey Fletcher, and probably others.

The following reports of progress in specific technical projects will be of interest:

INTERNATIONAL ELECTROTECHNICAL VOCABULARY—NUMBER 1

This work was undertaken by the IEC soon after its formation in 1904. It has now progressed to the point where it is planned to publish the first edition during 1937. The vocabulary will contain over 2,000 scientific and industrial terms used in the various branches of electrotechnics. The terms are given in both English and French, and translations of the title are given in German, Italian, Spanish, and Esperanto.

The whole work is divided into 14 sections, the first of which covers fundamental and general definitions. The others more specifically deal with: machines and transformers; switchgear and control gear; apparatus for scientific and industrial measurements; generation, transmission, distribution; electrical traction; power applications; thermic applications; lighting; electrochemistry; telegraphy, telephony; radiology; electrobiology.

While the committee developing this "International Vocabulary" appreciates that it does not constitute a complete unification of electrotechnical nomenclature, it believes that through periodic review and revision based on the constructive criticism of electricians of the world, it should become increasingly valuable to engineers.

As the edition will be limited, copies should be reserved at once by writing to the U.S. national committee of the International Electrotechnical Commission at 29 West 39th Street, New York. The price of the "Vocabulary" will be about $2.50.

STEAM TURBINES—NUMBER 5

The secretariat for this project is held by the U.S. national committee, and during the year they prepared an appendix to IEC Publication No. 46, "Rules for Acceptance Tests for Steam Turbines —Supplementary Notes to Section 4, Instruments and Methods of Measurement," which was sent to the central office during the year for circulation for final approval under the 6-months rule. Active work is now going forward on expanding the rules to cover non-condensing back pressure extraction and mixed pressure turbines.

INSULATING OILS—NUMBER 10

The U.S. national committee appointed a representative on an international subcommittee to draw up an ideal testing procedure for determining the sludging properties of insulating oil. This work is going forward.

TERMINAL MARKINGS—NUMBER 16

During the year the American standard on rotation, connections and terminal markings for electric power apparatus was approved and printed. This document has been transmitted to the central office to become the American part of the international specifications for terminal markings.

SWITCHGEAR—NUMBER 17

During the year the draft IEC specification for a-c circuit breakers was studied by the U.S. national committee, and approved for service as an international standard. It is expected that the revised edition will be published shortly. During the year IEC Publication No. 54 ("IEC recommendations for standard direction of motion of operating devices and for indicating lamps for circuit breakers") appeared in printed form.

ELECTRIC CABLES—NUMBER 20

During the year IEC specifications for tests on impregnated-paper-insulated lead-covered cables having voltages from 10 kv to 66 kv were considered and discussed. The U.S. national committee had technical objections to these rules, and voted against their issuance. However, these objections were withdrawn with the understanding that an immediate revision of the rules would be undertaken.

The next plenary meeting of the International Electrotechnical Commission is scheduled to be held in England, June 1938.

## Committee on Safety Codes

The committee submitted proposals for expanding the scope of its activities in order that it might study technical and engineering problems in connection with the safer use of electricity. The present by-laws limit the committee to matters connected with safety codes which for years have been handled by other organizations. After consideration by the Institute policy committee and the board, no formal action was taken on the proposal for enlarged scope. However, the board is interested in the possibility that the Institute within its proper scope may make further contributions to the cause of safety and has invited the committee on safety codes to make further suggestions to this end. The committee is preparing to comply with the board's invitation in the immediate future.

The chairman of the committee on safety codes, as the AIEE representative, attended the annual meeting of the electrical committee of the National Fire Protection Association. At this meeting the biennial revision of the national electrical code was made.

The chairman represents the Institute on the committee on low voltage hazards of the National Safety Council but was called upon for no action during the past year.

The chairman attended the annual meeting of the National Fire Waste Council in Washington. Little of electrical engineering interest is considered at these meetings.

## Co-ordination Committee

The committee followed the established practice of requesting District and Section officers to submit by January 1 applications for the authorization of any national conventions and District meetings desired in their respective Districts during the calendar year 1938, and a recommended schedule of such meetings has been presented to the board of directors and approved.

## Institute Policy Committee

The Institute policy committee has considered and reported upon 2 broad questions referred to it by the board of directors.

The first of these was the question of the possible enlargement of the scope of the committee on safety codes. A report was submitted to the board of directors generally endorsing the proposal and suggesting a review with specific suggestions from the committee itself.

The committee has also reported to the board of directors on the recommendation of the committee on research that the Institute contribute financially to the support of such researches as the Institute may recommend, under its sponsorship, to the Engineering Foundation. An extensive study was made of this question, and a report was submitted to the board of directors indicating a divided opinion within the committee, and the consequent inability to make a recommendation either for or against the proposal.

Two resolutions submitted to the board of directors, one proposing the establishment of the office of executive vice-president, and the other proposing an additional man, for further development of the work of the Institute committees, to be added to the staff of the national secretary, have been referred to this committee and are now under examination.

## Special Committee to Consider Dues of Associates and Related Matters

A final report of this committee was presented to the board of directors recommending no changes in the present

rules and dues. This was received and approved and the committee discharged.

## Committee on Code of Principles of Professional Conduct

During the year a number of points were raised by nonmembers of the committee and these points were presented by letter to the committee members. In no case has any member of the committee urged that any change be made in the present code of principles of professional conduct.

## Committee on Constitution and By-Laws

This committee had no meetings, as no matters had been referred to it until in the latter part of the year, when it was requested to consider several proposed amendments to the constitution and by-laws of the Institute.

## Committee on Economic Status of the Engineer

The committee has conducted a somewhat limited but pertinent study of the economic status of the engineer as it affects his ability to earn an income commensurate with his needs and his value to the welfare of mankind. This study has disclosed much information in reports made by various organizations interested in education. It is hoped a further study of these data will confirm the impression that in general engineers have "weathered" the depression pretty well.

This committee recommends activity on the part of engineers in seeking channels other than the AIEE through which they may take active part in educating the public regarding affairs of significance to our economic welfare which involve engineering works. For further information on this point, attention is called to the papers obtained by the special committee on Institute activities which will be presented and discussed at the summer convention.

## Committee on Award of Institute Prizes

Five national prizes and 13 District prizes for Institute papers presented in 1935 were awarded to the authors. These awards were announced in the 1936 issues of ELECTRICAL ENGINEERING for June and July.

The committee has made a careful study of a number of suggestions for changes in the rules for the award of Institute prizes. As a result they have recommended certain changes which have been adopted by the board of directors. These changes provide that in the future the national prize for Branch papers shall be based upon the college year, i.e., July 1 to June 30 inclusive, rather than the calendar year as at present. They also provide for a District prize for graduate student papers. A revised issue of the rules for the award of prizes including these changes is now being printed.

## Committee on Award of Columbia University Scholarships

By arrangement with Columbia University, this committee of the AIEE has the privilege of awarding each year a scholarship in electrical engineering for each class, the amount covering the annual tuition fees of $380.

As a result of improving business conditions, no definite application for the scholarship for the academic year 1936–37 was received.

## Edison Medal

The Edison Medal, which is awarded by a committee composed of 24 members of the Institute, was, for 1936, awarded to Doctor Alex Dow for "outstanding leadership in the development of the central station industry and its service to the public," and was presented on January 27, 1937, during the winter convention. The medal may be awarded annually "for meritorious achievement in electrical science, electrical engineering, or the electrical arts."

## John Fritz Medal

The John Fritz Medal board of award, composed of representatives of the national societies of civil, mining, mechanical, and electrical engineers, awarded the thirty-third medal (for 1937) to Arthur Newell Talbot, professor emeritus of engineering, University of Illinois, who was cited as "moulder of men, eminent consultant on engineering projects, leader of research, and outstanding educator in civil engineering."

## Lamme Medal

The Lamme Medal committee awarded the medal for 1936 to Doctor Frank Conrad "for his pioneering and basic developments in the fields of electric metering and protective systems." Arrangements are being made for the presentation of the medal at the annual summer convention at Milwaukee, Wis., June 21–25, 1937. The medal may be awarded annually to a member of the AIEE "who has shown meritorious achievement in the development of electrical apparatus or machinery."

## Alfred Noble Prize

This prize, established in 1929, consists of a certificate and a cash award of $500 from the income from a fund contributed by engineers and others to perpetuate the name and achievements of Alfred Noble, past-president of the ASCE and of the Western Society of Engineers. It may be made to a member of any of the co-operating societies, ASCE, AIME, ASME, AIEE, or WSE, for a technical paper of particular merit accepted by the publication committee of any of these societies, provided the author, at the time of such acceptance, is not over 30 years of age. The award for 1936 was presented to Abe Tilles, instructor in electrical engineering at the University of California, Berkeley.

## Washington Award

The Washington Award for 1937 was bestowed upon Doctor Frederick Gardner Cottrell, "for his social vision in dedicating to the perpetuation of research the rewards of his achievements in science and engineering," and was presented to him on February 23, 1937. This award may be made annually to an engineer by the commission of award composed of 9 representatives of the Western Society of Engineers and 2 each of the American Society of Civil Engineers, American Institute of Mining and Metallurgical Engineers, American Society of Mechanical Engineers, and AIEE.

## Iwadare Foundation Committee

The fifth lecturer to visit Japan was Doctor Edwin H. Colpitts, who has just retired from his position as executive vice-president of Bell Telephone Laboratories, Inc. Doctor Colpitts sailed from San Francisco on March 4 last and planned to be in Japan throughout the month of April. He gave 3 different lectures: "Organized Scientific Research in Bell Telephone Laboratories," "Recent Trends in Toll Transmission in the United States," and "Scientific Research Applied to the Telephone Transmitter and Receiver."

## Employment Service

The Institute co-operates with the national societies of civil, mining, and mechanical engineers in operation of the Engineering Societies Employment Service with its main office in the Engineering Societies Building, New York. Offices are operated in Chicago and San Francisco also. In addition to the societies named, others co-operate in certain of the offices as follows: New York—Society of Naval Architects and Marine Engineers; Chicago—Western Society of Engineers; San Francisco—California Section of the American Chemical Society; and the Engineers' Club of San Francisco.

The service is supported by the joint contributions of the societies and their individual members who are benefited. In addition to the publication of the employment service announcements monthly in ELECTRICAL ENGINEERING, weekly subscription bulletins are issued for those seeking positions.

An analysis of this employment service as reported to the national societies is given in table X.

## American Engineering Council

The American Engineering Council has continued its activities in the wide range of affairs which are found within the scope of its objectives: "to further the public welfare wherever technical and engineering knowledge and experience are involved, and to consider and act upon matters of common concern to the engineering and allied technical professions," and within the interests of its many member-bodies.

The work of Council has, during the past year, been carried on by 4 groups of committees:

1. Public affairs
2. Engineering-economics
3. United action of member organizations
4. AEC operating

Some of the principal actions taken by the assembly at its annual meeting held January 15 and 16, 1937, provide for:

1. Efforts to encourage the completion of the basic mapping program of the United States.
2. Continued support of efforts which will bring about ultimate unification of engineering in public works activities.
3. Support of the proposed plan for a single court of patent appeals, and opposition to the various proposals which would restrict the freedom of owners of patents.
4. Initiative to be taken by Council in the formation of co-operative relations between its staff and committees and representative groups in economics and social science to enable the engineering profession to make its proper contributions to the consideration and solution of problems in these broader fields.
5. Study by the executive committee of the possibility of developing and carrying out a broad educational program to encourage rural electrification.

A conference of secretaries of engineering societies was held under the sponsorship of Council on January 14, and was attended by secretaries of about 30 national, state, and local organizations.

A committee of Council has continued to confer with representatives of the Bureau of Labor Statistics regarding the contents of the report upon the 1935 survey of the engineering profession. Three articles have been published. A detailed report of the survey will be published later by the bureau.

Council appointed an advisory committee to co-operate with the Lewis Historical Publishing Company in connection with preparations for a new edition of "Who's Who in Engineering."

More detailed information regarding the work of Council has been published frequently in ELECTRICAL ENGINEERING.

**Table X. Analysis of Employment Service**

| Month | Men Registered | | | | Men Placed | | | |
|---|---|---|---|---|---|---|---|---|
| | New York | Chicago | San Francisco | Total | New York | Chicago | San Francisco | Total |
| 1936 | | | | | | | | |
| May | 186 | 61 | 71 | 318 | 46 | 31 | 32 | 109 |
| June | 228 | 113 | 73 | 414 | 48 | 23 | 22 | 93 |
| July | 154 | 60 | 66 | 280 | 47 | 41 | 35 | 123 |
| August | 114 | 35 | 58 | 207 | 51 | 39 | 33 | 123 |
| September | 125 | 82 | 57 | 264 | 60 | 36 | 26 | 122 |
| October | 125 | 49 | 67 | 241 | 51 | 30 | 27 | 108 |
| November | 128 | 37 | 39 | 204 | 57 | 36 | 27 | 120 |
| December | 115 | 65 | 44 | 224 | 64 | 36 | 24 | 124 |
| 1937 | | | | | | | | |
| January | 197 | 48 | 69 | 314 | 72 | 36 | 32 | 140 |
| February | 282 | 83 | 62 | 427 | 50 | 36 | 26 | 112 |
| March | 346 | 107 | 109 | 562 | 65 | 33 | 41 | 139 |
| April | 475 | 94 | 78 | 647 | 54 | 40 | 25 | 119 |
| Total | 2,475 | 834 | 793 | 4,102 | 665 | 417 | 350 | 1,432 |

## United Engineering Trustees, Inc.

This organization, as an agency of the founder societies, made further improvements in the Engineering Societies Building, including the redecoration of the rooms occupied by the library and improvements in elevator equipment and service, and presented a plan for resuming payments to the depreciation and renewal fund of the building. Much consideration has been given to investment problems in order to secure the maximum income consistent with safety of principal.

The UET continued as treasurer of the Engineers' Council for Professional Development.

An abstract of the annual report of the United Engineering Trustees, Inc., was published in ELECTRICAL ENGINEERING for December, 1936, pages 1400–01.

## Engineering Foundation

The Engineering Foundation suffered a serious loss in the death of its director, Doctor Alfred D. Flinn, on March 14, 1937.

During 1936, the Foundation supplied financial support for many research projects sponsored by the founder societies, notably the following: ASCE—earths and foundations; AIME—alloys of iron and barodynamic studies; ASME—cottonseed processing, cutting fluids, critical pressure steam boilers, fluid meters, boiler feed water, strength of gear teeth, "Cutting of Metals" handbook; AIEE—welding with pure iron electrodes (terminated on September 30, 1936) and comprehensive program under supervision of the welding research committee sponsored by the AIEE and the American Welding Society, with the co-operation of industries.

The Foundation also assisted in studies of the plastic flow of concrete at the University of California, and the plasticity of metals at the University of Pittsburgh.

It continued to assist the Engineers' Council for Professional Development and the Personnel Research Federation.

An abstract of the annual report of the Engineering Foundation was published in the December 1936 issue of ELECTRICAL ENGINEERING, pages 1401–02.

## Engineering Societies Library

The Engineering Societies Library, which was formed by combining the separate libraries of the 4 national societies of civil, mining and metallurgical, mechanical, and electrical engineers, and the preparation of a composite card catalog, has been expanded as a single engineering library, which probably constitutes the best collection of this type of literature in the country.

On September 30, 1936, the library had 138,742 volumes, 7,246 maps, and 4,298 bibliographies. Books, pamphlets, and maps totaling 12,148 were received during the year ending at that time. Current issues of 1,358 periodicals were received. Work progressed rapidly on a classified index to periodicals, and the index now contains more than 150,000 references to articles published since 1927.

Special services rendered by the library include: photoprints, searches, abstracts, translations, bibliographies, book loans by mail, etc.

An abstract of the annual report of the library was published on page 1402 of ELECTRICAL ENGINEERING for December 1936.

## Engineers' Council for Professional Development

This council, which was formally organized in 1932 for the enhancement of the professional status of the engineer, includes 3 representatives of each of the 7 participating organizations: the national societies of chemical, civil, electrical, mechanical, and mining and metallurgical engineers, the Society for the Promotion of Engineering Education, and the National Council of State Boards of Engineering Examiners.

The principal activities of ECPD include the guidance of young individuals thinking of entering the engineering field, the accrediting of engineering schools, encouragement and assistance to individuals continuing their engineering and cultural training during several years after graduation, and the establishment of suitable standards for indicating the attainment of the status of an engineer.

Actions were taken, at the annual meeting in October 1936, upon curricula of 39 institutions in regions I and II, and a list of accredited curricula in those regions was issued soon afterward. Actions upon curricula of a few additional institutions were taken on April 23, 1937. Consideration of engineering curricula throughout the remainder of the country is proceeding rapidly in preparation for actions at the annual meeting in October 1937.

The committe on professional training selected a few cities in which conditions seemed especially favorable for the establishment of operating programs for assisting junior engineers in their self-development. Excellent progress was made in Providence through the leadership of the Providence Engineering Society.

Detailed information regarding the recommendations submitted by ECPD to the participating organizations and other features of its activities were published during the year in numerous issues of ELECTRICAL ENGINEERING.

## Representatives

The Institute has continued its representation upon many joint committees and national bodies, with which it co-operates in a wide range of activities of interest and importance to engineers and others.

A complete list of representatives was published in the

September 1936 issue of ELECTRICAL ENGINEERING and in the 1937 Year Book.

## Finance Committee

The committee, as usual, recommended a detailed budget to the board of directors, passed upon the expenditures for various purposes, made recommendations regarding delinquent members, and performed the other duties prescribed for it in the constitution and by-laws.

Haskins and Sells, certified public accountants, have audited the books, and their report follows.

Respectfully submitted for the board of directors.

H. H. HENLINE,
*National Secretary*

May 24, 1937

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HASKINS & SELLS
CERTIFIED PUBLIC ACCOUNTANTS

22 EAST 40TH STREET
NEW YORK

May 21, 1937

American Institute of Electrical Engineers,
33 West 39th Street,
New York.

Dear Sirs:

We have made an examination of your balance sheet as of April 30, 1937, and of your recorded cash receipts and disbursements for the year ended that date. In connection therewith, we examined or tested your accounting records and other supporting evidence in a manner and to the extent which we considered appropriate in view of your system of internal accounting control. We present the following financial statements:

Balance Sheet, April 30, 1937 (Exhibit A).
Property and Restricted Funds Securities, Less Reserve for Bonds of Doubtful Value (Schedule 1).

Statement of Recorded Cash Receipts and Disbursements of General Fund for the Year Ended April 30, 1937 (Exhibit B).

Statement of Recorded Cash Receipts and Disbursements of Property and Restricted Funds for the Year Ended April 30, 1937 (Exhibit C).

In accordance with the terms of our engagement, members and other debtors were not requested to confirm to us the amounts receivable from them at April 30, 1937, and, in accordance with the usual practice of the Institute, no provision has been made for dues which may prove to be uncollectible.

In our opinion, based upon such examination and subject to the foregoing, the accompanying Exhibit A fairly presents your financial condition at April 30, 1937, and the accompanying Exhibits B and C set forth your recorded cash receipts and your disbursements of funds, as indicated, for the year ended that date.

Yours truly,

HASKINS & SELLS

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## AMERICAN INSTITUTE OF ELECTRICAL ENGINEERS

**Exhibit A** — Balance Sheet, April 30, 1937

### ASSETS

| | | |
|---|---|---|
| **Property Fund Investments:** | | |
| One-fourth interest in real estate and other assets of United Engineering Trustees, Inc., exclusive of Trust Funds | $496,948.48 | |
| Equipment: | | |
| Library—Volumes and fixtures | 37,296.37 | |
| Office furniture and fixtures (less reserve for depreciation, $27,386.77) | 6,856.55 | |
| Works of art, etc | 3,001.35 | |
| Securities—at cost (market quotation value, $10,556.28)—Schedule 1 | 10,042.53 | |
| Cash (See Exhibit C) | 22.47 | |
| Total property fund investments | | $554,167.75 |
| **Restricted Fund Investments:** | | |
| Securities—at cost, less reserve for bonds of doubtful value (market quotation value, $207,189.52)—Schedule 1 | $205,306.02 | |
| Cash (See Exhibit C) | 5,977.69 | |
| Accrued interest receivable | 209.16 | |
| Total restricted fund investments | | 211,492.87 |
| **Current Assets:** | | |
| Cash (See Exhibit B) | $ 51,700.32 | |
| Accounts receivable: | | |
| Members—For dues | 17,566.57 | |
| Advertisers | 582.00 | |
| Miscellaneous | 1,790.51 | |
| Accrued interest on investments | 2,736.58 | |
| Inventories: | | |
| TRANSACTIONS, etc. | 2,244.50 | |
| Text and cover paper | 4,974.21 | |
| Work in process (May issue of ELECTRICAL ENGINEERING) | 4,046.97 | |
| Badges | 1,006.10 | |
| Total current assets | | 86,647.76 |
| Total | | $852,308.38 |

### LIABILITIES

| | | |
|---|---|---|
| Property Fund Reserve | | $554,167.75 |
| **Restricted Fund Reserves:** | | |
| Reserve Capital Fund | $190,708.37 | |
| Life Membership Fund | 9,873.50 | |
| International Electrical Congress of St. Louis Library Fund | 5,272.25 | |
| Lamme Medal Fund | 4,567.33 | |
| Mailloux Fund | 1,071.42 | |
| Total restricted fund reserves | | 211,492.87 |
| Current Liabilities—Accounts Payable | | 8,017.81 |
| **Deferred Income:** | | |
| Dues received in advance | $ 3,858.31 | |
| Entrance fees and dues advanced by applicants for membership | 684.00 | |
| Deferred credits and other unallocated receipts | 691.70 | |
| Subscriptions for TRANSACTIONS received in advance | 28.00 | |
| Reserve for prepaid subscriptions for ELECTRICAL ENGINEERING | 7,500.00 | |
| Total deferred income | | 12,762.01 |
| Surplus | | 64,908.15 |
| Total | | $852,308.38 |

### Property and Restricted Funds Securities, Less Reserve for Bonds of Doubtful Value, April 30, 1937

**Exhibit A, Schedule 1**

| | Face Value of Bonds or Number of Shares of Stock | Property Fund (Equipment Replacements) | Restricted Funds: Reserve Capital Fund | Life Membership Fund | International Electrical Congress of St. Louis Library Fund | Lamme Medal Fund | Mailloux Fund | Total |
|---|---|---|---|---|---|---|---|---|
| **Railroad Bonds:** | | | | | | | | |
| Alleghany Corporation 20-year collateral trust convertible 5%, due 1949 | $15,000.00 | | $ 10,627.50 | | | $4,330.00 | | $ 14,957.50 |
| Baltimore & Ohio Railroad Company 6% refunding and general mortage series C, due 1995 | 12,000.00 | | 8,940.00 | | | | | 8,940.00 |
| Central of Georgia Railway Company 5% consolidated mortgage, due 1945 | 3,000.00 | | 1,477.50 | | | | | 1,477.50 |
| Chicago, Burlington & Quincy Railroad Company 5% first and refunding mortgage series A, due 1971 | 1,000.00 | | 1,010.00 | | | | | 1,010.00 |
| Chicago & Erie Railroad Company 5% first mortgage, due 1982 | 1,000.00 | | 1,105.00 | | | | | 1,105.00 |
| Chicago & Northwestern Railway Company 6½%, due March 1, 1936 | 9,000.00 | | 7,202.50 | | | | | 7,202.50 |
| Cleveland Union Terminals Company 5% sinking fund series B, due 1973 | 4,000.00 | $4,010.00 | | | | | | |
| Florida East Coast Railway Company 5% first and refunding mortgage series A, due 1974 (certificates of deposit) | 10,000.00 | | 9,818.75 | | | | | 9,818.75 |
| New York Central Railroad Company 5% refunding and improvement mortgage series C, due 2013 | 6,000.00 | | 5,742.50 | | | | | 5,742.50 |
| Northern Pacific Railway Company 6% refunding and improvement mortgage series B, due 2047 | 10,000.00 | | 10,962.50 | | | | | 10,962.50 |
| Pennsylvania Railroad Company 30-year secured serial 4%, due 1944 | 6,000.00 | | 5,337.50 | | $1,067.50 | | | 6,405.00 |
| St. Louis-San Francisco Railway Company 5% prior lien mortgage series B, due 1950 (certificates of deposit) | 6,000.00 | | 5,497.50 | | | | | 5,497.50 |
| Southern Pacific Oregon Lines 4½% first mortgage series A, due 1977 | 1,000.00 | | | | 996.25 | | | 996.25 |
| Texas and Pacific Railway Company, 4%, due 1977 | 5,000.00 | | | $5,306.25 | | | | 5,306.25 |
| Western Pacific Railroad Company 5% series A, due 1946 | 15,000.00 | | 7,225.00 | | | | | 7,225.00 |
| Total railroad bonds—(Forward) | | $ 4,010.00 | $ 74,946.25 | $5,306.25 | $2,063.75 | $4,330.00 | | $ 86,646.25 |

## AMERICAN INSTITUTE OF ELECTRICAL ENGINEERS

### Property and Restricted Funds Securities, Less Reserve for Bonds of Doubtful Value, April 30, 1937

### Exhibit A, Schedule 1 (Concluded)

| | Face Value of Bonds or Number of Shares of Stock | Property Fund (Equipment Replacements) | Restricted Funds: Reserve Capital Fund | Life Membership Fund | International Electrical Congress of St. Louis Library Fund | Lamme Medal Fund | Mailloux Fund | Total |
|---|---|---|---|---|---|---|---|---|
| TOTAL RAILROAD BONDS—(Forward) | | $ 4,010.00 | $ 74,946.25 | $5,306.25 | $2,063.75 | $4,330.00 | | $ 86,646.25 |
| **Public Utility Bonds:** | | | | | | | | |
| American Gas & Electric Company 5% debenture, due 2028 | $ 9,000.00 | | $ 9,596.25 | | | | | $ 9,596.25 |
| Georgia Power Company first and refunding mortgage 5%, due 1967 | 10,000.00 | | 9,725.00 | | | | | 9,725.00 |
| Monongahela-West Pennsylvania Public Service Company 6% debentures, due 1965 | 8,000.00 | | 8,660.00 | | | | | 8,660.00 |
| New York Telephone Company 4½%, due 1939 | 1,000.00 | | | | | | $1,000.00 | 1,000.00 |
| Philadelphia Company, secured 5% series A, due 1967 | 10,000.00 | | 10,000.00 | | | | | 10,000.00 |
| Shawinigan Water and Power Company 4½% first mortgage and collateral trust sinking fund series A, due 1967 | 5,000.00 | | 4,581.25 | | | | | 4,581.25 |
| Texas Electric Service Company 5% first mortgage, due 1960 | 10,000.00 | | 9,838.75 | | | | | 9,838.75 |
| United Light & Power Company 5½% first lien and consolidated mortgage, due 1959 | 5,000.00 | | 4,975.00 | | | | | 4,975.00 |
| Total public utility bonds | | | $ 57,376.25 | | | | $1,000.00 | $ 58,376.25 |
| **Industrial and Miscellaneous Bonds, Etc.:** | | | | | | | | |
| Fidelity Union Title and Mortgage Guaranty Company first mortgage certificates (on property 75–79 Prospect Street, East Orange, N. J.), 4%, due 1944 | $14,663.00 | $ 977.53 | $ 13,685.47 | | | | | $ 13,685.47 |
| International Match Corporation 5% convertible debenture, due 1941 (certificates of deposit) | 2,550.00 | | 2,424.15 | | | | | 2,424.15 |
| International Securities Corporation of America 5% debentures, due 1947 | 11,000.00 | | 11,070.00 | | | | | 11,070.00 |
| New York Steam Corporation 6% first mortgage, due 1947 | 10,000.00 | | 10,837.50 | | | | | 10,837 50 |
| United States Rubber Company 5% first and refunding mortgage series A, due 1947 | 2,000.00 | | 1,915.00 | | | | | 1,915.00 |
| Total industrial and miscellaneous bonds, etc | | $ 977.53 | $ 39,932.12 | | | | | $ 39,932.12 |
| **Municipal Bonds:** | | | | | | | | |
| City of Detroit public lighting 4½% A, due 1945 | $10,000.00 | | $ 10,262.50 | | | | | $ 10,262.50 |
| City of Union City, New Jersey, improvement bond of 1929 4¾%, due 1945 | 10,000.00 | | 10,154.50 | | | | | 10,154.50 |
| New York City 4½% corporate stock, due 1957 | 2,000.00 | | | | $2,204.05 | | | 2,204.05 |
| Total municipal bonds | | | $ 20,417.00 | | $2,204.05 | | | $ 22,621.05 |
| **Capital Stocks:** | | | | | | | | |
| Commonwealth Edison Company | 12 shares | | $ 2,892.00 | | | | | $ 2,892.00 |
| Commercial Investment Trust Corporation 4¼% preferred, series of 1935 | 100 shares | | 10,100.00 | | | | | 10,100.00 |
| Consolidated Edison Company of New York, Inc., $5.00 cumulative preferred | 30 shares | $ 3,060.00 | | | | | | |
| Public Service Corporation of New Jersey, $5.00 preferred | 30 shares | | 2,958.75 | | | | | 2,958.75 |
| United Gas Improvement Company, $5.00 preferred | 30 shares | 1,995.00 | 997.50 | | | | | 997.50 |
| | | | | | | | | $ 16,948.25 |
| Total capital stocks | | $ 5,055.00 | $ 16,948.25 | | | | | |
| Total | | $10,042.53 | $209,619.87 | $5,306.25 | $4,267.80 | $4,330.00 | $1,000.00 | $224,523.92 |
| **Less Reserve for Bonds of Doubtful Value:** | | | | | | | | |
| Central of Georgia Railway Company 5% consolidated mortgage, due 1945 | $ 3,000.00 | | $ 1,477.50 | | | | | $ 1,477.50 |
| Florida East Coast Railway Company 5% first and refunding mortgage series A, due 1974 | 10,000.00 | | 9,818.75 | | | | | 9,818.75 |
| International Match Corporation 5% convertible debentures, due 1941 | 2,550.00 | | 2,424.15 | | | | | 2,424.15 |
| St. Louis-San Francisco Railway Company 5% prior lien mortgage series B, due 1950 | 6,000.00 | | 5,497.50 | | | | | 5,497.50 |
| Total reserve for bonds of doubtful value | | | $ 19,217.90 | | | | | $ 19,217.90 |
| Total securities, less reserve | | $10,042.53 | $190,401.97 | $5,306.25 | $4,267.80 | $4,330.00 | $1,000.00 | $205,306.02 |
| Total Property Fund Securities | | $10,042.53 | | | | | | |
| Total Restricted Fund Securities | | | $190,401.97 | $5,306.25 | $4,267.80 | $4,330.00 | $1,000.00 | $205,306.02 |

## AMERICAN INSTITUTE OF ELECTRICAL ENGINEERS

### Statement of Recorded Cash Receipts and Disbursements of General Fund for the Year Ended April 30, 1937

**Exhibit B**

| | | |
|---|---|---|
| **Cash on Deposit, May 1, 1936, With National City Bank of New York** | | $ 48,367.77 |
| **Receipts:** | | |
| Dues (including $80,634.00 allocated to ELECTRICAL ENGINEERING subscriptions) | $186,305.30 | |
| Advertising | 29,947.01 | |
| TRANSACTIONS subscriptions | 6,651.68 | |
| ELECTRICAL ENGINEERING subscriptions | 14,011.80 | |
| Miscellaneous publications, etc. | 6,176.45 | |
| Students' fees | 10,413.00 | |
| Entrance fees | 7,160.63 | |
| Membership badges | 1,719.50 | |
| Transfer fees | 943.00 | |
| Interest on investments, less purchased interest | 9,057.82 | |
| Miscellaneous | 35.64 | |
| Total receipts | | 272,421.83 |
| Total | | $320,789.60 |
| **Disbursements:** | | |
| Publication expense: | | |
| ELECTRICAL ENGINEERING | $ 86,126.82 | |
| TRANSACTIONS | 3,714.89 | |
| YEAR BOOK | 3,346.15 | |
| Miscellaneous publications, etc. | 4,415.05 | |
| Administrative expenses | 43,089.23 | |
| Institute Sections | 35,560.93 | |
| Institute meetings | 10,883.57 | |
| Institute Branches | 2,888.26 | |
| American Engineering Council | 13,000.00 | |
| Traveling expenses: | | |
| National Nominating Committee | 907.38 | |
| Geographical districts: | | |
| Branch delegates | 6,853.06 | |
| Executive Committees | 1,405.90 | |
| Vice Presidents | 281.07 | |
| Board of Directors | 6,973.49 | |
| Institute representatives | 24.00 | |
| Forward | $219,469.80 | $320,789.60 |
| Total—(Forward) | | $320,789.60 |
| Disbursements—(Forward) | $219,469.80 | |
| United Engineering Trustees, Inc.: | | |
| Library assessment | 8,776.30 | |
| Building assessment | 7,596.88 | |
| Space assessment—E.C.P.D. | 450.00 | |
| Engineering Societies employment service | 2,257.28 | |
| Membership Committee | 7,511.80 | |
| Standards Committee | 5,513.96 | |
| American Standards Association | 1,166.67 | |
| President's appropriation | 1,791.26 | |
| Technical Committee | 190.69 | |
| Edison Medal Committee | 141.28 | |
| Membership badges | 1,765.51 | |
| Retirement salary | 2,700.00 | |
| Finance Committee | 1,600.00 | |
| Headquarters Committee | 44.85 | |
| United States Committee of International Commission on Illumination | 300.00 | |
| Code Committee | 60.00 | |
| John Fritz Medal | 50.00 | |
| Geographical district—Paper prizes | 125.50 | |
| Transfer to reserve capital fund | 7,577.50 | |
| Total disbursements | | 269,089.28 |
| **Cash on Deposit, April 30, 1937, With the National City Bank of New York** | | $ 51,700.32 |

### Statement of Recorded Cash Receipts and Disbursements of Property and Restricted Funds for the Year Ended April 30, 1937

**Exhibit C**

| | | Restricted Funds | | | | | |
|---|---|---|---|---|---|---|---|
| | Property Fund (Equipment Replacements) | Reserve Capital Fund | Life Membership Fund | International Electrical Congress of St. Louis Library Fund | Lamme Medal Fund | Mailloux Fund | Total Restricted Funds |
| **Cash on Deposit, May 1, 1936, With East River Savings Bank and National City Bank of New York** | $22.47 | | $ 4,732.99 | $ 665.05 | $177.63 | $ 3.92 | $ 5,579.59 |
| **Receipts:** | | | | | | | |
| Interest on bonds | | | $ 297.22 | $ 174.00 | $240.00 | $45.00 | $ 756.22 |
| Interest on bank balances | | | 83.84 | | | | 83.84 |
| Proceeds from sale and redemption of bonds | | $ 6,363.90 | 5,780.38 | 1,098.57 | | | 13,242.85 |
| Transfer from general fund | | 7,577.50 | | | | | 7,577.50 |
| Total receipts | | $13,941.40 | $ 6,161.44 | $1,272.57 | $240.00 | $45.00 | $21,660.41 |
| Total | $22.47 | $13,941.40 | $10,894.43 | $1,937.62 | $417.63 | $48.92 | $27,240.00 |
| **Disbursements:** | | | | | | | |
| Annual withdrawal authorized in by-laws | | | $ 972.32 | | | | $ 972.32 |
| Gold and bronze replicas of Lamme Medal | | | | | $280.30 | | 280.30 |
| Purchase of bonds | | $13,635.00 | 5,306.25 | $ 996.25 | | | 19,937.50 |
| All other disbursements | | | 69.44 | 2.75 | | | 72.19 |
| Total disbursements | | $13,635.00 | $ 6,348.01 | $ 999.00 | $280.30 | | $21,262.31 |
| **Balance on Deposit, April 30, 1937, With East River Savings Bank and National City Bank of New York** | $22.47 | $ 306.40 | $ 4,546.42 | $ 938.62 | $137.33 | $48.92 | $ 5,977.69 |

# A New Photoelectric Hysteresigraph

By R. F. EDGAR
ASSOCIATE AIEE

## Introduction

GRAPHICAL RECORDING of hysteresis loops or magnetization curves by means of a hysteresigraph is in many instances a much more convenient way of obtaining desired magnetic data than is the usual ballistic method. Unsymmetrical hysteresis loops, for example, may require considerable laborious procedure if obtained in the usual manner, but are easily recorded by some types of hysteresigraphs. The photoelectric hysteresigraph described herein is an instrument which readily records initial magnetization curves or any desired symmetrical or unsymmetrical hysteresis loops.

Several different forms of hysteresigraphs have been described. They are of 2 general types, depending upon whether the test specimen is magnetized by alternating current or by direct current. An a-c hysteresigraph may employ a cathode-ray oscillograph arranged in such a manner that the horizontal deflection of the electron beam is made proportional to magnetizing force while the vertical deflection is made proportional to induction.[1] Other types of a-c hysteresigraphs also have been described.[2,3] Eddy currents within the specimen tend to distort the shape of the recorded hysteresis loop, making laminated specimens necessary. A–c hysteresigraphs record only cyclic loops. Usually symmetrical loops are recorded, but minor or unsymmetrical loops may be obtained if the power supply furnishing the magnetizing current can be arranged to introduce current of suitable harmonic frequency superimposed upon the fundamental component of the magnetizing current. A-c hysteresigraphs appear to have been applied principally to testing sheet materials of low loss and high permeability.

An early form of cathode-ray tube hysteresigraph,[4] and a magnetic curve tracer described by Ewing,[5] may be used to obtain either cyclic a-c loops or d-c loops formed by slowly varying the magnetizing current through the desired cycles. In these devices part of the magnetic circuit is through air, and the strength of the magnetic field in the air path is measured as an indication of the induction in the specimen while the magnetizing current is taken as a measure of magnetizing force. Introduction of an air gap in the magnetic circuit, however, tends to prevent uniform magnetization of the specimen with resulting errors in the measurement of both induction and magnetizing force. A recent magnetic curve tracer [6] obtains d-c loops and is applicable to the testing of specimens in a closed magnetic circuit. It employs a search coil interlinking the specimen and a fluxmeter having its restoring torque automatically counterbalanced throughout its range of deflection so that it is accurately responsive to slow flux changes.

D-c hysteresigraphs do not require laminated specimens because the desired cycle of magnetization may be carried out so slowly that eddy currents do not become large enough to affect the results even if solid specimens are used. Initial magnetization curves and unsymmetrical hysteresis loops, as well as symmetrical hysteresis loops may be obtained. Besides being applicable to the testing of electrical sheet steels the d-c hysteresigraph may also be used in testing magnet materials, specimens of which are commonly solid rather than laminated.

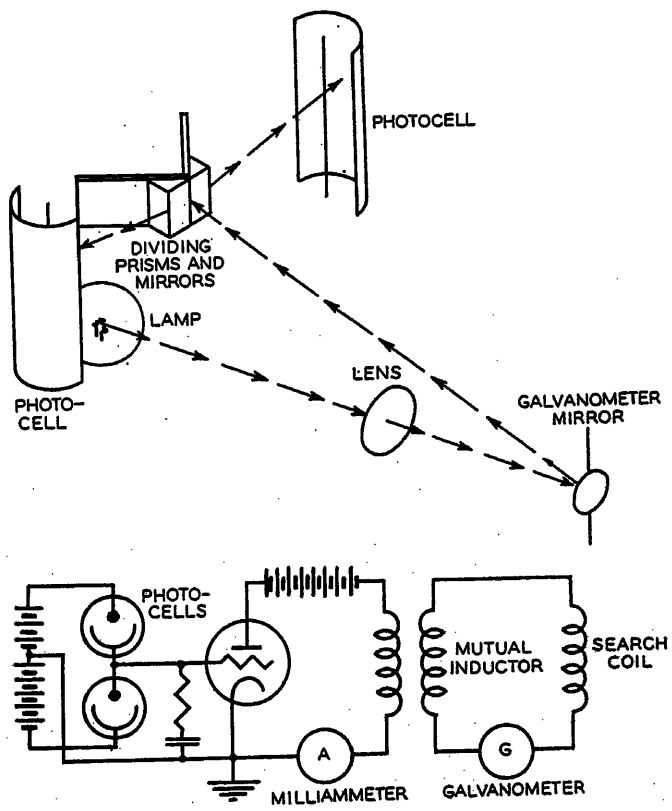



**Figure 1. Optical system and electrical circuit for photoelectric fluxmeter**

## Description

The hysteresigraph described herein is a d-c instrument which may be used to test either laminated or solid specimens in ring or bar form. For bar specimens it is connected to a permeameter in the same manner as the common ballistic galvanometer equipment. When used with the saturation permeameter [7] measurements may be made to a mag-

A paper recommended for publication by the AIEE committee on instruments and measurements. Manuscript submitted March 25, 1937; released for publication May 3, 1937.

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1. For all numbered references, see list at end of paper.

netizing force of 3,000 oersteds or higher. The equipment is sturdy and does not employ any delicate instruments which require careful handling, fine adjustment, or special mounting.

## The Photoelectric Fluxmeter

The heart of the instrument is a photoelectric fluxmeter[8] which is responsive to slow changes in flux linking a search coil, and provides an indication which remains constant without drift as long as the flux linking the search coil remains constant. Elementary diagrams of the fluxmeter are shown in figure 1. A galvanometer and search coil are used, and in series with them is connected the secondary coil of a mutual inductor. By means of an optical system and 2 photoelectric cells connected in a vacuum-tube circuit the galvanometer deflection is maintained at zero, the current in the primary coil of the mutual inductor being automatically varied so as to induce a voltage in the secondary coil equal and opposite to any voltage which may be induced in the search coil by a change of flux interlinking it. The change of interlinkage in the secondary coil caused by the change in primary current is then equal and opposite to the change of interlinkage in the search coil. The variation in primary current is, therefore, a measure of the flux variation in the search coil. Since the galvanometer remains at the zero position its suspension torque does not act to cause drift, and the primary current varies only when the flux linkage in the search coil varies.

The optical system and electrical circuit is adapted from the photoelectric recorder.[9] The beam from the galvanometer mirror is focused upon a set of mirrors and prisms which divides it into 2 parts and reflects each part into a photocell. Deflection of the galvanometer causes the light in one cell to increase and that in the other to diminish. The 2 photocells are connected in series with a voltage source, and to the grid of a vacuum tube in such a way that any unbalance of the divided light beam between the 2 cells causes a change in the grid voltage with a resultant change in plate current. The plate current, supplied by a second voltage source, flows in the primary coil of the above-mentioned mutual inductor. The direction of current flow is such that any change caused by a deflection of the galvanometer light beam causes a change of flux linking the secondary coil of the mutual inductor, tending to correct the galvanometer deflection and restore the orginal light balance.

A slight deflection of the galvanometer is evidently necessary to initiate the corrective change of plate current. This, however, is very small, and the final position when a new balance is restored is almost exactly the same as the original position. The photocells are of the vacuum type and are operated at a high voltage so that the current through them depends upon the light falling upon them and is nearly independent of voltage variation. The current for any constant value of grid voltage must be the same in both photocells, since they are in series, and any difference in current would necessarily alter the charge on the grid capacitor and change the grid voltage. The light division between the 2 cells must, therefore, be the same also, which means that the final position of the galvanometer beam must be the same for all steady values of flux linking the search coil. This was demonstrated in the development of the apparatus by setting up in place of the galvanometer a pivoted rod carrying a galvanometer mirror and having an arm 50 centimeters long projecting at right angles. The outer end of the arm was held lightly against the screw of a rigidly mounted micrometer. Turning the micrometer screw caused the end of the arm to move, rotating the mirror as it would rotate if mounted in the usual manner in a galvanometer. It was found that a motion at the outer end of the arm of 0.001 centimeter was sufficient to change the plate current of the tube from one extreme to the other. This corresponds to a light beam deflection of 0.0008 centimeter at the dividing prisms, and would be equivalent to a deflection of 0.004 centimeter on a scale set up at the customary meter distance.

Angular movement of the galvanometer coil equivalent to 0.001 centimeter deflection at the end of a 50 centimeter arm causes an interlinkage change in the galvanometer coil of about 30 maxwell-turns with the coil and field strength employed. In practice the galvanometer is used without any external shunt or series resistance, but is connected directly to the search coil and mutual inductor secondary winding. Since the total number of interlinkages in a circuit tends to remain constant, the difference between the change of flux linkages in the secondary coil of the mutual inductor and that in the search coil is about equal to that in the galvanometer coil. This difference is, therefore, about 30 maxwell-turns for a full-range change in the search coil. With the tube used in this test, the full-range change of plate current was

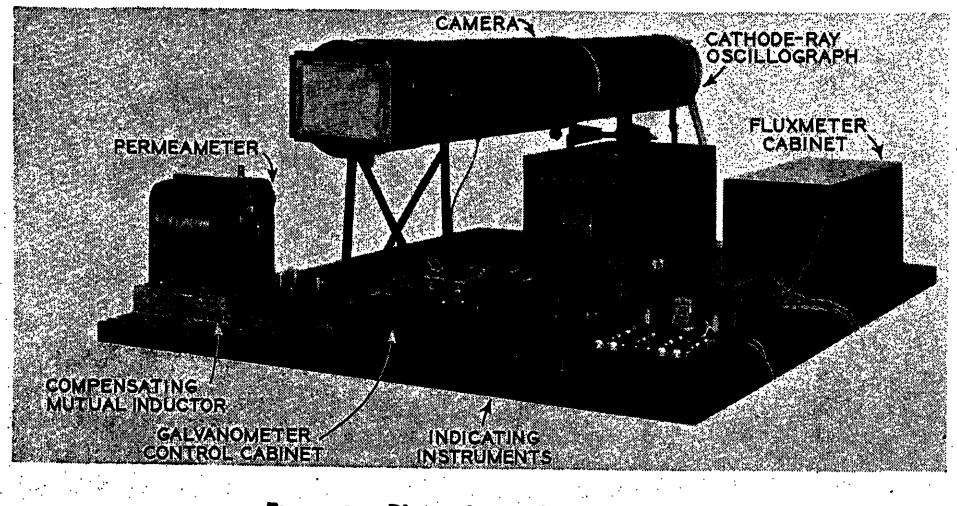



**Figure 2. Photoelectric hysteresigraph**

about 27 milliamperes. A mutual inductor of $10^7$ secondary maxwell-turns per primary ampere is used, so that full-range change of flux linkages was about 270,000 maxwell-turns. The difference between the actual change of interlinkage in the search coil and that indicated by the change in plate current through the primary winding of the mutual inductor is then about 0.0011 per cent. The tube has since been changed to a type which permits a larger change of plate current and has a higher mutual conductance so that the present figure is somewhat less.

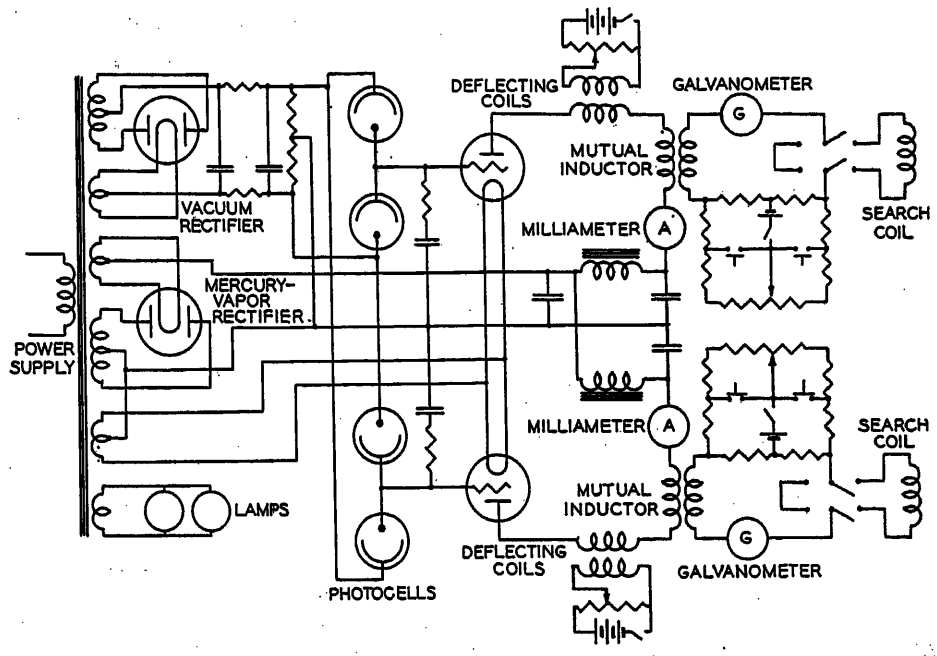



**Figure 3. Photoelectric hysteresigraph circuit diagram**

The amount of deflection during the flux change depends upon the rapidity of the flux change, the constants of the grid and plate circuits, and the characteristics of the galvanometer and its circuit. When the apparatus is used merely as an indicating fluxmeter this deflection is not important, since it returns to the small equilibrium value when the instrument indication becomes steady and can be read. It is necessary only that the deflection be small enough so that there is not sufficient suspension restoring torque to cause measurable drift during the flux change.

For use in automatic curve tracing, however, it is necessary that the current in the primary coil of the mutual inductor shall change accurately in agreement with the changing of interlinkages in the search coil. There must be no measurable lag between them. The galvanometer coil must have sufficiently low inertia to quickly begin to deflect and initiate a corrective change in the plate current when there is a change in interlinkages in the search coil. The capacitance in the grid circuit must be low enough so that the grid voltage quickly changes when there is an unbalance in the photocell circuit. The inductance in the plate circuit must be low enough to permit quick changes of plate current. It has been found that a portable reflecting galvanometer is entirely satisfactory, and no difficulty is experienced in making the constants of the circuits correct for accurate response to slow changes of interlinkage.

The accuracy of the measurement is not affected by small changes in supply voltage, vacuum-tube characteristics, photocell sensitivity, or light intensity. The optical system and photoelectric circuit are similar to those of the photoelectric recorder in being self-compensating for all normal changes in these variables.

The photoelectric fluxmeter is equivalent to a galvanometer of infinitely long period, in that it responds accurately to slow flux changes and its indication remains constant at any part of the range without drift. Moreover, the output of the instrument, instead of being merely deflection of a light beam on a scale, is in the form of electric current of sufficient power to operate sturdy and relatively insensitive indicating instruments or recording devices.

## The Hysteresigraph

The photoelectric hysteresigraph as illustrated in figure 2 consists of 2 such fluxmeters combined with a cathode-ray oscillograph. Magnetic deflection coils fitted to the oscillograph tube are connected in the plate circuits of the fluxmeters so that one fluxmeter causes vertical deflection of the electron beam and the other causes horizontal deflection. The search coil of the first fluxmeter is linked by the specimen under test and that of the second lies adjacent to the specimen but is not linked by it,[7] so that one fluxmeter measures induction changes and the other magnetizing force changes. Bar or strip specimens may be tested at high magnetizing force in the saturation permeameter. The hysteresigraph is adaptable to any type of permeameter in which the magnetizing force can be measured by means of a search coil as described, but which requires no varying compensating adjustment over the range of test. Ring specimens may be tested by using only one fluxmeter, a portion of the magnetizing current being passed directly through the horizontal deflection coils.

The circuit diagram for the hysteresigraph is shown in figure 3. It is similar to that of figure 1, the batteries being replaced by rectified a-c power sources, and 2 complete fluxmeters being provided. A small dry cell with fixed and variable resistors in each galvanometer circuit provide a means of balancing out any small thermoelectric or other voltage which may be present. Push buttons in this circuit facilitate shifting the plate current at will so

that it can be set at any desired value for the beginning of a test, and switches enable the search coils to be inserted in or removed from the circuit.

Figure 4 shows the arrangement of galvanometers, photocells, optical system, and vacuum tubes for both fluxmeters in one cabinet. Transformers, capacitors, and wiring are mounted on the under side of the subbase. The galvanometers are of the portable type[10] having sturdy suspensions and require no careful leveling or delicate adjustment. Moving systems of relatively low resistance are used. Stops are provided limiting the deflection to a small angle and preventing the beam from being thrown entirely off the dividing mirrors at any time. The light beams are supplied by 32-candlepower 6-volt automobile headlight bulbs in ventilated housings, and convex lenses in adjustable tubes. The photocells and prisms are enclosed in housings which prevent entrance of stray light. Voltage is supplied to the photocells by a vacuum rectifier tube through a resistance-capacitance filter circuit. Power is supplied to the plate circuits by a mercury-vapor rectifier tube having a low voltage drop, and a filter circuit of inductance and capacitance.

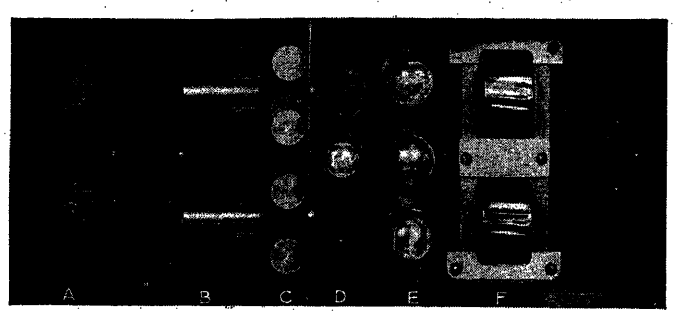



**Figure 4. Interior view of fluxmeter cabinet**

*A*—Galvanometers
*B*—Lens mountings
*C*—Photocell housings
*D*—Lamp housings and rectifier tube
*E*—Vacuum tubes and mercury-vapor rectifier
*F*—Filter reactors

Figure 5 shows the cabinet containing the 2 mutual inductors and the galvanometer control circuits. The 2 mutual inductors are each in 2 sections, astatic to uniform external fields, and are so mounted as to have no inductive coupling between them.

The cathode-ray oscillograph has a tube with a screen 7 inches in diameter, and is equipped with its own power supply. The magnetic deflection coils are located on 2 yokes of nickel-iron alloy having high permeability and low hysteresis, placed so as to produce magnetic fields at right angles to each other and to the electron beam. Two sets of coils are placed on each yoke, one being connected in the fluxmeter circuit and the other being connected to a battery and adjustable resistance. The second set is used to provide adjustment of the zero position of the electron beam.

A photographic record of the pattern traced on the fluorescent screen is made by means of the camera attached to the oscillograph. A piece of fiber tubing is fitted to the shield around the oscillograph tube. In the center is a lens equipped with a shutter and cable release, and at the end provision is made for exposing film or sensitized paper in 5-inch by 7-inch film holders. The shutter is normally used in the "bulb" position, and held open by means of the cable release while the record is being obtained.

A motor generator set has been provided to supply the magnetizing current for the specimen. Field control of the separately excited generator is used to obtain the desired maximum current. Reversing contactors included in the armature circuit of the generator permit a cyclic state of the sample to be obtained quickly, if desired, before tracing the loop. The magnetizing current is varied through the desired cycle by means of 2 rheostats having the resistance elements connected in parallel across the power supply line from the generator and the sliders connected to the magnetizing coil. The sliders are mechanically coupled together in such a way that moving them from one extreme to the other causes the magnetizing current to vary from a maximum value through zero to an equal and opposite maximum value. Not only symmetrical cycles, but any desired unsymmetrical and complicated cycle can be easily obtained.

When specimens are tested in the saturation permeameter a compensating variable mutual inductor may be used to compensate for any desired portion of the area of the potential coil measuring induction. By properly adjusting this inductor the space inside the coil but outside the specimen may be compensated for so that total induction in the sample is recorded. If desired, the entire area of the potential coil may be compensated for, so that intrinsic induction in the specimen is recorded. The primary coil is connected in series with the magnetizing coil of the permeameter, and the secondary coil is connected in series with the search coil measuring induction. The magnetizing force in the saturation permeameter is very

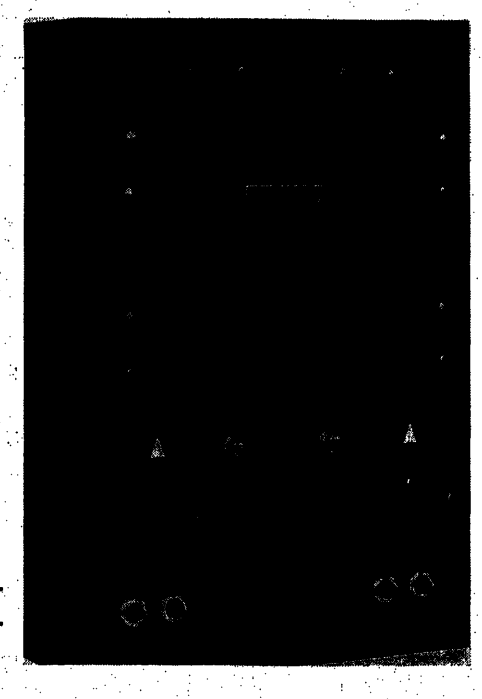


**Figure 5. Galvanometer control cabinet**

nearly proportional to the magnetizing current, so that by means of the compensating inductor a component of flux linkages proportional to the magnetizing force is introduced into the circuit containing the induction search coil. Since the flux linkages in this search coil due to space outside the specimen, or that due to the difference between total and intrinsic induction in the specimen, is proportional to magnetizing force, these flux linkages can be compensated by means of the compensating inductor.

## Records

Samples of records obtained with this equipment are shown in figures 6 and 7. Figure 6 shows portions of symmetrical hysteresis loops for 3 magnet materials. Figure 7 shows the upper portion of a loop having several minor loops traced in the second quadrant.

The co-ordinate lines are put in after the loop has been traced by switching the search coils out of the circuit, setting the plate current for one fluxmeter successively at values representing desired values of induction and varying the other through its entire range, then setting the plate current for the other fluxmeter successively at values representing desired values of magnetizing force and varying the former through its entire range. Values of plate

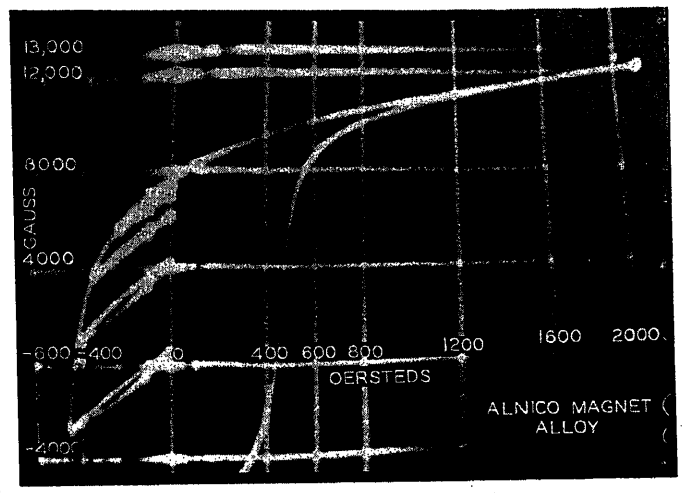



**Figure 7. Hysteresis loop for magnet material showing minor loops in the second quadrant**

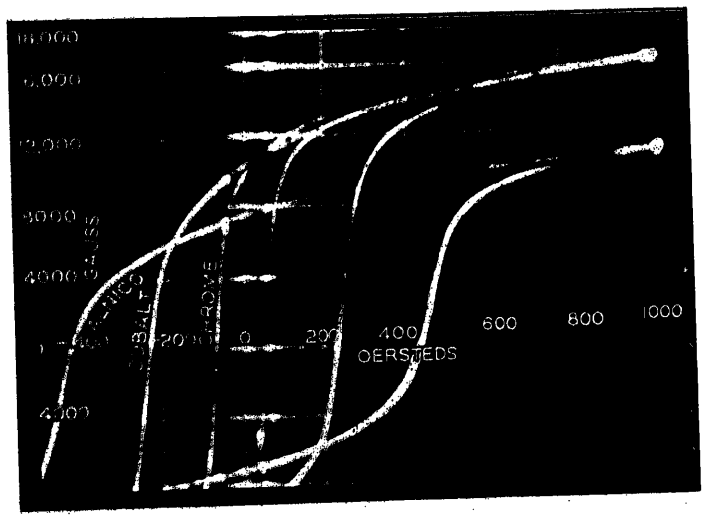



**Figure 6. Hysteresis loops for magnet materials**

current representing these quantities are calculated from a knowledge of the cross-sectional area of the sample, the number of turns and the areas of the search coils, and the mutual inductance of the inductors.

## Application

The hysteresigraph has been found particularly useful in the study of magnet materials, and in obtaining data for magnet design. Recent development of improved materials has brought about the use of permanent magnets in applications not previously considered practical, particularly in applications where the magnet may be subjected to varying external reluctance or strong demagnetizing magnetomotive force. For these applications the second quadrant of the symmetrical hysteresis loop alone is not sufficient for design calculations, but minor loops in this quadrant are also necessary. Figure 7 illustrates the type of data required.

Occasions frequently arise in which magnetic characteristics of a piece of equipment are desired for a particular type of unsymmetrical cycle. The hysteresigraph has been found to be a convenient instrument for obtaining such data.

## Conclusions

Development of the photoelectric fluxmeter and hysteresigraph was accomplished by combining only apparatus of known and tried characteristics to form a sturdy and accurate instrument simple to adjust and to operate. Testing of magnetic materials and of electrical equipment is facilitated, and magnet design data, not readily obtainable with other forms of testing equipment, are made available.

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# Low-Current Ignitors

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SLEPIAN AND LUDWIG'S discovery of the ignitron[1] principle of initiating the cathode spot of an arc has been followed by intensive investigation of the factors affecting the design and operation of the ignitron. Many of the design features of the ignitron follow conventional mercury-arc-rectifier practice. The distinguishing feature of the ignitron is the ignitor. An ignitor is an electrode of high resistivity material which is partially immersed in the cathode mercury. On sending a sufficiently large current through the ignitor into the mercury, a cathode spot forms upon the mercury at the ignitor mercury junction. The current to accomplish this varies in an inverse manner with the resistivity of the ignitor so that it is necessary to use relatively high resistivity material for practical ignitors. In practice the ignitor is connected to a suitable source of power with some means of switching so that the arc may be started at the proper time during the interval when the ignitron anode voltage is positive.

The most generally used circuit uses a thyratron for controlling the ignitor current as shown in figure 1.

When the grid control voltage of the thyratron and the anode voltage first become positive, the ignitor current flows and increases at a rate determined by the circuit until an arc starts in the ignitron. The current taken by the thyratron then drops to a low value depending on the relative arc drops of the thyratron and the ignitron and the resistance of the ignitor circuit. Generally this value is close to zero. The voltage across the ignitor at the same time drops to a few volts. Figure 2 shows approximately how the starting volts and amperes vary during operation.

The maximum instantaneous value of the current taken by the thyratron is many times larger than the average. It is necessary to use thyratrons with current ratings at least as large as the maximum current peaks required by the ignitors because their cathodes cannot repeatedly stand even momentary overloading without damage.

It is desirable to develop an ignitor requiring as little current as possible for several reasons. The smaller size thyratrons are cheaper than the larger, and usually the heating time of the smaller thermionic cathodes is shorter. If the starting current is reduced without changing the voltage, the load current is shifted from the ignitor circuit to the ignitron more readily at light loads. It is, therefore, more desirable to effect a reduction in starting current than to produce a cheaper thyratron to handle the ignitor load.

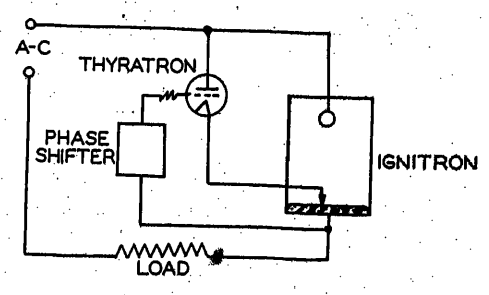
The theory advanced by Slepian and Ludwig[1] for the formation of the cathode spot at the ignitor mercury junction directs attention to the high current density and corresponding voltage gradient developed there, and points out the similarity between these conditions and the conditions existing at the last points of contact of separating electrodes. Other workers have used essentially the same picture.[2,3] Experience indicates that a material must satisfy the following conditions to be practically suitable for ignitors.

1. It must not be wet by mercury.
2. It must be workable.
3. It must not deteriorate in the arc.
4. It must have the proper electrical resistance.

The theory of Slepian and Ludwig suggests that the nature of the contact between the mercury and ignitor at the ignitor mercury junction is important. Hence, it is not surprising that if a material is wetted by the mercury during operation as an ignitor the starting current usually jumps to high values which may damage the thyratron. A convex meniscus seems to be necessary for low starting currents. If the material is wetted by the mercury a concave meniscus is obtained usually with large starting current. Also under these conditions the cathode spot tends to anchor at the ignitor instead of moving away from it in the usual way, and may damage it. This requirement eliminates many materials.

The substances which have been found to be useful ignitor materials are generally very hard in their crystalline form. Some of these materials are silicon carbide, boron carbide, and materials known under the trade names of Carborundum, Globar, and Silit. Shaping, mounting, and making electrical connection to these materials offers difficulties. Globar is easy to work when made up in high resistivity rods, but if processed to reduce the resistivity they become difficult to work because of increased hardness.

Figure 1




The need for working arises because it had been found desirable to shape ignitors to a point because this decreased the starting current. For example, comparing an ignitor made of quarter-inch rod and one made of the same material ground to a point, the latter required about one

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1. For all numbered references, see list at end of paper.

third of the current required by the rod at an increase in voltage of 20–25 per cent. The increase in voltage is due to the increase in the resistance of the ignitor due to reducing the section.

The cathode spot starts at the ignitor afresh each cycle and then does not have time to get very far away from it in the conducting period. Ignitrons also are usually built with the anode close to the cathode and often operate red hot. Hence, the ignitor frequently is required to run hot because it has little chance to dissipate heat through the ignitor lead or the mercury. Under these conditions the material must be stable. Materials have been found and are used that show no sign of deterioration, wear, or erosion after thousands of hours operation as ignitors. Some appear to have unlimited life.

The electrical characteristics depend on the resistivity and the geometric form of the ignitor. The geometric form and dimensions need to be a compromise between several conflicting conditions.

It is desirable to have the area of the ignitor actually under the mercury as small as possible, as this makes the ratio of the useful current which flows in the close vicinity of the junction, to the total current large. Also, it is desirable to make the length of the ignitor above the mercury as short as possible to reduce the voltage drop required to send the starting current through the length of the ignitor. The splashing of the mercury sets limits to what may be done in both of these directions. To avoid missing due to the ignitor losing contact with the mercury, it has been found necessary to use immersion depths of the order of a quarter of an inch. The distance from mercury to the conducting head, holder, or ignitor lead must be of the order of one half of an inch to prevent short circuiting of the ignitor by the splashing of the cathode mercury. Such short circuits may damage the cathode of the control tube if too much current passes through the circuit. Hence, we have the length fixed at $^3/_4$ of an inch plus the length of a head, or additional length to provide for some sort of mounting to make connection to the ignitor lead.

The thickness and shape are also reached by compromise between mechanical and electrical characteristics. The ignitor materials are brittle, therefore, they must be made in such diameters and shapes which will be strong enough to stand handling in assembly and the forces due to mercury when moving the ignitrons or during operation when some force is exerted by the mercury vapor and the motion of the mercury under the influence of the cathode spots. The shape generally used is approximately that of a cantilever beam of uniform strength. A typical ignitor is shown in figure 3. The tip diameter is of the order of 0.080 to 0.090 inch.

**Figure 4**

*W*—Width of slot

*D*—Depth of tip immersion

*S*—Surface tension of mercury = 0.0475 grams per millimeter

Pressure of immersed mercury = 0.0136 grams per square millimeter

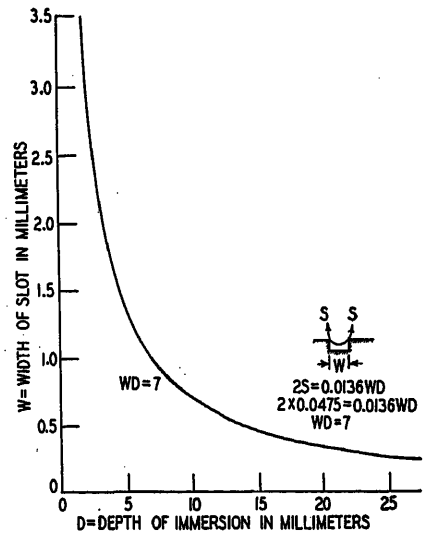



**Table I**

| Ignitor | Starting Amperes Before Slotting | Starting Amperes After Slotting | Starting Volts Before Slotting | Starting Volts After Slotting | Current Ratio After Slotting / Before Slotting |
|---|---|---|---|---|---|
| *PAN* 9 | 24 | 11 | 40 | 42 | 0.46 |
| *PAN* 14 | 20 | 7 | 50 | 50 | 0.35 |
| *PAL* 15 | 21 | 12 | 43 | 45 | 0.57 |
| *PAH* 20 | 18 | 9 | 38 | 40 | 0.50 |
| *PAH* 8 | 24 | 11 | 50 | 50 | 0.46 |
| *PAN* 19 | 14 | 7 | 75 | 80 | 0.50 |

The use of such a shape has a definite effect on the starting volts and amperes as mentioned before. For a definite size and shape of ignitor the starting voltage is directly and the starting current inversely proportional approximately to the resistivity of the material used. Thus increased resistivity generally means increased voltage and decreased current. The law has not been definitely established but examination of the characteristics of a large number of ignitors shows the trend toward such a law. The most desirable resistance to use is governed by the voltage and current limits that can be tolerated. The upper voltage limit is generally set at 100 volts for the present though it is desirable to have it as low as can be obtained. Many ignitors require less than this maximum limit. The current for an ignitor of a resistance that will give starting voltage of 100 volts would be more or less constant in value from one igniter to another if uniformly shaped ignitors were made of a material of a certain resistivity, but it happens that the problem of manufacturing ignitors is far from being as simple as that. The problem of wetting has driven the ignitor maker to treat ignitors, or make them of certain materials by processes that are

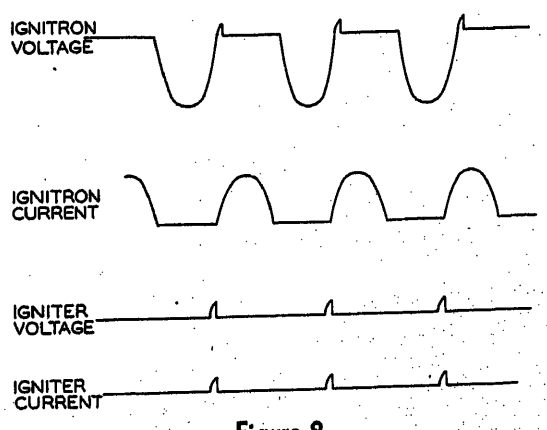



**Figure 2**

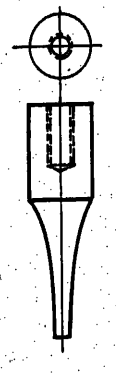


**Figure 3**

difficult to control and repeat exactly. Hence, the product varies in starting characteristics so an upper limit to the current required is set and the ignitors accepted if the current is less than 15 amperes and the voltage less than 100 volts.

The current is influenced a great deal by the surface of the part of the ignitor immersed in the cathode mercury. An ignitor with a smooth polished surface requires more current than one with a rough surface though the resistivities are the same. One may easily reduce the starting current, without affecting the voltage, by covering part of the immersed surface with insulation. However, fastening a suitable insulator on an ignitor is difficult and has been applied only in laboratory experiments.

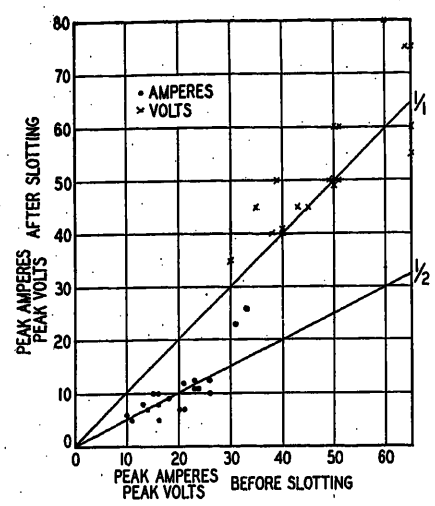



**Figure 5. Effects of slotting on starting volts and amperes**

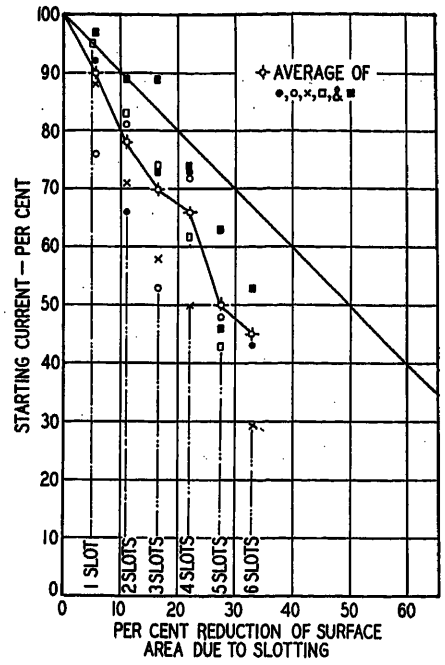



**Figure 6**

Slepian suggested a very effective method of reducing the surface area of the ignitor which could come in contact with the mercury and at the same time not appreciably increasing the resistance through the ignitor to the mercury junction. He estimated that the mercury would not enter slots of the order of one millimeter wide at ordinary ignitor immersion depths due to the high surface tension of the mercury. A simple experiment with 2 glass plates immersed in mercury proved the theory and calculations were made to show the relationship between the width of slot and depth of immersion when the surface tension forces just balance the static pressure. The results of these calculations are plotted in a curve, figure 4.

If the mercury level stayed always constant, the ideal slot would vary in width from tip to mercury surface. An ignitor with such slots has not been produced. It was convenient to take some of the present design of boron carbide ignitors which have a tip diameter of 0.080 or 0.090 inch and cut slots which were approximately 0.020 inch wide. Six slots were cut in each ignitor.

A few of the results are tabulated in table I.

A large number of ignitors were tested and the results spotted on figure 5. This shows the effect of slotting quite clearly. The slight increase in voltage may be due to the increase in resistance due to the cutting away of material. The current was reduced to nearly one half of the original. The picture figure 7 shows several slotted ignitors and an unslotted one for comparison.

It was observed that the current reduction was greater than the reduction in area. This was investigated by cutting one slot at a time and measuring the current after each slot was cut. The results are shown in figure 6, which shows starting current in per cent plotted against reduction of surface area in per cent.

An examination of the surface of the mercury at the slots and between slots showed that the line of contact of the mercury with the ignitor between slots was not a plane curve but was lower at the slots than between the slots. This fact coupled with a change in current distribution in the ignitor and mercury may account for the additional reduction in current.

The minimum current and voltage at which an ignitor will initiate an arc has not been determined. If the currents can be reduced sufficiently it becomes possible to use smaller and cheaper thyratrons and other means of supplying the ignitor current. Some ignitors do not suffer when back current passes through them so if the current requirement is reduced other methods of control become possible which, at present, are too costly or unwieldy to be useful.

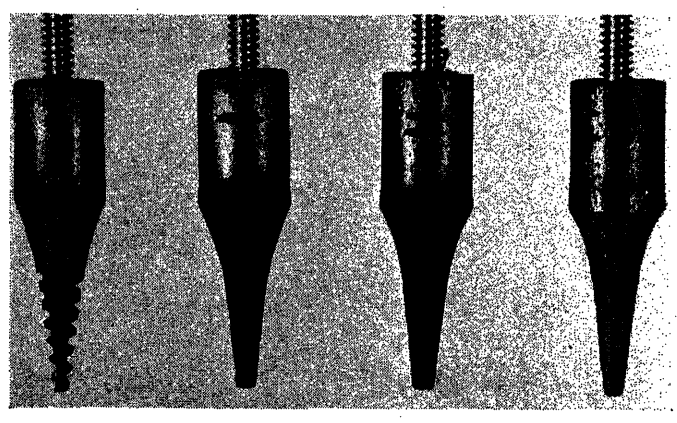


**Figure 7**

## References


1. Slepian-Ludwig, AIEE TRANSACTIONS, volume 52, 1933, page 693.
2. G. Meirdel, *Wiss. Veroff a. d. Siemens-Werken*, volume 15, part 2, page 36.
3. J. M. Cage, *General Electric Review*, volume 38, 1935, page 464.

## AMERICAN INSTITUTE OF ELECTRICAL ENGINEERS

### Property and Restricted Funds Securities, Less Reserve for Bonds of Doubtful Value, April 30, 1937

### Exhibit A, Schedule 1 (Concluded)

| | Face Value of Bonds or Number of Shares of Stock | Property Fund (Equipment Replacements) | Restricted Funds: Reserve Capital Fund | Life Membership Fund | International Electrical Congress of St. Louis Library Fund | Lamme Medal Fund | Mailloux Fund | Total |
|---|---|---|---|---|---|---|---|---|
| TOTAL RAILROAD BONDS—(Forward) | | $ 4,010.00 | $ 74,946.25 | $5,306.25 | $2,063.75 | $4,330.00 | | $ 86,646.25 |
| **Public Utility Bonds:** | | | | | | | | |
| American Gas & Electric Company 5% debenture, due 2028 | $ 9,000.00 | | $ 9,596.25 | | | | | $ 9,596.25 |
| Georgia Power Company first and refunding mortgage 5%, due 1967 | 10,000.00 | | 9,725.00 | | | | | 9,725.00 |
| Monongahela-West Pennsylvania Public Service Company 6% debentures, due 1965 | 8,000.00 | | 8,660.00 | | | | | 8,660.00 |
| New York Telephone Company 4½%, due 1939 | 1,000.00 | | | | | | $1,000.00 | 1,000.00 |
| Philadelphia Company, secured 5% series A, due 1967 | 10,000.00 | | 10,000.00 | | | | | 10,000.00 |
| Shawinigan Water and Power Company 4½% first mortgage and collateral trust sinking fund series A, due 1967 | 5,000.00 | | 4,581.25 | | | | | 4,581.25 |
| Texas Electric Service Company 5% first mortgage, due 1960 | 10,000.00 | | 9,838.75 | | | | | 9,838.75 |
| United Light & Power Company 5½% first lien and consolidated mortgage, due 1959 | 5,000.00 | | 4,975.00 | | | | | 4,975.00 |
| Total public utility bonds | | | $ 57,376.25 | | | | $1,000.00 | $ 58,376.25 |
| **Industrial and Miscellaneous Bonds, Etc.:** | | | | | | | | |
| Fidelity Union Title and Mortgage Guaranty Company first mortgage certificates (on property 75–79 Prospect Street, East Orange, N. J.), 4%, due 1944 | $14,663.00 | $ 977.53 | $ 13,685.47 | | | | | $ 13,685.47 |
| International Match Corporation 5% convertible debenture, due 1941 (certificates of deposit) | 2,550.00 | | 2,424.15 | | | | | 2,424.15 |
| International Securities Corporation of America 5% debentures, due 1947 | 11,000.00 | | 11,070.00 | | | | | 11,070.00 |
| New York Steam Corporation 6% first mortgage, due 1947 | 10,000.00 | | 10,837.50 | | | | | 10,837 50 |
| United States Rubber Company 5% first and refunding mortgage series A, due 1947 | 2,000.00 | | 1,915.00 | | | | | 1,915.00 |
| Total industrial and miscellaneous bonds, etc. | | $ 977.53 | $ 39,932.12 | | | | | $ 39,932.12 |
| **Municipal Bonds:** | | | | | | | | |
| City of Detroit public lighting 4½% A, due 1945 | $10,000.00 | | $ 10,262.50 | | | | | $ 10,262.50 |
| City of Union City, New Jersey, improvement bond of 1929 4¾%, due 1945 | 10,000.00 | | 10,154.50 | | | | | 10,154.50 |
| New York City 4½% corporate stock, due 1957 | 2,000.00 | | | | $2,204.05 | | | 2,204.05 |
| Total municipal bonds | | | $ 20,417.00 | | $2,204.05 | | | $ 22,621.05 |
| **Capital Stocks:** | | | | | | | | |
| Commonwealth Edison Company | 12 shares | | $ 2,892.00 | | | | | $ 2,892.00 |
| Commercial Investment Trust Corporation 4¼% preferred, series of 1935 | 100 shares | | 10,100.00 | | | | | 10,100.00 |
| Consolidated Edison Company of New York, Inc., $5.00 cumulative preferred | 30 shares | $ 3,060.00 | | | | | | |
| Public Service Corporation of New Jersey, $5.00 preferred | 30 shares | | 2,958.75 | | | | | 2,958.75 |
| United Gas Improvement Company, $5.00 preferred | 30 shares | 1,995.00 | 997.50 | | | | | 997.50 |
| | | $ 5,055.00 | $ 16,948.25 | | | | | $ 16,948.25 |
| Total capital stocks | | | | | | | | |
| Total | | $10,042.53 | $209,619.87 | $5,306.25 | $4,267.80 | $4,330.00 | $1,000.00 | $224,523.92 |
| **Less Reserve for Bonds of Doubtful Value:** | | | | | | | | |
| Central of Georgia Railway Company 5% consolidated mortgage, due 1945 | $ 3,000.00 | | $ 1,477.50 | | | | | $ 1,477.50 |
| Florida East Coast Railway Company 5% first and refunding mortgage series A, due 1974 | 10,000.00 | | 9,818.75 | | | | | 9,818.75 |
| International Match Corporation 5% convertible debentures, due 1941 | 2,550.00 | | 2,424.15 | | | | | 2,424.15 |
| St. Louis-San Francisco Railway Company 5% prior lien mortgage series B, due 1950 | 6,000.00 | | 5,497.50 | | | | | 5,497.50 |
| Total reserve for bonds of doubtful value | | | $ 19,217.90 | | | | | $ 19,217.90 |
| Total securities, less reserve | | $10,042.53 | $190,401.97 | $5,306.25 | $4,267.80 | $4,330.00 | $1,000.00 | $205,306.02 |
| **Total Property Fund Securities** | | $10,042.53 | | | | | | |
| **Total Restricted Fund Securities** | | | $190,401.97 | $5,306.25 | $4,267.80 | $4,330.00 | $1,000.00 | $205,306.02 |

## AMERICAN INSTITUTE OF ELECTRICAL ENGINEERS

### Exhibit B — Statement of Recorded Cash Receipts and Disbursements of General Fund for the Year Ended April 30, 1937

| | | |
|---|---|---|
| **Cash on Deposit, May 1, 1936, With National City Bank of New York** | | $ 48,367.77 |
| **Receipts:** | | |
| Dues (including $80,634.00 allocated to ELECTRICAL ENGINEERING subscriptions) | $186,305.30 | |
| Advertising | 29,947.01 | |
| TRANSACTIONS subscriptions | 6,651.68 | |
| ELECTRICAL ENGINEERING subscriptions | 14,011.80 | |
| Miscellaneous publications, etc. | 6,176.45 | |
| Students' fees | 10,413.00 | |
| Entrance fees | 7,160.63 | |
| Membership badges | 1,719.50 | |
| Transfer fees | 943.00 | |
| Interest on investments, less purchased interest | 9,057.82 | |
| Miscellaneous | 35.64 | |
| Total receipts | | 272,421.83 |
| Total | | $320,789.60 |
| **Disbursements:** | | |
| Publication expense: | | |
| ELECTRICAL ENGINEERING | $ 86,126.82 | |
| TRANSACTIONS | 3,714.89 | |
| YEAR BOOK | 3,346.15 | |
| Miscellaneous publications, etc. | 4,415.05 | |
| Administrative expenses | 43,089.23 | |
| Institute Sections | 35,560.93 | |
| Institute meetings | 10,883.57 | |
| Institute Branches | 2,888.26 | |
| American Engineering Council | 13,000.00 | |
| Traveling expenses: | | |
| National Nominating Committee | 907.38 | |
| Geographical districts: | | |
| Branch delegates | 6,853.06 | |
| Executive Committees | 1,405.90 | |
| Vice Presidents | 281.07 | |
| Board of Directors | 6,973.49 | |
| Institute representatives | 24.00 | |
| Forward | $219,469.80 | $320,789.60 |
| Total—(Forward) | $219,469.80 | $320,789.60 |
| Disbursements—(Forward) | | |
| United Engineering Trustees, Inc.: | | |
| Library assessment | 8,776.30 | |
| Building assessment | 7,596.88 | |
| Space assessment—E.C.P.D. | 450.00 | |
| Engineering Societies employment service | 2,257.28 | |
| Membership Committee | 7,511.80 | |
| Standards Committee | 5,513.96 | |
| American Standards Association | 1,166.67 | |
| President's appropriation | 1,791.26 | |
| Technical Committee | 190.69 | |
| Edison Medal Committee | 141.28 | |
| Membership badges | 1,765.51 | |
| Retirement salary | 2,700.00 | |
| Finance Committee | 1,600.00 | |
| Headquarters Committee | 44.85 | |
| United States Committee of International Commission on Illumination | 300.00 | |
| Code Committee | 60.00 | |
| John Fritz Medal | 50.00 | |
| Geographical district—Paper prizes | 125.50 | |
| Transfer to reserve capital fund | 7,577.50 | |
| Total disbursements | | 269,089.28 |
| **Cash on Deposit, April 30, 1937, With the National City Bank of New York** | | $ 51,700.32 |

### Exhibit C — Statement of Recorded Cash Receipts and Disbursements of Property and Restricted Funds for the Year Ended April 30, 1937

| | | Restricted Funds | | | | | |
|---|---|---|---|---|---|---|---|
| | Property Fund (Equipment Replacements) | Reserve Capital Fund | Life Membership Fund | International Electrical Congress of St. Louis Library Fund | Lamme Medal Fund | Mailloux Fund | Total Restricted Funds |
| **Cash on Deposit, May 1, 1936, With East River Savings Bank and National City Bank of New York** | $22.47 | | $ 4,732.99 | $ 665.05 | $177.63 | $ 3.92 | $ 5,579.59 |
| **Receipts:** | | | | | | | |
| Interest on bonds | | | $ 297.22 | $ 174.00 | $240.00 | $45.00 | $ 756.22 |
| Interest on bank balances | | | 83.84 | | | | 83.84 |
| Proceeds from sale and redemption of bonds | | $ 6,363.90 | 5,780.38 | 1,098.57 | | | 13,242.85 |
| Transfer from general fund | | 7,577.50 | | | | | 7,577.50 |
| Total receipts | | $13,941.40 | $ 6,161.44 | $1,272.57 | $240.00 | $45.00 | $21,660.41 |
| Total | $22.47 | $13,941.40 | $10,894.43 | $1,937.62 | $417.63 | $48.92 | $27,240.00 |
| **Disbursements:** | | | | | | | |
| Annual withdrawal authorized in by-laws | | | $ 972.32 | | | | $ 972.32 |
| Gold and bronze replicas of Lamme Medal | | | | | $280.30 | | 280.30 |
| Purchase of bonds | | $13,635.00 | 5,306.25 | $ 996.25 | | | 19,937.50 |
| All other disbursements | | | 69.44 | 2.75 | | | 72.19 |
| Total disbursements | | $13,635.00 | $ 6,348.01 | $ 999.00 | $280.30 | | $21,262.31 |
| **Balance on Deposit, April 30, 1937, With East River Savings Bank and National City Bank of New York** | $22.47 | $ 306.40 | $ 4,546.42 | $ 938.62 | $137.33 | $48.92 | $ 5,977.69 |

# A New Photoelectric Hysteresigraph

By R. F. EDGAR
ASSOCIATE AIEE

## Introduction

GRAPHICAL RECORDING of hysteresis loops or magnetization curves by means of a hysteresigraph is in many instances a much more convenient way of obtaining desired magnetic data than is the usual ballistic method. Unsymmetrical hysteresis loops, for example, may require considerable laborious procedure if obtained in the usual manner, but are easily recorded by some types of hysteresigraphs. The photoelectric hysteresigraph described herein is an instrument which readily records initial magnetization curves or any desired symmetrical or unsymmetrical hysteresis loops.

Several different forms of hysteresigraphs have been described. They are of 2 general types, depending upon whether the test specimen is magnetized by alternating current or by direct current. An a-c hysteresigraph may employ a cathode-ray oscillograph arranged in such a manner that the horizontal deflection of the electron beam is made proportional to magnetizing force while the vertical deflection is made proportional to induction.[1] Other types of a-c hysteresigraphs also have been described.[2,3] Eddy currents within the specimen tend to distort the shape of the recorded hysteresis loop, making laminated specimens necessary. A–c hysteresigraphs record only cyclic loops. Usually symmetrical loops are recorded, but minor or unsymmetrical loops may be obtained if the power supply furnishing the magnetizing current can be arranged to introduce current of suitable harmonic frequency superimposed upon the fundamental component of the magnetizing current. A-c hysteresigraphs appear to have been applied principally to testing sheet materials of low loss and high permeability.

An early form of cathode-ray tube hysteresigraph,[4] and a magnetic curve tracer described by Ewing,[5] may be used to obtain either cyclic a-c loops or d-c loops formed by slowly varying the magnetizing current through the desired cycles. In these devices part of the magnetic circuit is through air, and the strength of the magnetic field in the air path is measured as an indication of the induction in the specimen while the magnetizing current is taken as a measure of magnetizing force. Introduction of an air gap in the magnetic circuit, however, tends to prevent uniform magnetization of the specimen with resulting errors in the measurement of both induction and magnetizing force. A recent magnetic curve tracer[6] obtains d-c loops and is applicable to the testing of specimens in a closed magnetic circuit. It employs a search coil interlinking the specimen and a fluxmeter having its restoring torque automatically counterbalanced throughout its range of deflection so that it is accurately responsive to slow flux changes.

D-c hysteresigraphs do not require laminated specimens because the desired cycle of magnetization may be carried out so slowly that eddy currents do not become large enough to affect the results even if solid specimens are used. Initial magnetization curves and unsymmetrical hysteresis loops, as well as symmetrical hysteresis loops may be obtained. Besides being applicable to the testing of electrical sheet steels the d-c hysteresigraph may also be used in testing magnet materials, specimens of which are commonly solid rather than laminated.

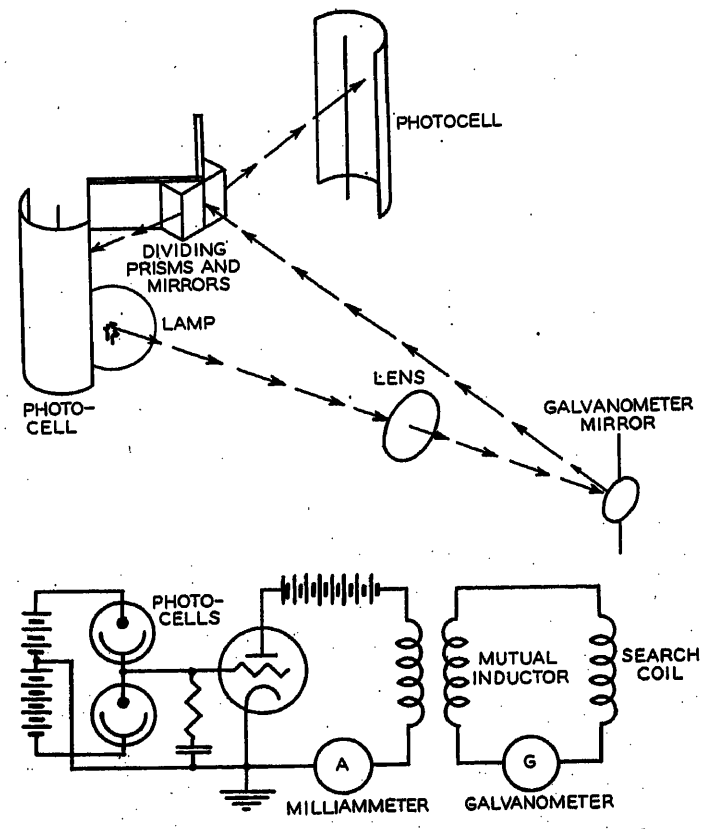



**Figure 1. Optical system and electrical circuit for photoelectric fluxmeter**

## Description

The hysteresigraph described herein is a d-c instrument which may be used to test either laminated or solid specimens in ring or bar form. For bar specimens it is connected to a permeameter in the same manner as the common ballistic galvanometer equipment. When used with the saturation permeameter[7] measurements may be made to a mag-

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1. For all numbered references, see list at end of paper.

netizing force of 3,000 oersteds or higher. The equipment is sturdy and does not employ any delicate instruments which require careful handling, fine adjustment, or special mounting.

## The Photoelectric Fluxmeter

The heart of the instrument is a photoelectric fluxmeter[8] which is responsive to slow changes in flux linking a search coil, and provides an indication which remains constant without drift as long as the flux linking the search coil remains constant. Elementary diagrams of the fluxmeter are shown in figure 1. A galvanometer and search coil are used, and in series with them is connected the secondary coil of a mutual inductor. By means of an optical system and 2 photoelectric cells connected in a vacuum-tube circuit the galvanometer deflection is maintained at zero, the current in the primary coil of the mutual inductor being automatically varied so as to induce a voltage in the secondary coil equal and opposite to any voltage which may be induced in the search coil by a change of flux interlinking it. The change of interlinkage in the secondary coil caused by the change in primary current is then equal and opposite to the change of interlinkage in the search coil. The variation in primary current is, therefore, a measure of the flux variation in the search coil. Since the galvanometer remains at the zero position its suspension torque does not act to cause drift, and the primary current varies only when the flux linkage in the search coil varies.

The optical system and electrical circuit is adapted from the photoelectric recorder.[9] The beam from the galvanometer mirror is focused upon a set of mirrors and prisms which divides it into 2 parts and reflects each part into a photocell. Deflection of the galvanometer causes the light in one cell to increase and that in the other to diminish. The 2 photocells are connected in series with a voltage source, and to the grid of a vacuum tube in such a way that any unbalance of the divided light beam between the 2 cells causes a change in the grid voltage with a resultant change in plate current. The plate current, supplied by a second voltage source, flows in the primary coil of the above-mentioned mutual inductor. The direction of current flow is such that any change caused by a deflection of the galvanometer light beam causes a change of flux linking the secondary coil of the mutual inductor, tending to correct the galvanometer deflection and restore the orginal light balance.

A slight deflection of the galvanometer is evidently necessary to initiate the corrective change of plate current. This, however, is very small, and the final position when a new balance is restored is almost exactly the same as the original position. The photocells are of the vacuum type and are operated at a high voltage so that the current through them depends upon the light falling upon them and is nearly independent of voltage variation. The current for any constant value of grid voltage must be the same in both photocells, since they are in series, and any difference in current would necessarily alter the charge on the grid capacitor and change the grid voltage. The light division between the 2 cells must, therefore, be the same also, which means that the final position of the galvanometer beam must be the same for all steady values of flux linking the search coil. This was demonstrated in the development of the apparatus by setting up in place of the galvanometer a pivoted rod carrying a galvanometer mirror and having an arm 50 centimeters long projecting at right angles. The outer end of the arm was held lightly against the screw of a rigidly mounted micrometer. Turning the micrometer screw caused the end of the arm to move, rotating the mirror as it would rotate if mounted in the usual manner in a galvanometer. It was found that a motion at the outer end of the arm of 0.001 centimeter was sufficient to change the plate current of the tube from one extreme to the other. This corresponds to a light beam deflection of 0.0008 centimeter at the dividing prisms, and would be equivalent to a deflection of 0.004 centimeter on a scale set up at the customary meter distance.

Angular movement of the galvanometer coil equivalent to 0.001 centimeter deflection at the end of a 50 centimeter arm causes an interlinkage change in the galvanometer coil of about 30 maxwell-turns with the coil and field strength employed. In practice the galvanometer is used without any external shunt or series resistance, but is connected directly to the search coil and mutual inductor secondary winding. Since the total number of interlinkages in a circuit tends to remain constant, the difference between the change of flux linkages in the secondary coil of the mutual inductor and that in the search coil is about equal to that in the galvanometer coil. This difference is, therefore, about 30 maxwell-turns for a full-range change in the search coil. With the tube used in this test, the full-range change of plate current was

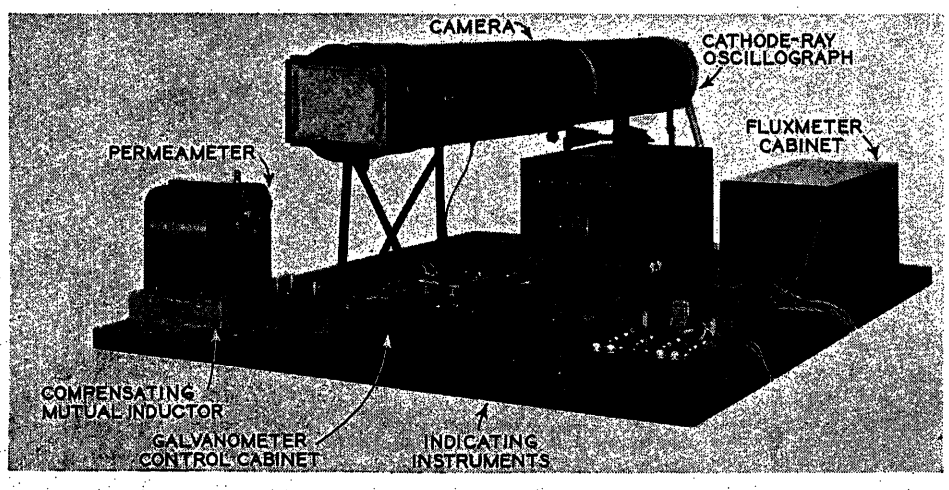



**Figure 2. Photoelectric hysteresigraph**

about 27 milliamperes. A mutual inductor of $10^7$ secondary maxwell-turns per primary ampere is used, so that full-range change of flux linkages was about 270,000 maxwell-turns. The difference between the actual change of interlinkage in the search coil and that indicated by the change in plate current through the primary winding of the mutual inductor is then about 0.0011 per cent. The tube has since been changed to a type which permits a larger change of plate current and has a higher mutual conductance so that the present figure is somewhat less.

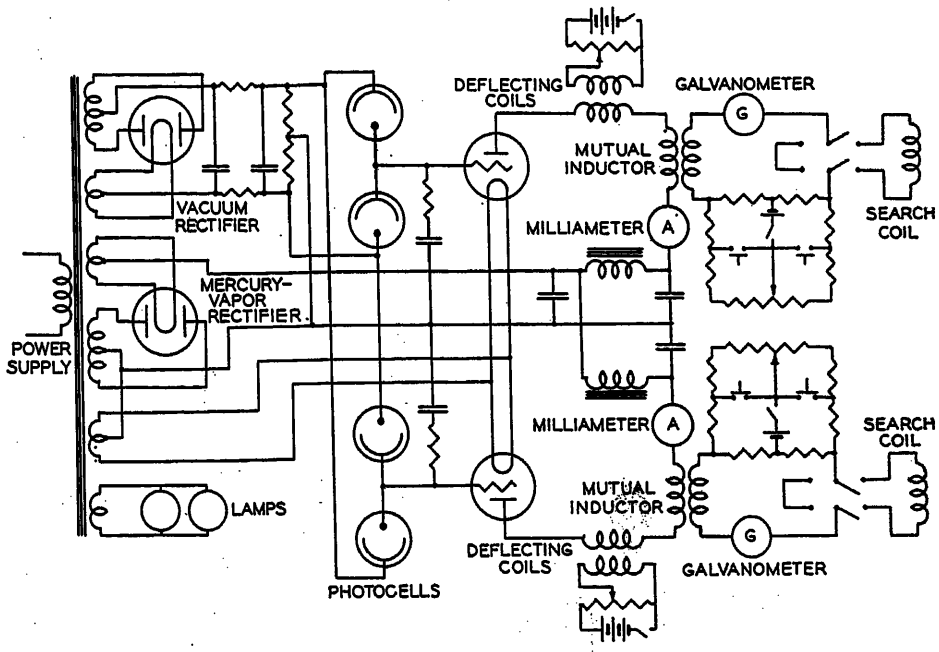



**Figure 3. Photoelectric hysteresigraph circuit diagram**

The amount of deflection during the flux change depends upon the rapidity of the flux change, the constants of the grid and plate circuits, and the characteristics of the galvanometer and its circuit. When the apparatus is used merely as an indicating fluxmeter this deflection is not important, since it returns to the small equilibrium value when the instrument indication becomes steady and can be read. It is necessary only that the deflection be small enough so that there is not sufficient suspension restoring torque to cause measurable drift during the flux change.

For use in automatic curve tracing, however, it is necessary that the current in the primary coil of the mutual inductor shall change accurately in agreement with the changing of interlinkages in the search coil. There must be no measurable lag between them. The galvanometer coil must have sufficiently low inertia to quickly begin to deflect and initiate a corrective change in the plate current when there is a change in interlinkages in the search coil. The capacitance in the grid circuit must be low enough so that the grid voltage quickly changes when there is an unbalance in the photocell circuit. The inductance in the plate circuit must be low enough to permit quick changes of plate current. It has been found that a portable reflecting galvanometer is entirely satisfactory, and no difficulty is experienced in making the constants of the circuits correct for accurate response to slow changes of interlinkage.

The accuracy of the measurement is not affected by small changes in supply voltage, vacuum-tube characteristics, photocell sensitivity, or light intensity. The optical system and photoelectric circuit are similar to those of the photoelectric recorder in being self-compensating for all normal changes in these variables.

The photoelectric fluxmeter is equivalent to a galvanometer of infinitely long period, in that it responds accurately to slow flux changes and its indication remains constant at any part of the range without drift. Moreover, the output of the instrument, instead of being merely deflection of a light beam on a scale, is in the form of electric current of sufficient power to operate sturdy and relatively insensitive indicating instruments or recording devices.

## The Hysteresigraph

The photoelectric hysteresigraph as illustrated in figure 2 consists of 2 such fluxmeters combined with a cathode-ray oscillograph. Magnetic deflection coils fitted to the oscillograph tube are connected in the plate circuits of the fluxmeters so that one fluxmeter causes vertical deflection of the electron beam and the other causes horizontal deflection. The search coil of the first fluxmeter is linked by the specimen under test and that of the second lies adjacent to the specimen but is not linked by it,[7] so that one fluxmeter measures induction changes and the other magnetizing force changes. Bar or strip specimens may be tested at high magnetizing force in the saturation permeameter. The hysteresigraph is adaptable to any type of permeameter in which the magnetizing force can be measured by means of a search coil as described, but which requires no varying compensating adjustment over the range of test. Ring specimens may be tested by using only one fluxmeter, a portion of the magnetizing current being passed directly through the horizontal deflection coils.

The circuit diagram for the hysteresigraph is shown in figure 3. It is similar to that of figure 1, the batteries being replaced by rectified a-c power sources, and 2 complete fluxmeters being provided. A small dry cell with fixed and variable resistors in each galvanometer circuit provide a means of balancing out any small thermoelectric or other voltage which may be present. Push buttons in this circuit facilitate shifting the plate current at will so

that it can be set at any desired value for the beginning of a test, and switches enable the search coils to be inserted in or removed from the circuit.

Figure 4 shows the arrangement of galvanometers, photocells, optical system, and vacuum tubes for both fluxmeters in one cabinet. Transformers, capacitors, and wiring are mounted on the under side of the subbase. The galvanometers are of the portable type[10] having sturdy suspensions and require no careful leveling or delicate adjustment. Moving systems of relatively low resistance are used. Stops are provided limiting the deflection to a small angle and preventing the beam from being thrown entirely off the dividing mirrors at any time. The light beams are supplied by 32-candlepower 6-volt automobile headlight bulbs in ventilated housings, and convex lenses in adjustable tubes. The photocells and prisms are enclosed in housings which prevent entrance of stray light. Voltage is supplied to the photocells by a vacuum rectifier tube through a resistance-capacitance filter circuit. Power is supplied to the plate circuits by a mercury-vapor rectifier tube having a low voltage drop, and a filter circuit of inductance and capacitance.

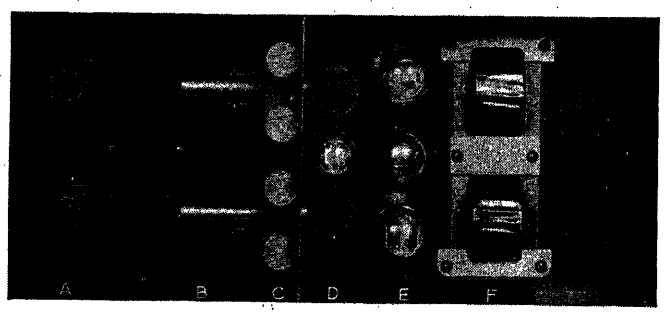



**Figure 4. Interior view of fluxmeter cabinet**

*A*—Galvanometers
*B*—Lens mountings
*C*—Photocell housings
*D*—Lamp housings and rectifier tube
*E*—Vacuum tubes and mercury-vapor rectifier
*F*—Filter reactors

Figure 5 shows the cabinet containing the 2 mutual inductors and the galvanometer control circuits. The 2 mutual inductors are each in 2 sections, astatic to uniform external fields, and are so mounted as to have no inductive coupling between them.

The cathode-ray oscillograph has a tube with a screen 7 inches in diameter, and is equipped with its own power supply. The magnetic deflection coils are located on 2 yokes of nickel-iron alloy having high permeability and low hysteresis, placed so as to produce magnetic fields at right angles to each other and to the electron beam. Two sets of coils are placed on each yoke, one being connected in the fluxmeter circuit and the other being connected to a battery and adjustable resistance. The second set is used to provide adjustment of the zero position of the electron beam.

A photographic record of the pattern traced on the fluorescent screen is made by means of the camera attached to the oscillograph. A piece of fiber tubing is fitted to the shield around the oscillograph tube. In the center is a lens equipped with a shutter and cable release, and at the end provision is made for exposing film or sensitized paper in 5-inch by 7-inch film holders. The shutter is normally used in the "bulb" position, and held open by means of the cable release while the record is being obtained.

A motor generator set has been provided to supply the magnetizing current for the specimen. Field control of the separately excited generator is used to obtain the desired maximum current. Reversing contactors included in the armature circuit of the generator permit a cyclic state of the sample to be obtained quickly, if desired, before tracing the loop. The magnetizing current is varied through the desired cycle by means of 2 rheostats having the resistance elements connected in parallel across the power supply line from the generator and the sliders connected to the magnetizing coil. The sliders are mechanically coupled together in such a way that moving them from one extreme to the other causes the magnetizing current to vary from a maximum value through zero to an equal and opposite maximum value. Not only symmetrical cycles, but any desired unsymmetrical and complicated cycle can be easily obtained.

When specimens are tested in the saturation permeameter a compensating variable mutual inductor may be used to compensate for any desired portion of the area of the potential coil measuring induction. By properly adjusting this inductor the space inside the coil but outside the specimen may be compensated for so that total induction in the sample is recorded. If desired, the entire area of the potential coil may be compensated for, so that intrinsic induction in the specimen is recorded. The primary coil is connected in series with the magnetizing coil of the permeameter, and the secondary coil is connected in series with the search coil measuring induction. The magnetizing force in the saturation permeameter is very

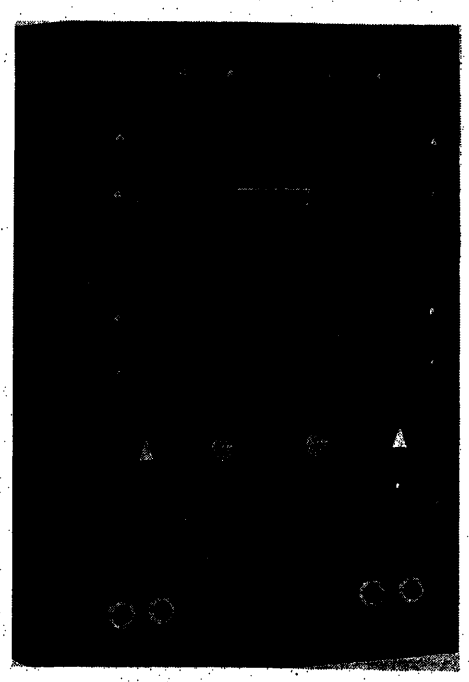


**Figure 5. Galvanometer control cabinet**

nearly proportional to the magnetizing current, so that by means of the compensating inductor a component of flux linkages proportional to the magnetizing force is introduced into the circuit containing the induction search coil. Since the flux linkages in this search coil due to space outside the specimen, or that due to the difference between total and intrinsic induction in the specimen, is proportional to magnetizing force, these flux linkages can be compensated by means of the compensating inductor.

## Records

Samples of records obtained with this equipment are shown in figures 6 and 7. Figure 6 shows portions of symmetrical hysteresis loops for 3 magnet materials. Figure 7 shows the upper portion of a loop having several minor loops traced in the second quadrant.

The co-ordinate lines are put in after the loop has been traced by switching the search coils out of the circuit, setting the plate current for one fluxmeter successively at values representing desired values of induction and varying the other through its entire range, then setting the plate current for the other fluxmeter successively at values representing desired values of magnetizing force and varying the former through its entire range. Values of plate

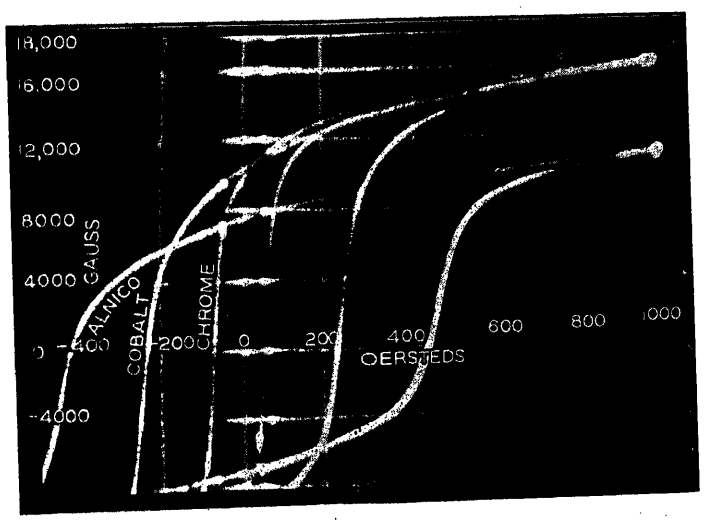



**Figure 6. Hysteresis loops for magnet materials**

current representing these quantities are calculated from a knowledge of the cross-sectional area of the sample, the number of turns and the areas of the search coils, and the mutual inductance of the inductors.

## Application

The hysteresigraph has been found particularly useful in the study of magnet materials, and in obtaining data for magnet design. Recent development of improved materials has brought about the use of permanent magnets in applications not previously considered practical, particularly in applications where the magnet may be subjected to varying external reluctance or strong demagnetizing magnetomotive force. For these applications the second quadrant of the symmetrical hysteresis loop alone is not sufficient for design calculations, but minor loops in this quadrant are also necessary. Figure 7 illustrates the type of data required.

Occasions frequently arise in which magnetic characteristics of a piece of equipment are desired for a particular

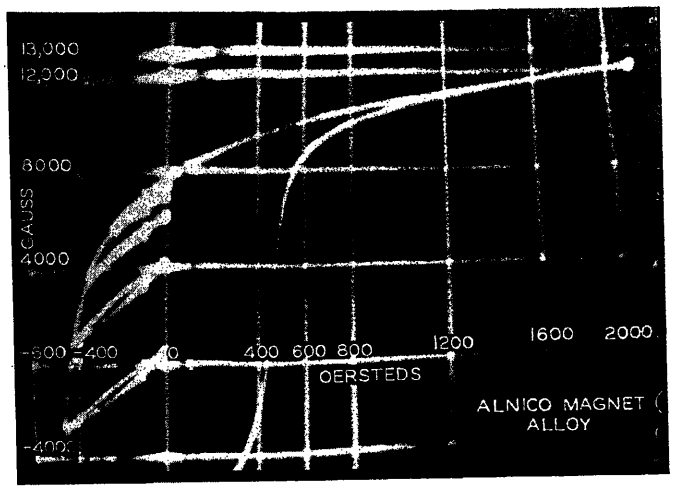



**Figure 7. Hysteresis loop for magnet material showing minor loops in the second quadrant**

type of unsymmetrical cycle. The hysteresigraph has been found to be a convenient instrument for obtaining such data.

## Conclusions

Development of the photoelectric fluxmeter and hysteresigraph was accomplished by combining only apparatus of known and tried characteristics to form a sturdy and accurate instrument simple to adjust and to operate. Testing of magnetic materials and of electrical equipment is facilitated, and magnet design data, not readily obtainable with other forms of testing equipment, are made available.

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# Low-Current Ignitors

By A. H. TOEPFER
ASSOCIATE AIEE

SLEPIAN AND LUDWIG'S discovery of the ignitron[1] principle of initiating the cathode spot of an arc has been followed by intensive investigation of the factors affecting the design and operation of the ignitron. Many of the design features of the ignitron follow conventional mercury-arc-rectifier practice. The distinguishing feature of the ignitron is the ignitor. An ignitor is an electrode of high resistivity material which is partially immersed in the cathode mercury. On sending a sufficiently large current through the ignitor into the mercury, a cathode spot forms upon the mercury at the ignitor mercury junction. The current to accomplish this varies in an inverse manner with the resistivity of the ignitor so that it is necessary to use relatively high resistivity material for practical ignitors. In practice the ignitor is connected to a suitable source of power with some means of switching so that the arc may be started at the proper time during the interval when the ignitron anode voltage is positive.

The most generally used circuit uses a thyratron for controlling the ignitor current as shown in figure 1.

When the grid control voltage of the thyratron and the anode voltage first become positive, the ignitor current flows and increases at a rate determined by the circuit until an arc starts in the ignitron. The current taken by the thyratron then drops to a low value depending on the relative arc drops of the thyratron and the ignitron and the resistance of the ignitor circuit. Generally this value is close to zero. The voltage across the ignitor at the same time drops to a few volts. Figure 2 shows approximately how the starting volts and amperes vary during operation.

The maximum instantaneous value of the current taken by the thyratron is many times larger than the average. It is necessary to use thyratrons with current ratings at least as large as the maximum current peaks required by the ignitors because their cathodes cannot repeatedly stand even momentary overloading without damage.

It is desirable to develop an ignitor requiring as little current as possible for several reasons. The smaller size thyratrons are cheaper than the larger, and usually the heating time of the smaller thermionic cathodes is shorter. If the starting current is reduced without changing the voltage, the load current is shifted from the ignitor circuit to the ignitron more readily at light loads. It is, therefore, more desirable to effect a reduction in starting current than to produce a cheaper thyratron to handle the ignitor load.

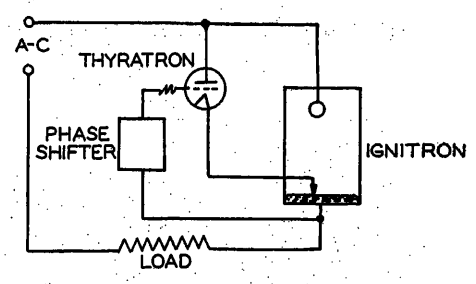
The theory advanced by Slepian and Ludwig[1] for the formation of the cathode spot at the ignitor mercury junction directs attention to the high current density and corresponding voltage gradient developed there, and points out the similarity between these conditions and the conditions existing at the last points of contact of separating electrodes. Other workers have used essentially the same picture.[2,3] Experience indicates that a material must satisfy the following conditions to be practically suitable for ignitors.

1. It must not be wet by mercury.
2. It must be workable.
3. It must not deteriorate in the arc.
4. It must have the proper electrical resistance.

The theory of Slepian and Ludwig suggests that the nature of the contact between the mercury and ignitor at the ignitor mercury junction is important. Hence, it is not surprising that if a material is wetted by the mercury during operation as an ignitor the starting current usually jumps to high values which may damage the thyratron. A convex meniscus seems to be necessary for low starting currents. If the material is wetted by the mercury a concave meniscus is obtained usually with large starting current. Also under these conditions the cathode spot tends to anchor at the ignitor instead of moving away from it in the usual way, and may damage it. This requirement eliminates many materials.

The substances which have been found to be useful ignitor materials are generally very hard in their crystalline form. Some of these materials are silicon carbide, boron carbide, and materials known under the trade names of Carborundum, Globar, and Silit. Shaping, mounting, and making electrical connection to these materials offers difficulties. Globar is easy to work when made up in high resistivity rods, but if processed to reduce the resistivity they become difficult to work because of increased hardness.

Figure 1




The need for working arises because it had been found desirable to shape ignitors to a point because this decreased the starting current. For example, comparing an ignitor made of quarter-inch rod and one made of the same material ground to a point, the latter required about one

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1. For all numbered references, see list at end of paper.

third of the current required by the rod at an increase in voltage of 20–25 per cent. The increase in voltage is due to the increase in the resistance of the ignitor due to reducing the section.

The cathode spot starts at the ignitor afresh each cycle and then does not have time to get very far away from it in the conducting period. Ignitrons also are usually built with the anode close to the cathode and often operate red hot. Hence, the ignitor frequently is required to run hot because it has little chance to dissipate heat through the ignitor lead or the mercury. Under these conditions the material must be stable. Materials have been found and are used that show no sign of deterioration, wear, or erosion after thousands of hours operation as ignitors. Some appear to have unlimited life.

The electrical characteristics depend on the resistivity and the geometric form of the ignitor. The geometric form and dimensions need to be a compromise between several conflicting conditions.

It is desirable to have the area of the ignitor actually under the mercury as small as possible, as this makes the ratio of the useful current which flows in the close vicinity of the junction, to the total current large. Also, it is desirable to make the length of the ignitor above the mercury as short as possible to reduce the voltage drop required to send the starting current through the length of the ignitor. The splashing of the mercury sets limits to what may be done in both of these directions. To avoid missing due to the ignitor losing contact with the mercury, it has been found necessary to use immersion depths of the order of a quarter of an inch. The distance from mercury to the conducting head, holder, or ignitor lead must be of the order of one half of an inch to prevent short circuiting of the ignitor by the splashing of the cathode mercury. Such short circuits may damage the cathode of the control tube if too much current passes through the circuit. Hence, we have the length fixed at $^3/_4$ of an inch plus the length of a head, or additional length to provide for some sort of mounting to make connection to the ignitor lead.

The thickness and shape are also reached by compromise between mechanical and electrical characteristics. The ignitor materials are brittle, therefore, they must be made in such diameters and shapes which will be strong enough to stand handling in assembly and the forces due to mercury when moving the ignitrons or during operation when some force is exerted by the mercury vapor and the motion of the mercury under the influence of the cathode spots. The shape generally used is approximately that of a cantilever beam of uniform strength. A typical ignitor is shown in figure 3. The tip diameter is of the order of 0.080 to 0.090 inch.

**Figure 4**

*W*—Width of slot

*D*—Depth of tip immersion

*S*—Surface tension of mercury = 0.0475 grams per millimeter

Pressure of immersed mercury = 0.0136 grams per square millimeter

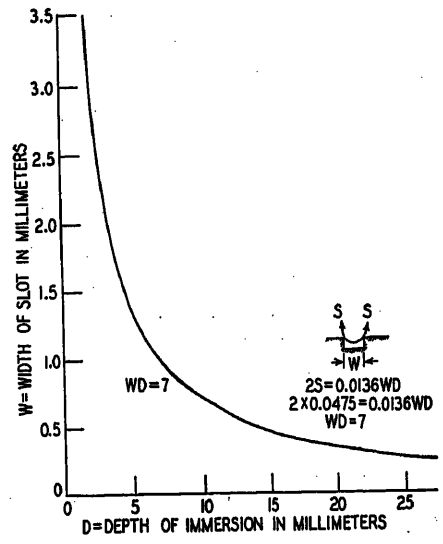



**Table I**

| Ignitor | Starting Amperes Before Slotting | Starting Amperes After Slotting | Starting Volts Before Slotting | Starting Volts After Slotting | Current Ratio After Slotting / Before Slotting |
|---|---|---|---|---|---|
| *PA N* 9 | 24 | 11 | 40 | 42 | 0.46 |
| *PA N* 14 | 20 | 7 | 50 | 50 | 0.35 |
| *PA L* 15 | 21 | 12 | 43 | 45 | 0.57 |
| *PA H* 20 | 18 | 9 | 38 | 40 | 0.50 |
| *PA H* 8 | 24 | 11 | 50 | 50 | 0.46 |
| *PA N* 19 | 14 | 7 | 75 | 80 | 0.50 |

The use of such a shape has a definite effect on the starting volts and amperes as mentioned before. For a definite size and shape of ignitor the starting voltage is directly and the starting current inversely proportional approximately to the resistivity of the material used. Thus increased resistivity generally means increased voltage and decreased current. The law has not been definitely established but examination of the characteristics of a large number of ignitors shows the trend toward such a law. The most desirable resistance to use is governed by the voltage and current limits that can be tolerated. The upper voltage limit is generally set at 100 volts for the present though it is desirable to have it as low as can be obtained. Many ignitors require less than this maximum limit. The current for an ignitor of a resistance that will give starting voltage of 100 volts would be more or less constant in value from one igniter to another if uniformly shaped ignitors were made of a material of a certain resistivity, but it happens that the problem of manufacturing ignitors is far from being as simple as that. The problem of wetting has driven the ignitor maker to treat ignitors, or make them of certain materials by processes that are

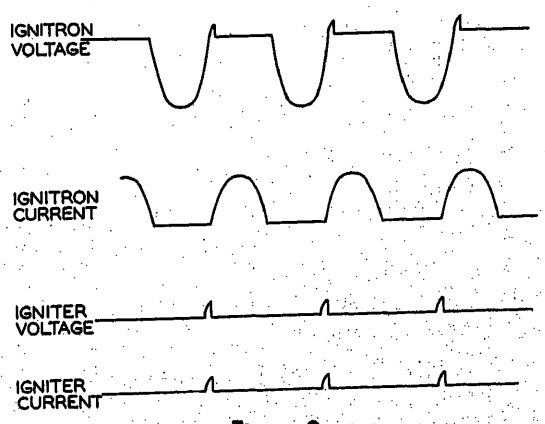



**Figure 2**

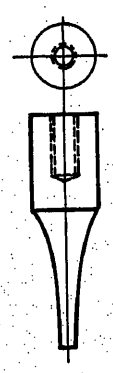


**Figure 3**

difficult to control and repeat exactly. Hence, the product varies in starting characteristics so an upper limit to the current required is set and the ignitors accepted if the current is less than 15 amperes and the voltage less than 100 volts.

The current is influenced a great deal by the surface of the part of the ignitor immersed in the cathode mercury. An ignitor with a smooth polished surface requires more current than one with a rough surface though the resistivities are the same. One may easily reduce the starting current, without affecting the voltage, by covering part of the immersed surface with insulation. However, fastening a suitable insulator on an ignitor is difficult and has been applied only in laboratory experiments.

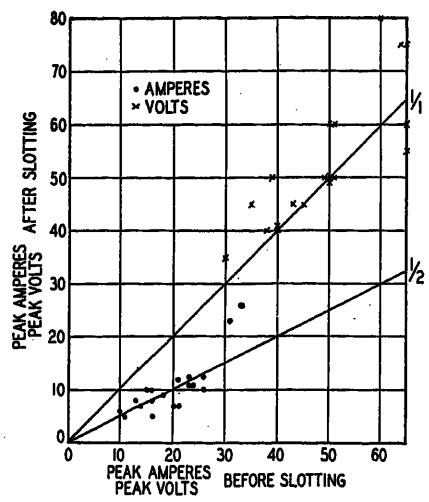



**Figure 5. Effects of slotting on starting volts and amperes**

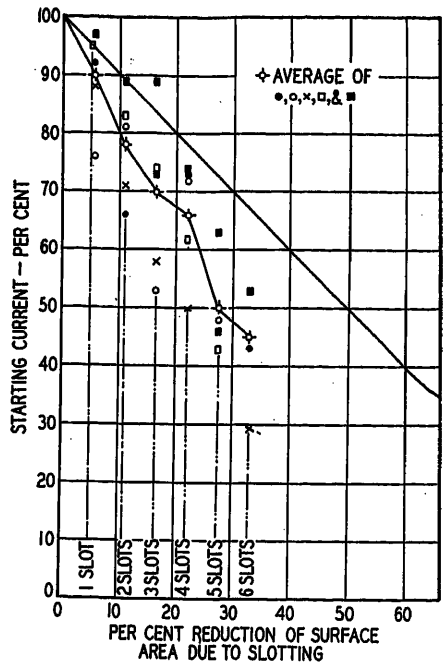



**Figure 6**

Slepian suggested a very effective method of reducing the surface area of the ignitor which could come in contact with the mercury and at the same time not appreciably increasing the resistance through the ignitor to the mercury junction. He estimated that the mercury would not enter slots of the order of one millimeter wide at ordinary ignitor immersion depths due to the high surface tension of the mercury. A simple experiment with 2 glass plates immersed in mercury proved the theory and calculations were made to show the relationship between the width of slot and depth of immersion when the surface tension forces just balance the static pressure. The results of these calculations are plotted in a curve, figure 4.

If the mercury level stayed always constant, the ideal slot would vary in width from tip to mercury surface. An ignitor with such slots has not been produced. It was convenient to take some of the present design of boron carbide ignitors which have a tip diameter of 0.080 or 0.090 inch and cut slots which were approximately 0.020 inch wide. Six slots were cut in each ignitor.

A few of the results are tabulated in table I.

A large number of ignitors were tested and the results spotted on figure 5. This shows the effect of slotting quite clearly. The slight increase in voltage may be due to the increase in resistance due to the cutting away of material. The current was reduced to nearly one half of the original. The picture figure 7 shows several slotted ignitors and an unslotted one for comparison.

It was observed that the current reduction was greater than the reduction in area. This was investigated by cutting one slot at a time and measuring the current after each slot was cut. The results are shown in figure 6, which shows starting current in per cent plotted against reduction of surface area in per cent.

An examination of the surface of the mercury at the slots and between slots showed that the line of contact of the mercury with the ignitor between slots was not a plane curve but was lower at the slots than between the slots. This fact coupled with a change in current distribution in the ignitor and mercury may account for the additional reduction in current.

The minimum current and voltage at which an ignitor will initiate an arc has not been determined. If the currents can be reduced sufficiently it becomes possible to use smaller and cheaper thyratrons and other means of supplying the ignitor current. Some ignitors do not suffer when back current passes through them so if the current requirement is reduced other methods of control become possible which, at present, are too costly or unwieldy to be useful.

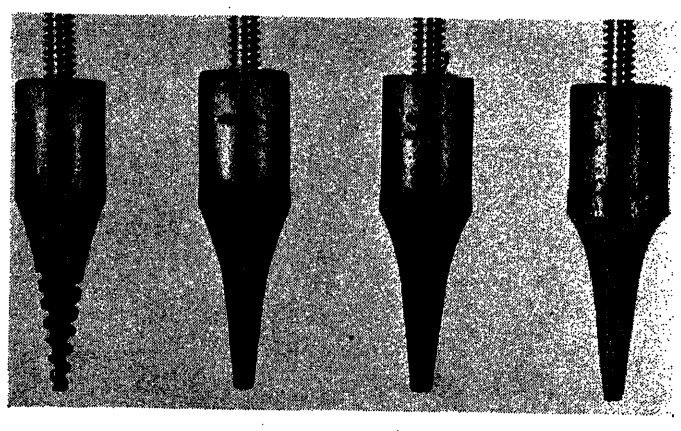


**Figure 7**

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# Approximating Potier Reactance

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POTIER REACTANCE is a somewhat fictitious reactance, because it is a combination of reactance, change of saturation, and change of flux form. Nevertheless, it is sometimes a rather useful fiction because it can be easily tested, and because it can be used to obtain full load field currents of synchronous machines when only the no-load saturation curve is available. It is also useful for determining effects of saturation on stability.

The following discussion attempts only to give 3 approximate empirical methods of calculating $X_p$ and to show the probable accuracy of the methods for typical machines. The value of the methods can best be judged by a comparison of calculated values with test values, as is done in table I and in figures 6 to 9. This is because the equations used involve certain approximations and in addition are made up of 3 terms, all of which must be calculated by approximate or by semiempirical formulas. A discussion of some of the difficulties involved in the accurate predetermination of $X_p$ is also included, but formulas for accurate calculation are not developed.

Potier reactance is tested as the difference between 2 saturation curves, one taken at no load, and the other taken at full current, zero power factor. These curves for a typical machine are shown in figure 1, and the geometrical construction usually employed in obtaining the reactance from these 2 curves is shown by the triangle $ABC$. (The altitude of the triangle is the Potier reactance drop in volts so that per cent $X_p$ equals $(CD/VB') \times 100$.) Expressed in words, the process is to find the triangle which will fit between the 2 curves at both the location $ABC$ and the location $A'B'C'$, where the point $A$ is at the voltage at which the reactance is desired.

The process of finding a triangle that will fit at 2 places is simple, but, as might be supposed, the actual value of reactance obtained will depend on the voltage at which the upper triangle is constructed. To illustrate this, figure 2 has been drawn showing Potier reactance of the machine of figure 1 plotted against terminal voltage, and reference can be made to several similar curves in the first article of the bibliography. Another difficulty associated with the process of fitting 2 triangles is that of determining when they fit, and to illustrate this point, the curve of figure 3 has been drawn. This curve is identical with figure 2 except that the field currents at any point on the given test saturation curves of figure 1 have been assumed to be accurate only within ±1 per cent, and the resulting effect on Potier reactance has been shown as a crosshatched band. Stated in words, this question of fit resolves itself into the fact that since Potier reactance is measured geometrically as a voltage drop parallel to the air-gap line, it can be measured accurately only when the slope of the no-load saturation curve differs appreciably from that of the air-gap line. In the following discussion, therefore, the value of $X_p$ will not be discussed below the point where the slope of the no-load saturation curve at the peak of the Potier triangle equals twice the slope of the air-gap line.

## Analysis of Machine Internal Conditions Affecting $X_p$

To get a better physical picture of what constitutes Potier reactance, let us first consider in detail the fluxes existing when a machine is operating as a synchronous condenser, that is, at the point $A$ in figure 1. Under these conditions, the internal or air-gap voltage is ordinarily considered to be greater than the terminal voltage, because of reactance drops. The end winding reactance, for example, can be considered merely as external reactance so that all machine fluxes are raised by the drop across the end winding reactance. The slot reactance causes the flux in the air gap to be greater than that in the core, since part of the flux crossing the gap is shunted across the slots (because of the armature current) and does not reach the core, but only cuts the conductors near the top of the slot. Similarly, part of the flux through the poles does not even cross the gap, but crosses directly from the side of one pole to the side of the next, and may be said to produce a field reactance drop quite similar to the slot winding or end winding reactance drop.

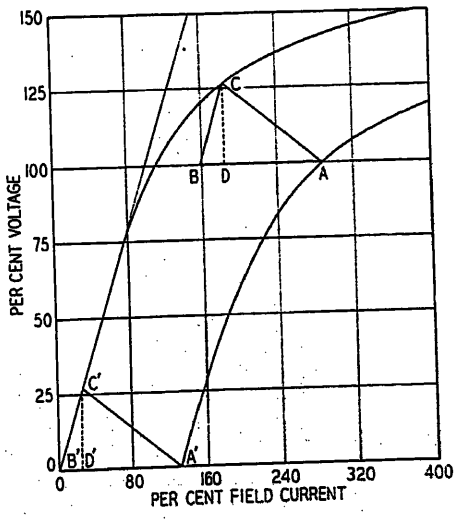



**Figure 1. Typical synchronous-machine saturation curves showing construction for obtaining $X_p$. (These are actual test curves)**

In figure 4, the no-load saturation curve has been broken up into its component parts, representing pole, air-gap,

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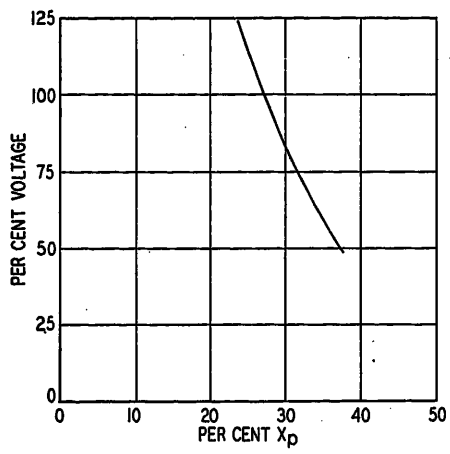
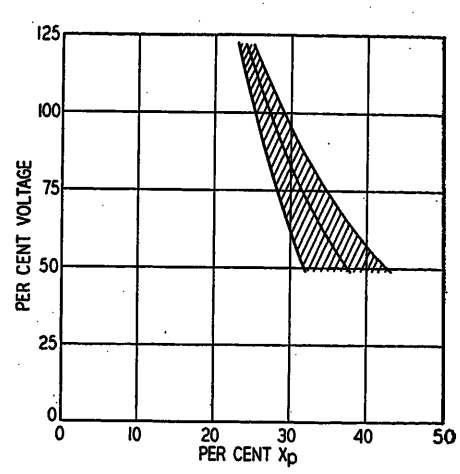



**Figure 2. $X_p$ as obtained from the test curves of figure 1**

**Figure 3. Inherent chance of error in testing $X_p$**




This curve is the same as that of figure 2, except that the field currents at any point on the given test saturation curves of figure 1 have been assumed to be accurate only within ±1 per cent, and the resulting effect on $X_p$ has been shown as a crosshatched band

tooth, and core saturation. To be exact, each of these components should be broken down into still smaller parts, and should vary with load conditions on the machine, but the additional complications would only confuse the relations to be brought out now. The reactance drops mentioned above have been shown in figure 4, so that the points $P$, $G$, $T$, and $C$ represent the internal voltages in the pole, air gap, teeth, and core, respectively. Figure 4 can be simplified by making the following assumptions: (1) the core saturation is negligible; (2) the saturation in the teeth is largely at the tips of the teeth (see appendix), so that the flux determining saturation in the teeth can be assumed to be the same as the flux in the air gap; and (3) the effective flux in the pole can be considered to be increased above no-load conditions by the amount of transient reactance drop, since transient reactance represents leakage reactance plus flux which crosses between poles and does not link the field winding. Transient reactance flux is not identical with leakage flux because of harmonics, change of wave form, saturation and other factors, but in developing the following approximate formula, it will be considered identical.

## Table I. Comparison of Test and Calculations

| Machine | | | Per Cent Reactances | | | | Per Cent Potier Reactance | | | | | | Saturation Data | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| No. | Kva | Poles | $X_d$ | $X_l$ | $X_d'$ | Test | Calculated by Eq 1 | Difference | Average Difference | Calculated by Eq 2 | Difference | Calculated by Eq 3 | Difference | Pole AT / Tooth + Pole AT | $K_{nl}$ | $K_q$ |
| 1 | 200 | 6 | 108 | 6.3 | 19.9 | 19.8 | 18.0 | +1.8 | | 14.8 | +5.0 | 15.9 | +4.0 | 0.88 | 1.19 | 1.37 |
| 2 | 5,000 | 8 | 142 | 13.7 | 35.3 | 26.0 | 26.4 | −0.4 | | 27.3 | −1.3 | 28.3 | −2.3 | 0.59 | 1.12 | 1.43 |
| 3 | 10,000 | 8 | 170 | 13.5 | 41.1 | 31.1 | 29.7 | +1.4 | +3.4 | 30.8 | +0.3 | 33.0 | −2.0 | 0.59 | 1.09 | 1.49 |
| 4 | | | | | | | 25.9 | +5.2 | | | | | | 0.45 | | |
| 5 | 100 | 10 | 160 | 12.7 | 33.7 | 31.6 | 27.1 | +4.5 | | 25.9 | +5.7 | 27.0 | +4.6 | 0.68 | 1.24 | 1.94 |
| 6 | 500 | 10 | 129 | 9.4 | 28.5 | 22.9 | 20.7 | +2.2 | | 21.4 | +1.5 | 22.8 | +0.1 | 0.59 | 1.17 | 1.49 |
| 7 | 800 | 14 | 71 | 8.6 | 21.7 | 15.9 | 18.3 | −2.4 | | 16.8 | −0.9 | 17.4 | −1.5 | 0.74 | 1.3 | 1.7 |
| 8 | 200 | 18 | 124 | 17.0 | 33.0 | 26.6 | 28.9 | −2.3 | | 27.0 | −0.4 | 26.4 | +0.2 | 0.75 | 1.21 | 1.82 |
| 9 | 220 | 18 | 125 | 16.0 | 32.3 | 25.3 | 28.2 | −2.9 | | 26.2 | −0.9 | 25.9 | −0.6 | 0.75 | 1.18 | 1.43 |
| 10 | 250 | 18 | 149 | 9.3 | 17.6 | 16.5 | 15.3 | +1.2 | +2.1 | 14.5 | +2.0 | 14.1 | +2.4 | 0.73 | 1.15 | 1.42 |
| 11 | | | | 8.3 | 16.7 | | 13.6 | +2.9 | | | | | | 0.63 | | |
| 12 | 450 | 18 | 132 | 14.7 | 33.8 | 25.2 | 28.2 | −3.0 | | 26.7 | −1.5 | 27.1 | −1.9 | 0.71 | 1.12 | 1.28 |
| 13 | 850 | 18 | 153 | 16.2 | 36.6 | 28.6 | 26.2 | +2.4 | | 29.0 | −0.4 | 29.2 | −0.7 | 0.49 | 1.09 | 1.42 |
| 14 | 625 | 22 | 118 | 14.8 | 32.8 | 33.3 | 30.5 | +2.8 | | 26.1 | +7.2 | 26.3 | +7.0 | 0.87 | 1.24 | 2.06 |
| 15 | 875 | 24 | | 19.1 | 44.0 | 38.2 | 34.6 | +3.6 | | 34.7 | +3.5 | 35.2 | +3.0 | 0.62 | 1.16 | 2.46 |
| 16 | 300 | 26 | | 22.4 | 39.7 | 32.5 | 29.7 | +2.8 | +0.9 | 33.2 | −0.7 | 31.8 | +0.8 | 0.42 | | 2.20 |
| 17 | | | | | | | 33.5 | −1.0 | | | | | | 0.52 | | |
| 18 | 750 | 26 | 80 | 10.8 | 23.4 | 15.3 | 18.7 | −3.4 | −4.2 | 18.7 | −3.4 | 18.7 | −3.4 | 0.63 | 1.44 | 2.10 |
| 19 | | | | | | | 20.3 | −5.0 | | | | | | 0.75 | | |
| 20 | 1,100 | 28 | 127 | 15.6 | 36.8 | 31.0 | 28.1 | +2.9 | | 28.9 | +2.1 | 29.3 | +1.7 | 0.59 | 1.09 | 1.73 |
| 21 | 2,200 | 30 | 102 | 15.0 | 32.5 | 27.4 | 28.3 | −0.9 | | 26.0 | +1.4 | 26.0 | +1.4 | 0.75 | 1.23 | 1.93 |
| 22 | 375 | 32 | 116 | 19.3 | 38.4 | 35.6 | 35.6 | 0 | 0 | 31.3 | +4.3 | 30.9 | +4.7 | 0.85 | 1.19 | 2.10 |
| 23 | | | | | | | 36.3 | −0.7 | | | | | | 0.89 | | |
| 24 | | | | | | | 34.9 | +0.7 | | | | | | 0.82 | | |
| 25 | 1,875 | 32 | 124 | 18.7 | 39.3 | 30.8 | 32.5 | −1.7 | | 31.6 | −0.8 | 31.5 | −0.7 | 0.67 | 1.23 | 1.66 |
| 26 | 625 | 40 | 62 | 10.1 | 22.3 | 20.0 | 19.9 | +0.1 | | 17.7 | +2.3 | 17.9 | +2.1 | 0.80 | 1.21 | 1.46 |
| 27 | 7,500 | 44 | 114 | 20.0 | 42.0 | 29.2 | 31.2 | −2.0 | −3.1 | 33.8 | −4.6 | 33.6 | −4.4 | 0.51 | 1.12 | 1.72 |
| 28 | | | | | | | 34.1 | −4.9 | | | | | | 0.64 | | |
| 29 | | | | | | | 31.6 | −2.4 | | | | | | 0.53 | | |
| 30 | 1,000 | 48 | 97 | 18.5 | 35.0 | 33.7 | 29.7 | +4.0 | +3.6 | 28.8 | +4.9 | 28.0 | +5.7 | 0.68 | 1.13 | 1.63 |
| 31 | | | | | | | 30.5 | +3.2 | | | | | | 0.73 | | |
| 32 | 5,000 | 56 | 148 | 16.8 | 34.7 | 24.0 | 26.3 | −2.3 | | 28.0 | −4.0 | 27.8 | −3.8 | 0.53 | 1.39 | |
| 33 | 5,000 | 56 | 104 | 16.8 | 34.3 | 27.4 | 28.3 | −0.9 | | 27.8 | −0.4 | 27.5 | −0.1 | 0.66 | 1.39 | |
| 34 | 800 | 60 | 134 | 11.5 | 29.9 | 19.3 | 22.2 | −2.9 | | 23.0 | −3.7 | 23.9 | −4.6 | 0.58 | 1.19 | 1.46 |

Note: Test values were taken from regular commercial tests and not from special tests. $X_l$ has been calculated by Kilgore's formulas. $X_d'$ has been calculated either by Kilgore's formulas or by a simplified formula. Ratio of pole ampere turns to pole plus tooth ampere turns has been calculated in several cases by more than one method.

## Approximate Graphical Method for Calculating $X_p$

Using these simplifications, then, figure 4 can be reduced to figure 5, and the point $A$ of figure 1, which is the operating point at zero power factor, can be determined as the sum of the ampere turns in the gap (equals $NG$ in figure 5) plus the tooth ampere turns (equals $NT$ in figure 5) plus the pole ampere turns (equals $SP$ in figure 5) plus the effective demagnetizing ampere turns of the armature current (equals $D'A'$ in figure 1). After the point $A$ has been obtained, the determination of $X_p$ can be made by the usual method shown in figure 1.

## First Approximation for $X_p$

The above procedure for calculating $X_p$ is a graphical one. The same procedure can easily be reduced to an approximate formula by considering 2 limiting conditions,

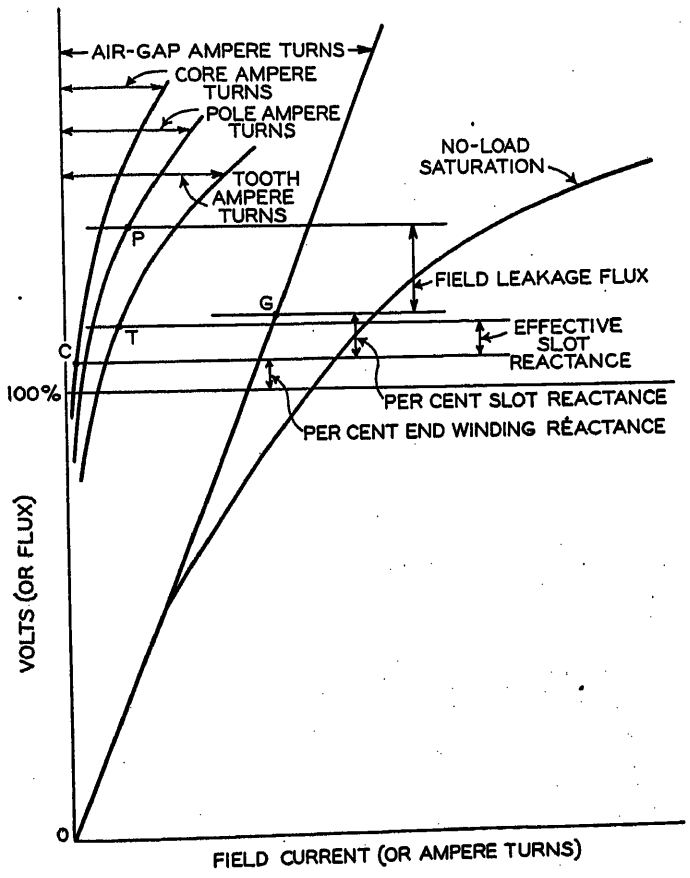



**Figure 4. Internal conditions determining $X_p$**

and assuming linear variation between these 2 conditions. The first limiting condition exists when there is no saturation in the poles, all saturation being in the teeth. For this case Potier reactance equals leakage reactance. The second limiting condition exists when all saturation occurs in the poles, and the teeth are unsaturated. For this case Potier reactance equals transient reactance. If intermediate points are assumed to depend directly upon the ratio of pole saturation to total saturation, the formula for $X_p$ becomes

$$X_p = X_l + (X_d' - X_l) \frac{\text{pole ampere turns}}{\text{pole plus tooth ampere turns}} \qquad (1)$$

This equation is a simplified form of one given by L. A. Kilgore in his discussion of reference 1.

## Second Approximation for $X_p$

For use where the ratio of pole ampere turns to pole plus tooth ampere turns cannot be determined, an average value for this ratio can be assumed, so that equation 1 becomes

$$X_p = X_l + 0.63\,(X_d' - X_l) \qquad (2)$$

## Third Approximation for $X_p$

In cases where $X_l$ is not available, an empirical formula applicable to average machines has been found to be merely

$$X_p = 0.8\,(X_d') \qquad (3)$$

## Comparison of Test and Calculated Results

Results of 34 calculations using formulas 1, 2, and 3 are compared with test in table I, and the same results are shown in graphical form in figures 6 to 9. In figures 7, 8,

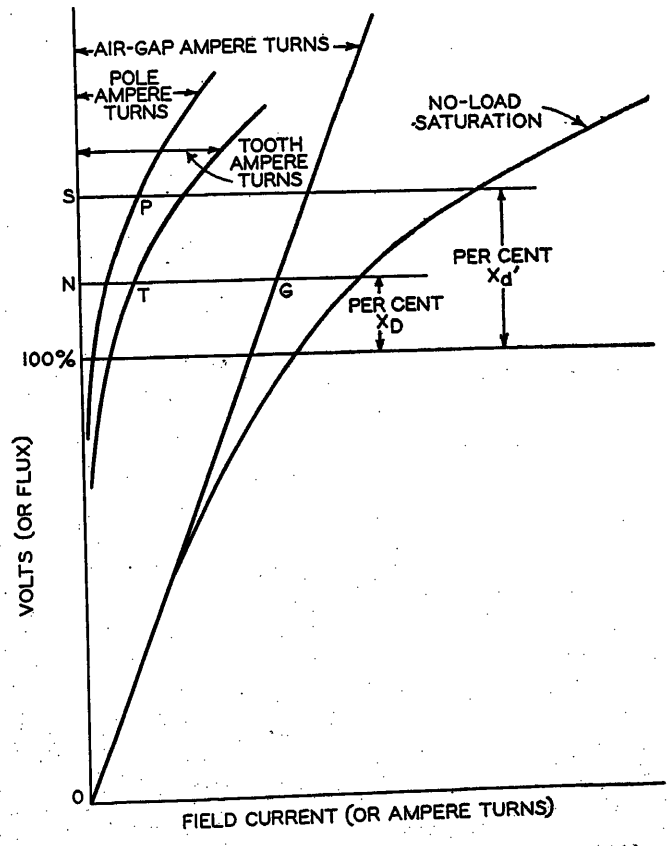



**Figure 5. Simplified internal conditions determining $X_p$**

and 9, the difference between test and calculated values for each machine has been drawn as a line above or below a zero axis, and the lines have been arranged in order of descending magnitude to give in effect a distribution curve. The abscissa can consequently be labeled "number of machines exceeding a given per cent error." Thus in figure 8

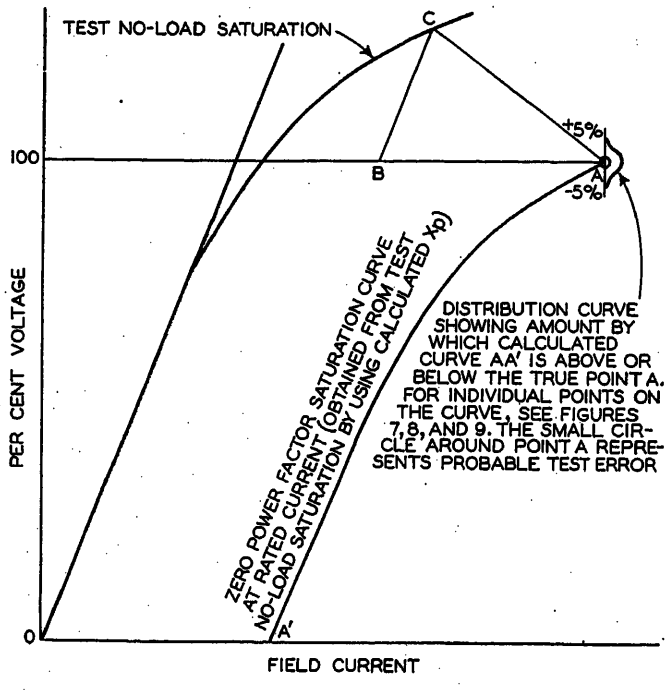


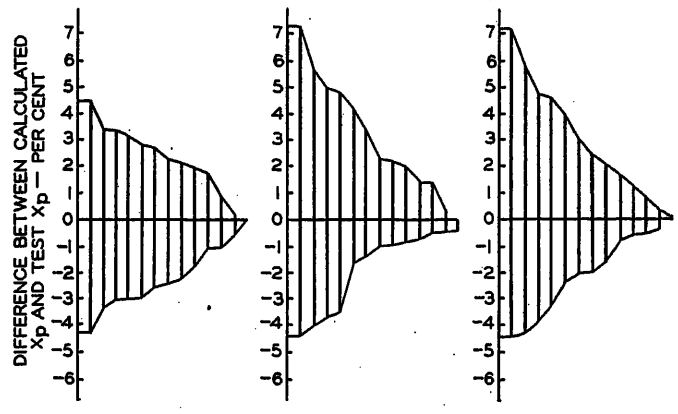

**Figure 6. Comparison of calculated $X_p$ with test $X_p$**

the ordinate for $-3$ per cent error yields an abscissa whose value is 4, which is the number of machines for which test $X_p$ was more than 3 per cent less than calculated $X_p$. Per cent has everywhere been taken as per cent of rated terminal voltage, in order to avoid confusion and so that the distribution curves of figures 7, 8, and 9 can be more easily visualized in their true significance as per cent of terminal voltage above and below the true point $A$ in figure 6. In this figure, the assumption made is that the no-load saturation curve has been obtained from test, and that calculated $X_p$ is being used to obtain the full load zero power factor curve which will then be above or below the true point $A$ by an amount exactly equal to test $X_p$ minus calculated $X_p$.

When judging the results, it should be remembered that the quantity being calculated varies with test error and voltage rating as shown in figure 3. Furthermore, the values of end winding leakage reactance and also those of transient reactance as calculated by published formulas differ slightly from each other and from test. The other term in equation 1 is the ratio of pole saturation to tooth plus pole saturation, and it is hardly necessary to say that its value will depend upon the method of calculation used, since all practical methods of calculating saturation in a magnetic circuit as complicated as a synchronous machine involve approximations or empirical factors. In table I, the ratio of pole to tooth plus pole ampere turns for several of the machines has been calculated by 2 or 3 different methods just to show the variation that is likely to be obtained.

In compiling table I, most machines were chosen at random, and the remaining few machines were chosen because they did not check the usual method of calculating saturation. All results have been included in the table, and no machines for which $X_p$ has been calculated have been omitted.

Considerable data have been included in table I just to give a better picture of each machine. Thus the values of $K_{nl}$, $K_p$, $X_d$, and $X_p$ are sufficient to permit virtual reconstruction of the saturation curves, and the division




**Figures 7, 8, and 9. Difference between test $X_p$ and $X_p$ calculated by equations 1, 2, and 3, respectively**

Note: In these figures, each machine is represented by a line from the zero axis up or down to the proper per cent difference. The lines are arranged from left to right in the order of decreasing magnitude to give, in effect, a distribution curve. These curves are indicated to a more correct scale in figure 6

of saturation between stator and rotor can be determined from the ratio of pole ampere turns to pole plus tooth ampere turns given in column 15.

## Comments on the Difficulties of Calculating Accurately Potier Reactance

As mentioned before, Potier reactance is a somewhat fictitious reactance, and consequently the more exact method of calculating it to be discussed below will be quite different from the usual method of calculating a reactance, and will consist only of calculating 2 saturation curves, one under full-load zero power factor conditions, and the other under no-load conditions. Furthermore, since the usual methods of calculating saturation curves are so well known, the following discussion will assume a knowledge of the general method, and will discuss only 3 details that have particular bearing on the difference between the no-load curve and the full current zero power factor curve.

1. At no-load, the flux form in the air gap is shown for a typical machine in figure 10. The estimated effect of saturation on this flux form is shown at 125 per cent

voltage by the dotted curve on the same figure. The flux form constants of these waves are tabulated in the figure. The ratio between the fundamental peak and the actual peak flux is $C_1$. The ratio of the average to the peak value of the actual flux wave is $C_p$.

2. Under full current zero power factor conditions, the same curve and its constants are also shown in figure 10. The obtaining of these curves, especially the ones under saturated conditions, may involve considerable cut and try work or else good approximations, but the calculation of tooth and of gap ampere turns is relatively simple once the constants have been obtained. It is assumed that tooth flux and gap flux are identical because, as shown in the appendix, tooth saturation occurs largely at the tips of the teeth. Actually, the flux form changes continuously between the tips and the base of the teeth. In general, the flux forms become flat-topped soon after saturation occurs in the teeth. Saturation in the pole between damper bars or in the pole tips has been neglected, but may be quite important in the occasional machines where it occurs.

3. Having calculated tooth and gap ampere turns by

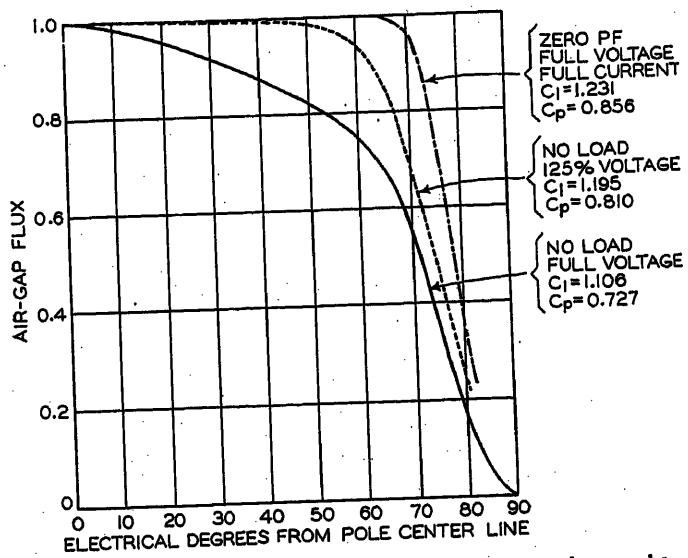



**Figure 10. Flux forms for a typical salient-pole machine under different operating conditions**

the usual methods, but using the above corrected values of $C_1$ and $C_p$, the next step is to calculate pole ampere turns; but in order to do this, the field leakage flux must be obtained. If a constant permeance is assumed in the leakage flux paths between pole sides regardless of the amount of flux or shape of the field, then the leakage flux is this permeance times the number of ampere turns acting, and the per unit leakage is this flux divided by the average flux from figure 10.

For help in approximating the ampere turns acting to produce flux between pole sides, the sketches of figure 11 have been drawn. Two things should be noted: first, that the ampere turns acting between pole heads is practically the sum of the gap ampere turns plus the demagnetizing ampere turns plus the tooth ampere turns—all under the proper conditions of flux form and saturation; second, that the ampere turns acting between the pole sides may sometimes act in a direction that tends to reduce the pole density instead of increasing it. In other words, the leakage flux between pole sides may actually become negative so that the effective permeance between pole sides does not remain constant. This second effect takes place only when the pole saturation becomes an appreciable part of the total ampere turns, but the amount of the effect will always differ between no-load and full load because of demagnetizing ampere turns, and consequently, will affect Potier reactance.

The above 3 items (1. change of wave shape with tooth saturation, 2. change of wave shape with demagnetizing ampere turns, 3. change of pole side leakage flux with pole saturation) are the major ones causing difference between the no-load and full-load saturation curves. Items 1 and 2, for example, cause the air gap ampere-turn line to bend back at higher voltages as shown in figure 12 instead of being the straight line it is often considered to be. Item 3 causes appreciable reduction in pole density at the high voltages and currents where pole ampere turns are greater than gap ampere turns.

It must be remembered in considering the above, that all practical methods of calculating synchronous machine

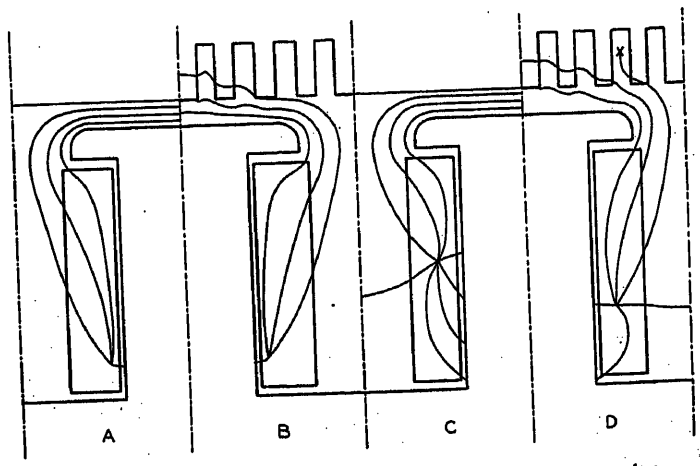



**Figure 11. Approximate flux maps for different conditions (ampere turn lines only are shown)**

*A*—No load, no saturation
*B*—No load, no pole saturation. Tooth ampere turns equal gap ampere turns
*C*—No load, no tooth saturation. Pole ampere turns equal gap ampere turns
*D*—Full load, zero power factor. Pole, tooth, gap and demagnetizing ampere turns equal

saturation are approximate, and that the only really exact method is to make flux plots of the entire circuit, including both saturated and unsaturated portions.

## Saturation of Potier Reactance

In the preceding analysis, no attempt has been made to show in detail the effect of saturation on $X_p$. In com-

piling table I, all comparisons have been made arbitrarily at rated voltage and rated current, and the unsaturated value of $X_d'$ has been used. The use of the saturated value of $X_d'$ is not thought to be justified because saturated reactance depends upon $d\phi/dI$, that is, upon rate of change of saturation, while saturated $X_p$ does not.

## Symbols

$X_{d'}$ = direct axis transient reactance
$X_p$ = Potier reactance
$X_d$ = direct axis synchronous reactance
$X_l$ = armature leakage reactance
$X_{ad}$ = direct axis demagnetizing reactance ($= X_d - X_l$)
$AT$ = ampere turns per pole
$K_{nl}$ = ratio of no-load ampere turns to gap ampere turns at 100 per cent voltage
$K_p$ = ratio of no-load ampere turns to gap ampere turns at (100 per cent plus per cent $X_p$) voltage
$C_1$ = ratio of fundamental to maximum of air gap flux form
$C_p$ = ratio of average to maximum of air gap flux form

## Appendix—Use of Exponential Formula for Saturation Curve

The saturation curve of iron very closely approximates an exponential curve over the usual ranges used in synchronous machines. In figure 13, the ampere turns per inch required by a saturated wedge-shaped tooth are shown for 2 values of maximum density—140,000 and 110,000 lines per square inch. The actual curve and the exponential representation of it have both been drawn in order to show the substantial agreement that exists between them. The

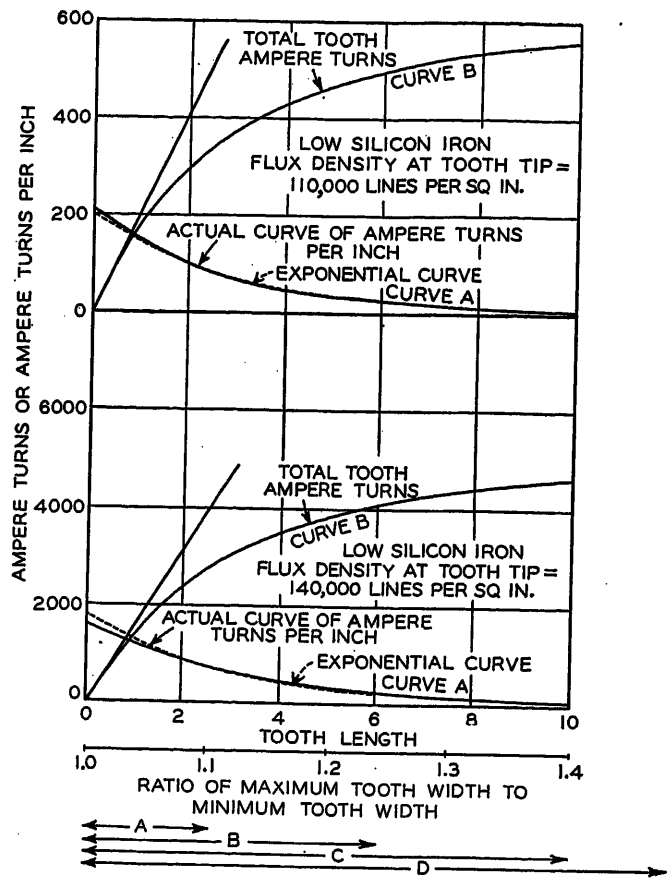



**Figure 13. Saturation of a trapezoidal tooth (with 100 per cent air area in parallel)**

*A*—Ratio of maximum to minimum tooth width for average 60-pole machine

*B*—Ratio of maximum to minimum tooth width for average 20-pole machine

*C*—Ratio of maximum to minimum tooth width for average 8–10-pole machine

*D*—Ratio of maximum to minimum tooth width for average 2–4-pole machine

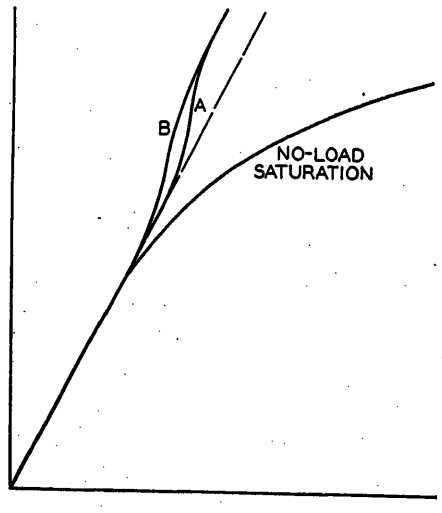



**Figure 12. Effect of change of flux form on air-gap line of a typical machine**

*A*—Under no-load conditions

*B*—Under full-load zero - power - factor conditions

total ampere turns required to force the flux from tooth tip to any ordinate of the curve is shown by curve $B$ of the same figure, and is equal to a constant times the integral of curve $A$. The interesting thing to note is that if the exponential representation is chosen, the curve of total ampere turns (curve $B$) becomes the usual curve of exponential decay or build up, from which it can be seen that if the wedge-shaped tooth were replaced by a parallel-sided tooth whose length was equal to the distance from the tooth tip to the point where $\frac{\text{tooth width}}{\text{minimum tooth width}} = 1.10$, approximately the same total ampere turns as in the whole wedge-shaped tooth would be obtained.

If an exponential equation is used for saturation, then the ratio of tooth to pole ampere turns can be approximated as

$$\frac{\text{tooth ampere turns}}{\text{pole ampere turns}} = \left(\frac{\text{tooth length}}{\text{pole length}}\right)^{\epsilon \frac{0.07\ (\text{tooth density} - \text{pole density})}{1{,}000}} \tag{4}$$

And equation 1 will become:

$$X_p = X_l + (X_d - X_l) \times \frac{1}{1 + \left(\frac{\text{tooth length}}{\text{pole length}}\right)^{\epsilon \frac{0.07\ (\text{tooth density} - \text{pole density})}{1{,}000}}} \tag{5}$$

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1. Armature Leakage Reactance of Synchronous Machines, L. A. March and S. B. Crary. Electrical Engineering (AIEE Transactions), April 1935, pages 378–81.

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# Characteristics of the New Station-Type Autovalve Lightning Arrester

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ASSOCIATE AIEE

THIS PAPER is a description of the characteristics of a new line of station-type autovalve arresters. These arresters are designed to limit the surge voltage to a low value for all types of surges, and at the same time to have high enough 60-cycle breakdown and cut off characteristics to be practically free from trouble due to transient 60-cycle overvoltages.

The arrester elements are sealed in porcelain weather casings having aluminum-alloy castings cemented to each end. The castings serve to make electrical connection to the arrester elements and to bolt the separate units of a complete arrester together. The autovalve blocks are cemented in the porcelain casing with a hard chlorinated wax which acts as a mechanical support for the blocks and prevents any movement during shipping or erection. The gap assemblies are sealed in porcelain tubes having spun metal caps soldered directly to a band of metallic glaze on the porcelain. The gaps are dried before making the final seal by forcing hot dry air through them for several hours. Figure 1 is a cut-away view showing details of the construction of a 60,000-volt arrester.

In developing this arrester it was found that improvements in protective ratio, 60-cycle breakdown characteristics, and interrupting ability of the gaps could be made by utilizing 2 independent gap structures, each of which was designed for its particular purpose. The 2 gap structures have been called switch gap and quench gap. Normally the switch gap is located at the top, and the quench gap at the bottom of the arrester. In the higher-voltage arresters, the quench gap is in 2 or more units. Each gap unit, together with the proper number of porous blocks, is assembled in a separate casing, as in the lower half of figure 1. The complete arrester is built up of these quench-gap and block units with a switch gap either mounted directly on them or suspended above them.

The quench gap has a high 60-cycle breakdown and power follow interrupting ability, and at the same time a low surge breakdown. The high interrupting ability has been obtained by using a large number of closely spaced gaps. The high 60-cycle and low surge breakdown has been obtained by using a gap element which has an impulse ratio of very nearly unity, and by using a resistance shunt to distribute the voltage evenly across all of the gaps. In figure 2 is shown a unit of 3 gaps assembled inside the molded resistance ring. The low impulse ratio of this type of gap is probably due to the formation of a corona or similar discharge near the points of contact of of the mica washer and the electrode. This discharge furnishes an abundance of ions for the gap, and as a result the gap is very fast and has a low impulse ratio. As a check on this, tests were made in which a ring of Micarta between the outside edges of the electrodes was substituted for the mica washers. Although the gap spacing was the same, the impulse breakdown became erratic and impulse ratios as high as 2 were obtained. In the assembled gap a number of units of 3 gaps and a resistance ring stacked on top of each other are sealed in a porcelain gap tube. The spring spacer between units assures good contact to the resistor and takes up any manufacturing variation in the parts.

The switch gap insulates the arrester from the line voltage and prevents the continuous passage of leakage current through the resistance shunt of the quench gap. This is a multiple gap using pressed-brass electrodes separated by porcelain spacers. Improvement has been obtained in the impulse ratio of these gaps by using a molded insert of granulated carborundum in the face of the electrode. A double-gap element of this type is shown in figure 3. The surface of the insert is slightly below the face of the electrode and the arc takes place between the metal surfaces and not to the surface of the carborundum insert. The chart of figure 4 shows the results of tests on 4 gap assemblies, each composed of 2 gaps, as in figure 3, in series. The 60-cycle breakdown and 10 front-of-wave breakdowns were taken on each gap assembly. Each gap assembly, in series with an autovalve block, was then surged 50 times with a 4,000-ampere surge while connected to a 3,000-volt power source. Then the 60-cycle and impulse tests were repeated. This was continued until a total of 200 power follow shots had been reached In the chart the vertical lines represent the spread in the impulse ratio of a particular gap assembly for 10 tests. The number above each line designates the gap assembly tested. The line in the column at the right shows the spread in impulse ratio of a similar gap assembly without the inserts.

The operation of the dual gap in the complete arrester is as follows: When the surge voltage becomes 50 to 75 per cent above the crest of the arrester rating, the switch gap breaks down and the entire voltage is applied to the quench gap. If the voltage continues to rise, the quench gap breaks down when the voltage reaches 125 to 150 per cent above the crest of the arrester rating. The surge is then discharged through the autovalve blocks which hold the surge voltage to a safe value. After the surge is discharged, the normal-frequency current of approximately 20 amperes crest passed by the autovalve blocks is inter-

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1. For all numbered references, see list at end of paper.

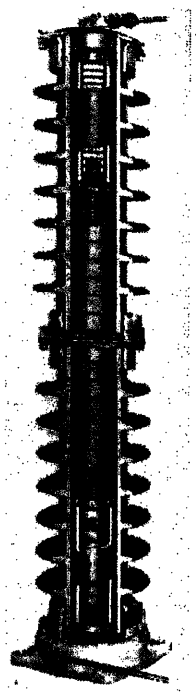


**Figure 1 (left). Cut-away view of a 60,000-volt type SV arrester showing details of the internal construction**

*A*—Switch-gap assembly
*B*—Quench-gap assembly
*C*—Autovalve blocks

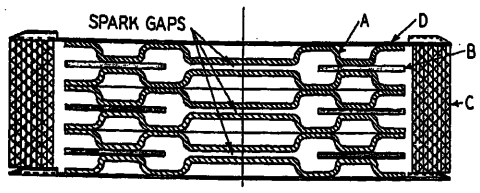



**Figure 2. Quench-gap unit consisting of 3 gaps and a shunting resistor**

*A*—Pressed-brass electrode
*B*—Mica washer
*C*—Molded ring of resistance material
*D*—Spring contact plate

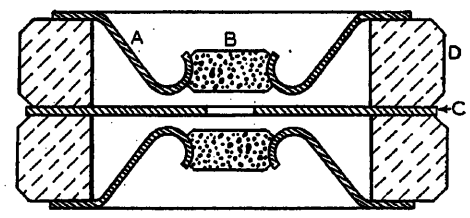
rupted at the first current zero by the quench gap. The leakage current of less than a milliampere passed by the quench-gap shunting resisters is then interrupted by the switch gap.

Figure 5 is a curve of the protective ratio as a function of the time to breakdown of the dual gap on various wave fronts. The time to breakdown was taken as the time from zero to breakdown voltage on an average front taken between the 10 and 90 per cent points. In order to get a common scale for the different ratings, the actual breakdowns in kilovolts were divided by the crest value of the maximum arrester rating in kilovolts. The actual gap breakdown of any particular arrester can be obtained by multiplying the crest of maximum arrester rating by the protective ratio for any time to breakdown. This curve shows how fast the arrester gap is. For example, on the standard rate of rise of 100 kilovolts per microsecond for each 11.5 kilovolts of arrester rating the breakdown occurs in about 0.4 microseconds and the ratio is about 2.4. Even doubling the rate of rise, which means a breakdown in the very short time of 0.2 microseconds, only increases the gap protective ratio to about 2.6.

The autovalve block has a high surge-current-discharge capacity and at the same time a low protective ratio. The protective ratio on the standard 1,500-ampere 10x20 wave is 2.1. This means that for a current of this type the voltage across the arrester elements will be limited to 2.1 times the crest of the arrester rating. In order to compare the protective characteristics of the arrester with the characteristics of insulation to be protected, its performance on various rates of rise of current, as well as crest currents must be known. The results of tests on these blocks at crest currents of 1,500, 5,000, and 10,000 amperes with the rates of rise of currents varying from 300 amperes per microsecond to 10,000 amperes per microsecond are shown in the curves of figure 6. An idea of the meaning of a current rising at the rate of 10,000 amperes per microsecond can be seen when it is considered that a traveling wave on an open line of 400 ohms surge impedance rising at the rate of 2,000,000 volts per microsecond would be needed in order to produce this rate of rise of current in an arrester connected at the end of the line. These curves strikingly show the flat characteristic of the autovalve block. Even at surge currents of 10,000 amperes and rates of rise of 10,000 amperes per microsecond, the protective ratio is held to the low value of 2.8. These data have been replotted in a more useful form in the curves figure 7. These curves give the protective ratio of the arrester at various surge current for the rates of rise of current of 1,000, 5,000, and 10,000 amperes per microsecond. Since the curves are relatively close together, rates of rise between the values shown can be easily interpolated. From these curves the voltage which will appear across any given arrester for any assumed current wave shape can be easily determined. The protective ratio for any rate of rise and crest current can be determined from the curves. The crest value of the maximum 60-cycle rating of the arrester multiplied by this ratio gives the surge voltage across the arrester.

This arrester can safely discharge surge currents in excess of 50,000 amperes without damaging the arrester. On surge currents of this high magnitude the arrester still offers protection to insulation, as can be seen by examining the oscillograms of figure 8. These oscillograms

**Figure 3. Gap elements used in switch gap**




*A*—Pressed-brass electrode
*B*—Molded insert of granulated carborundum
*C*—Brass plate
*D*—Wet-process porcelain spacing ring

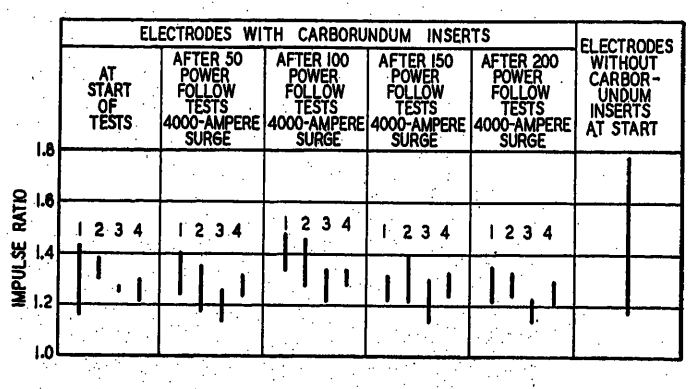



**Figure 4. Performance of gaps, as in figure 3, with carborundum inserts**

Each vertical line represents the spread in the impulse ratio on 10 successive front wave breakdowns. The numbers above the lines designate the gap tested. The line in the column at the right shows the spread in impulse ratio on a similar gap assembly without the carborundum inserts

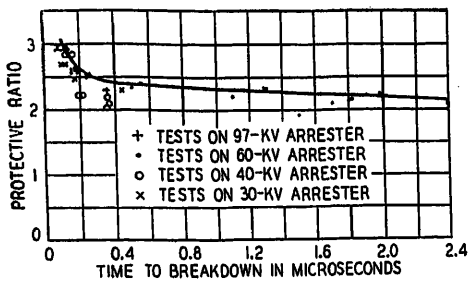
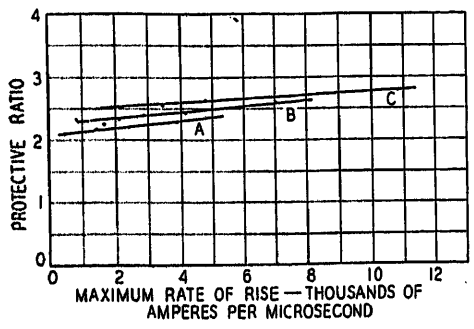



**Figure 5. Surge breakdown of the dual gap as a function of the time to breakdown**

In order to obtain a common scale for the arresters of different ratings, the actual breakdown voltage was divided by the crest of the rated voltage of the arrester tested. All breakdowns were on the front of the wave. The time to breakdown was taken as the time from zero to breakdown voltage on a line through the 10 and 90 per cent points




*A*—Crest current of 1,500 amperes
*B*—Crest current of 5,000 amperes
*C*—Crest current of 10,000 amperes

**Figure 6. Protective ratio of the autovalve blocks as a function of the rate of rise of current for different crest currents**

The maximum rate of rise of current was taken as the rate of rise of approximately the first half of the front of the current wave

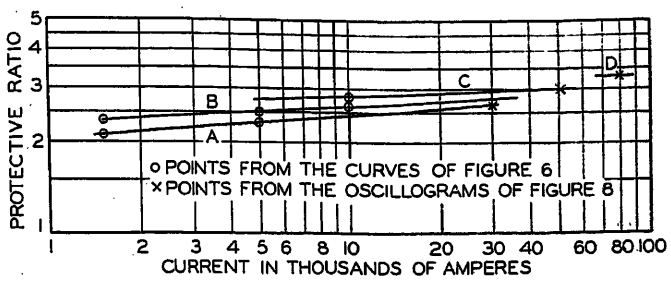



**Figure 7. Protective ratio of the autovalve blocks as a function of surge current for different maximum rates of rise of current**

*A*—Maximum rate of rise of 1,000 amperes per microsecond
*B*—Maximum rate of rise of 5,000 amperes per microsecond
*C*—Maximum rate of rise of 10,000 amperes per microsecond
*D*—Maximum rate of rise of 20,000 amperes per microsecond

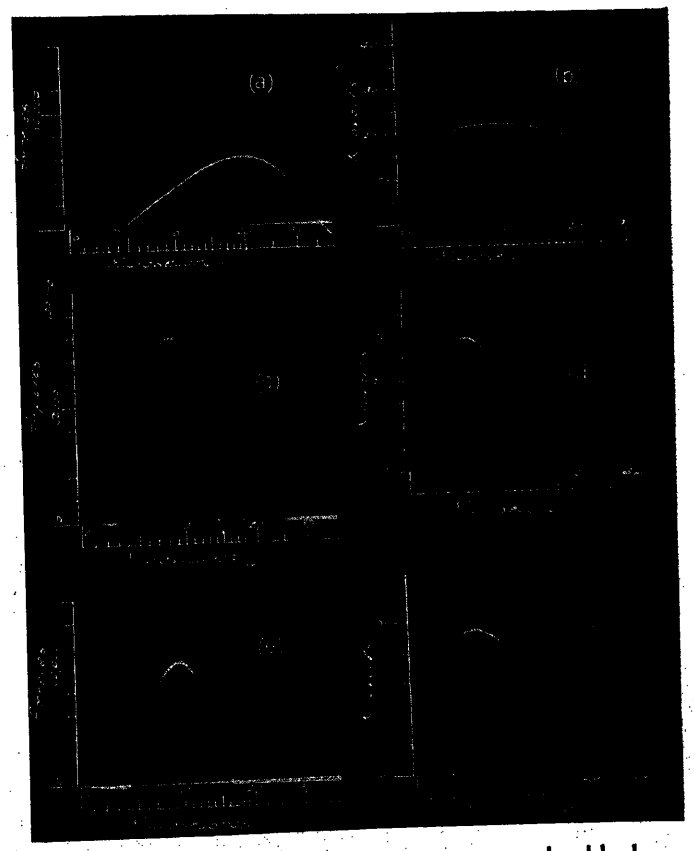



**Figure 8. High-current surge tests on autovalve blocks**

*A, B*—Ampere-time and volt-time curves of a 6-kv autovalve block discharging a surge current of 30,000 amperes with a maximum rate of rise of 3,000 amperes per microsecond. The voltage is limited to 22 kv or a protective ratio of 22/6 × 1.41 = 2.6

*C, D*—A 6-kv block discharging 79,000 amperes—20,000 ampere per microsecond. The crest voltage of 29 kv represents a protective ratio of 3.4

*E, F*—Two 6-kv blocks in series discharging 53,000 amperes—13,000 amperes per microsecond. The crest voltage of 48 kv represents a protective ratio of 48/(12 × 1.41) = 2.8

were taken on 6-kv autovalve block units. Since the characteristics of the autovalve block add directly, tests on single blocks can be extrapolated to any arrester rating.

At its maximum rated 60-cycle voltage the *SV* arrester will pass a power follow current of between 20 and 30 amperes crest. This power follow current is interrupted at the first current zero by the arrester gap. The power follow current is low enough and of such short duration that it will not cause any system disturbances. Power-follow tests have been made on this design of arrester on ratings up to 60 kv, both dry and with a spray to simulate rain. Under no conditions has a failure been produced.

The results of various investigations on the surge current in the direct stroke in this country and abroad, show that the current in the majority of the strokes is below 50,000 amperes, with occasional very heavy strokes where the current reaches magnitudes of the order of 200,000 amperes. Norinder, of Sweden, has made measurements of the rate of rise of current by means of measurements of the magnetic field produced by the stroke, and he reaches the conclusion that in about 65 per cent of these strokes the maximum rate of rise of current is below 6,000 amperes per microsecond. Because of the nature of the instrument used in making these measurements, it is highly probable that a large number of strokes of low current and low rate of rise are not recorded at all, and therefore these data only include the strokes of most severity. Even taking this data as it is, we find that the new type of *SV* arrester will discharge the majority of the currents of direct strokes without damage to the arrester, and the arrester while discharging these high currents will offer a fair degree of protection to connected equipment. A station-type arrester is rarely called upon to discharge the entire current of a heavy direct stroke, because the arrester is normally

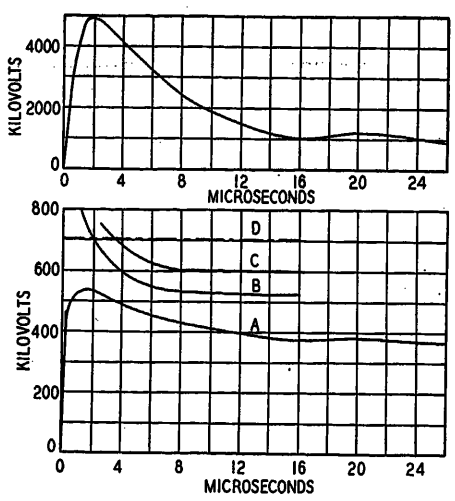



**Figure 9a. Retrace of 5,000,-000-volt lightning surge recorded on a 115,000-volt wood-pole line in Arkansas**

**Figure 9b. Performance of a 121,000-volt arrester for 115,-000-volt ungrounded neutral service on a surge as in (a). The arrester on the end of a line of 400 ohms surge impedance**

*A*—Voltage across arrester
*B*—Time-lag curve of 31½-inch co-ordinating gap
*C*—Time-lag curve of 115,000-volt transformer bushing
*D*—Transformer major insulation, 115,000-volt class

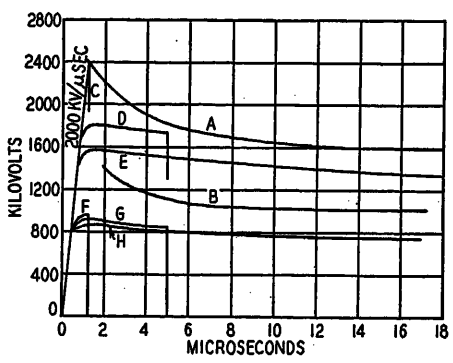



**Figure 10. Performance of a 242,000-volt arrester for 230,-000-volt ungrounded neutral service on surges entering a station on a steel-tower line of 400 ohms surge impedance insulated with 18 standard insulators**

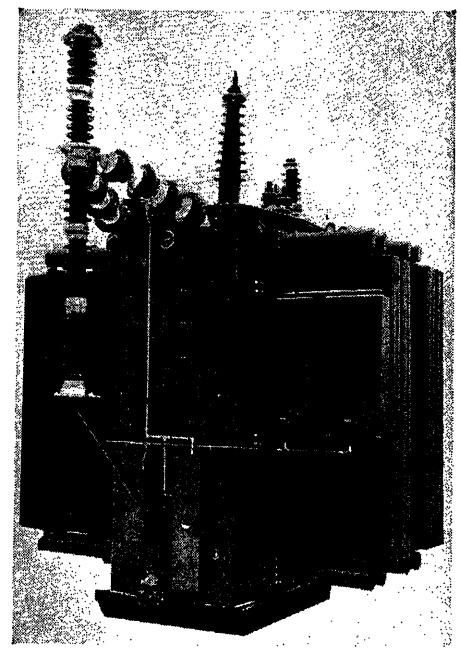
*A*—Time-lag curve 18 insulators
*B*—Time-lag curve 64-inch co-ordinating gap
*C*—Wave chopped on rising front by line insulators
*D*—Wave chopped at 5 microseconds by line insulators
*E*—Maximum 1½x40 wave passed by line insulators
*F*—Voltage across arrester for a traveling wave as in *C*
*G*—Voltage across arrester for wave *D*
*H*—Voltage across arrester for wave *E*

effectively shielded from direct strokes by the station itself. When heavy strokes occur to the line even in the span next to the station, they will probably cause a flashover of the line insulators, which will offer a parallel path to ground for the lightning currents.

The voltage, and therefore the current, associated with a traveling wave entering a station over the overhead lines is limited by the flashover voltage of the line insulation. It is interesting to analyze the performance of this *SV* arrester for the type of surge which would be expected to enter the station from an overhead line. On a 115,000-volt wood-pole line in Arkansas a cathode-ray oscillogram of a lightning surge was obtained which reached a crest voltage of 5,000,000 volts in slightly less than 2 microseconds and decayed to half value in about 8 microseconds.[1] This is the highest voltage lightning surge that has been

**Figure 11. Lightning arresters mounted directly on a power transformer**

The arrester for the solidly grounded neutral 132,000-volt primary winding is in the foreground. The top of the arrester for the 46,-000-volt grounded neutral secondary can be seen above the secondary bushings



recorded on a line. In figure 9*a* a replot of this oscillogram is shown,. Figure 9*b* shows the voltage which would appear across a type *SV* arrester rated at 121,000 volts maximum for ungrounded 115,000-volt application. Assuming a line surge impedance of 400 ohms, the crest current through the arrester would be approximately 24,-000 amperes and the rate of rise would be 20,000 amperes per microsecond. The arrester voltage reaches a maximum of about 530 kv. In figure 9 are also shown the time-lag curves of the 31½-inch co-ordinating gap and the transformer bushing. The co-ordinating gap has a minimum flashover of about 525 kv and therefore would probably flashover at a relatively long time lag.[2] The arrester voltage is well below the transformer bushing and the transformer major insulation level.[3] In figure 10 are shown performance curves for a 240-kv arrester applied on a 230-kv ungrounded system in which the line is on steel towers and insulated with 18 standard insulators. The arrester voltage is calculated for a line surge impedance of 400 ohms and a traveling wave rising at the rate of 2,000 kv per microsecond chopped on the rising front, at 5 microseconds, and the maximum full wave passed by the insulators. These voltages are all below the minimum flashover voltage of the 64-inch co-ordinating gap. In both of these examples the arrester for the ungrounded neutral application was used. If the neutral were solidly grounded, arresters rated at 80 per cent of these ratings would normally be used and the margin of protection would be correspondingly better.

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2. Proposed Transformer Standards, J. E. Clem, chairman, transformer subcommittee of AIEE committee on electrical machinery. Electrical Engineering, volume 56, January 1937, pages 32–6.

3. Factors Influencing the Insulation Co-ordination of Transformers, F. J. Vogel and P. L. Bellaschi. (I) AIEE Transactions, volume 52, 1933, page 411; (II) AIEE Transactions, volume 53, 1934, page 870.

# Relay Operation During System Oscillations

By C. R. MASON
ASSOCIATE AIEE

## Introduction

THE BETTER relays are made, the better they must be made. This is because better relays enable more economical transmission of power by permitting operation nearer to the stability limits of a system;[1] and the nearer to its stability limits a system operates, the more dependence is placed on its relays.

Relays have often been called superhuman, but they still believe what they see. Reference is made to system oscillations defined here as the oscillating interchange of power between synchronous machines when they hunt or go out of step with one another. Protective relays sometimes mistake these oscillations for short circuits, and trip important transmission lines.[2]

The chance tripping of a sound line is bad at any time. If it happens during hunting, a system might not regain synchronism through its other interconnections. If it happens when generating sources are out of step, a small source might be isolated with a large load, or vice versa. The necessary separation of generating sources on loss of synchronism should be performed by purposely designed relays at prearranged locations. Protective relays should function only for short circuits.[1]

The purpose of this paper is to show wherein a relay's vision is defective and to suggest remedies. We shall first discover what a system oscillation looks like to a relay. Then we shall compare this with short circuits and attempt to find a difference in their appearance. And finally, we shall apply whatever corrective measures are possible.

## Characteristics of System Oscillations

In order to simplify the problem, it is assumed that as far as system oscillations are concerned

1. The system can be represented by figure 1
2. All parts of the system always have the same ratio of reactance to resistance, and the impedance of each part is constant
3. The generator voltages behind transient reactance are always equal and constant in magnitude
4. All electrical quantities are referred to the secondary sides of current and potential transformers which transform without change in phase angle

Because the type of system oscillations involved here are balanced 3-phase phenomena, it is sufficient to consider the current of only one phase and its relation to its line-to-neutral voltage as in figure 2. The difference voltage $(V_A - V_F)$ impressed across the total line-to-neutral impedance of the system, causes the current $I$ to flow between the sources. The angle $\phi$ by which $I$ lags the difference voltage is a constant. As $\theta$ changes, the magnitude of $I$ and its angular relation to each of the substation voltages changes. The voltage difference between any 2 points is always a constant proportion of the total difference $(V_A - V_F)$, and hence each vector, which on figure 2 represents a substation voltage, always terminates at a constant division point on the difference voltage. This constant, which defines any location, and which will be called $n$, is often called the "per unit impedance" from the neutral of source $F$ to the given location.

The following values of $n$ are chosen to locate the various points shown in figure 1.

| Point | n |
|---|---|
| Source *F* | 0 |
| Substation *E* | 0.2 |
| Substation *D* | 0.4 |
| Substation *C* | 0.6 |
| Substation *B* | 0.8 |
| Source *A* | 1.0 |

For one cycle of slip between the 2 sources, the voltage vector of one source describes a complete rotation with re-

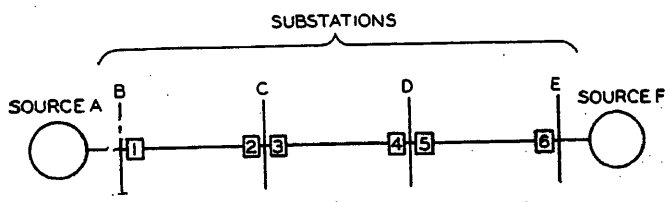



**Figure 1. One-line diagram of 3 sections of transmission line connecting 2 generating sources. The numbered rectangles represent circuit breakers arranged to be tripped by protective relays**

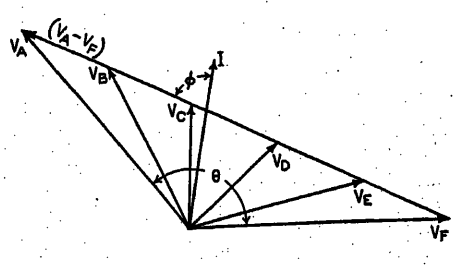



**Figure 2. Line-to-neutral voltage and current relations of one phase at the various substations of figure 1 when the voltage $V_A$ back of transient reactance of source A has advanced the angle $\theta$ ahead of the corresponding voltage $V_F$ of source F**

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1. For all numbered references, see list at end of paper.

spect to the voltage vector of the other source. If only hunting occurs, one voltage swings within a limited sector both sides of the other.

The following equations describe the numerical relations between $\theta$ and each electrical quantity affecting relay

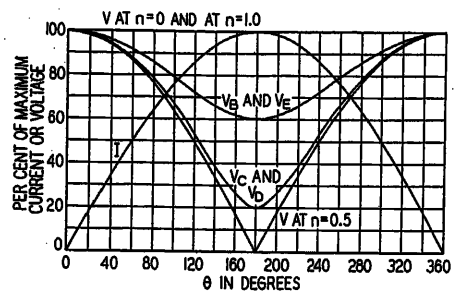



**Figure 3. Voltage and current magnitudes at each substation for one complete slip cycle, or for 0 to 360 degrees displacement between the 2 sources**

operation. In all of the following discussions, $\theta$ will be measured counterclockwise from $V_F$ to $V_A$.

$$I = \frac{2V_A}{Z'} \sin \frac{\theta}{2} \tag{1}$$

$$V = V_A \sqrt{\cos^2 \frac{\theta}{2} + (1 - 2n)^2 \sin^2 \frac{\theta}{2}} \tag{2}$$

$$\omega = (90 - \phi) + \tan^{-1}\left[(1 - 2n) \tan \frac{\theta}{2}\right] \tag{3}$$

where $\omega$ is the angle between $V$ and $I$. When $\omega$ is positive, $I$ leads $V$.

$Z'$ = total line-to-neutral impedance of the system
$V$ = voltage for any intermediate point

In these and in equations to follow, $V_A$ and $V_F$ may be used interchangeably because they are assumed to be equal in magnitude.

Figure 3 shows how $V$ and $I$ at each station vary with $\theta$, and figure 4 shows the relation between $\omega$ and $\theta$ when $\phi$ is assumed to be 75 degrees.

A step toward obtaining a clear understanding of the picture seen by relays is to put the relations of equations 1 and 3 into the form of figure 5. The arrow heads on the curves show the direction in which the head of the current vector moves as $\theta$ increases from zero. Current vectors are shown for a value of $\theta$ less than 180 degrees. Note that for a given angle, all current vectors have the same length. The curves are symmetrical about an axis inclined at the angle $\phi$ below the reference axis. The curves for $n = 1$ and $n = 0$ are equal circles externally tangent at the origin and centered on the axis of symmetry.

The curve for $n = 0.5$ is shown dotted. As $\theta$ increases, the current increases maintaining a constant angular position with respect to its reference voltage. When $\theta$ goes through 180 degrees, the line-to-neutral voltage decreases to zero and reverses, but since this voltage is the reference, the current must be shown as increasing to a maximum and reversing in zero time. What happens to the curve when $\theta$ is 180 degrees may be matter for conjecture, but for values of $n$ slightly greater or less than 0.5, the curves approach the dotted circle shown.

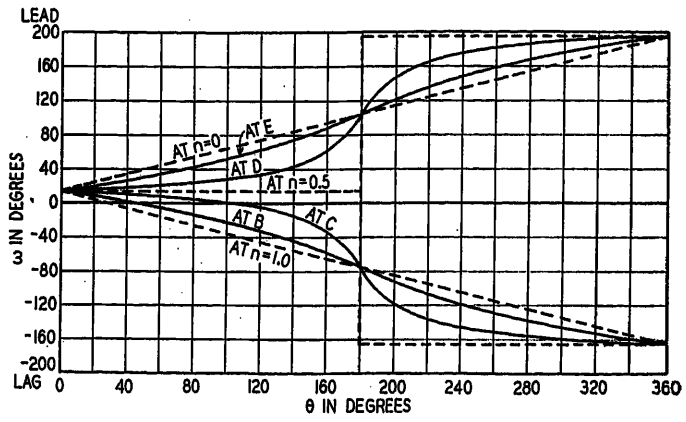



**Figure 4. Phase angle between the current and the voltage at each station for one complete slip cycle**

The final step in preparing the picture of oscillations as seen by relays is to correct some of the curves of figure 5 by taking into account the point of view of the various relays. Thus far, our picture is one looking down the line from $A$ toward $F$. The relays connected to trip breakers 1, 3, and 5 are arranged to look in this direction, but the relays at breakers 2, 4, and 6 view the oscillation from the other direction, and to them the current is reversed.

Making the necessary corrections, and separating the curves so as to place each next to the point for which it applies, we have the final picture shown in figure 6. These curves are not expected to show quantitative data, but they have been found invaluable for visualizing the oper-

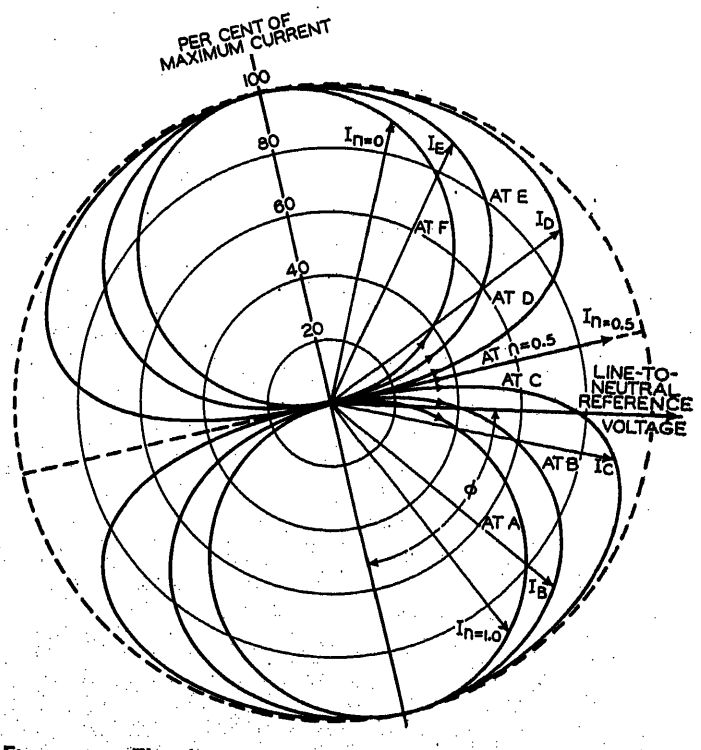



**Figure 5. The locus traced by the head of the current vector at each station with respect to the line-to-neutral voltage at the corresponding station for one complete slip cycle. Each locus is lettered to correspond to the station of figure 1 for which it applies**

ating tendencies of various relays and for interpreting quantitative data derived from trigonometric analysis.

## Operation of a Simple Directional Relay

Because system oscillations are balanced 3-phase phenomena, a polyphase directional relay operates the same as a single-phase relay. Typical operating characteristics of a single-phase directional relay are shown in figure 7 for various voltage magnitudes. The line-to-neutral voltage vector is the reference. For the relay to close its tripping contacts at a given voltage, the current vector for the phase corresponding to the reference voltage must intersect the operating characteristic for the particular voltage as shown by $I$ for 5 per cent of rated voltage. At any given voltage the least current required for operation is that at the angle $\tau$, and hence $\tau$ is called "the angle of maximum torque." The least current which will cause operation at normal, or rated, voltage of the relay is called "the minimum pick-up current." This current is shown as $I_{MIN}$.

The angle of maximum torque is chosen, and the relay is connected, so that the operating region, lying to the right of each characteristic, and extending nearly 90 degrees either side of the angle of maximum torque, will encompass any short-circuit current for which the relay must operate. Generally, the angle of maximum torque is chosen to lie approximately mid-way between the extreme angular positions which the short-circuit current can take for different faults.

If we superimpose the operating characteristic for normal voltage with the proper scale on each of the curves of figure 6, we are provided with an excellent perspective of directional-relay operation during system oscillations. Even though the effect of voltage variation is not shown, the conception gained by this procedure is of much value.

In order to obtain quantitative data, it is necessary to resort to an analysis, the result of which is given in the following equation:

$$T = K_1 V_A \left\{ \pm I_{MAX} \left[ (2n-1)\cos(\tau-\phi)\sin^2\frac{\theta}{2} - \sin(\tau-\phi)\sin\frac{\theta}{2}\cos\frac{\theta}{2} \right] - I_{MIN} \right\} \quad (4)$$

where

$T$ = relay torque; positive torque closes the relay contacts; negative torque opens the contacts
$K_1$ = a constant
$I_{MIN}$ = the minimum pick-up current of the relay
$I_{MAX}$ = the current which the relay gets when the 2 sources are 180 degrees out of phase

The $\pm$ sign before the first term in the braces is necessary to account for the fact that different relays view a system oscillation in different directions; the $+$ sign applies to relays connected to trip breakers 1, 3, and 5; the $-$ sign applies to relays at breakers 2, 4, and 6.

Equation (4) is general and can be used to determine the operation of a directional relay at any location under any assumed conditions, such as those assumed for figure 8 *a*, *b*, and *c*.

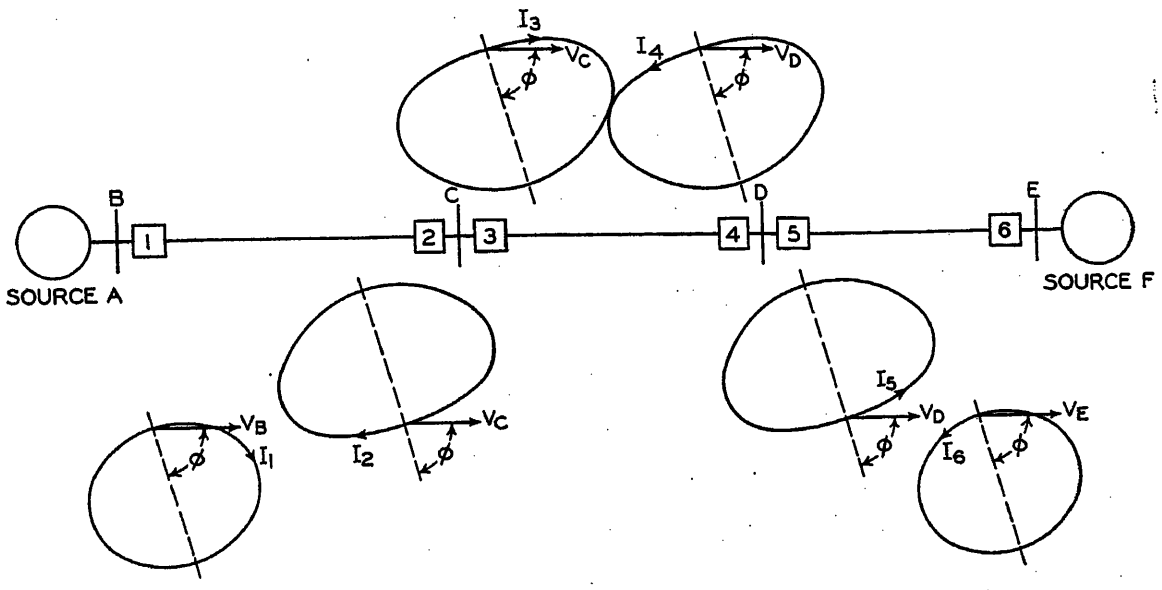



**Figure 6. Paths traced by the head of the current vector with respect to its line-to-neutral voltage at each substation for one complete slip cycle. These loci are corrected for current transformer polarity according to the direction in which relays view the current at each station**

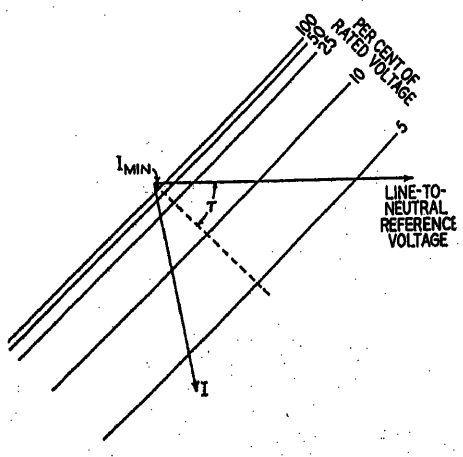



**Figure 7. Operating characteristics of a single-phase directional relay, with reference to its line-to-neutral voltage for various voltage magnitudes**

Along the abscissa of each curve of figure 8 are the angles by which source $A$ *leads* source $F$. If source $A$ starts to *lag* source $F$, we must start at 360 degrees and move to the left in reading the curves. Thus during hunting, if source $A$ leads $F$ and then swings back and goes lagging, we should start from zero degrees and move to the right until source $A$ begins to swing back; then we must retrace our path to zero, start from 360 degrees, and move to the left as $A$ goes lagging, etc.

The curves of figure 8 show that for small displacement angles between the oscillating sources, the directional relays which face in the direction from the leading to the lagging source immediately close their tripping contacts, while the relays facing in the other direction have the opposite tendency. Thus, in the early stages of an out-of-step oscillation, the relays think that there is a short circuit at the lagging end of the system. As the swing progresses, there comes a time when the relays at both ends of a line perceive a flow of current as to a short circuit in the line which they protect. This condition occurs first for a section of line nearest the lagging end, and then progresses successively through each line toward the leading end as the displacement angle increases further. And finally, as the displacement widens still more, the end which had been leading becomes lagging, and the apparent short circuit passes on toward that end.

During hunting the apparent short circuit moves in from one end, retreats, moves in from the other end, retreats, etc. If the swing is not severe, only the end sections of line alternately may seem to contain a short circuit.

The assumed value of $(\tau - \phi)$ for figure 8 is representative of most relay applications. The limiting values which $(\tau - \phi)$ may have are zero and $-90$. For the former, there would be danger of failure of the relay to operate for arcing faults near the relay location, and for the latter, the relay might operate sluggishly on highly lagging short circuit current. If $(\tau - \phi) = 0$, the relays at breakers 2 and 5 would never close their tripping contacts, while the relays at breakers 1, 3, 4, and 6 would always close their contacts regardless of the displacement or of which source went leading. If $(\tau - \phi) = -90$ the relays at opposite ends of each line would always have opposite directions of torque which would reverse with no overlap when the displacement went through 180 degrees.

It is evident that all directional relays throughout a system cannot separately be adjusted to preclude the operation of some of them during system oscillations. Since other types of relays are invariably used with directional relays, we must of course examine their characteristics too before drawing conclusions as to the over-all operation of any protective scheme.

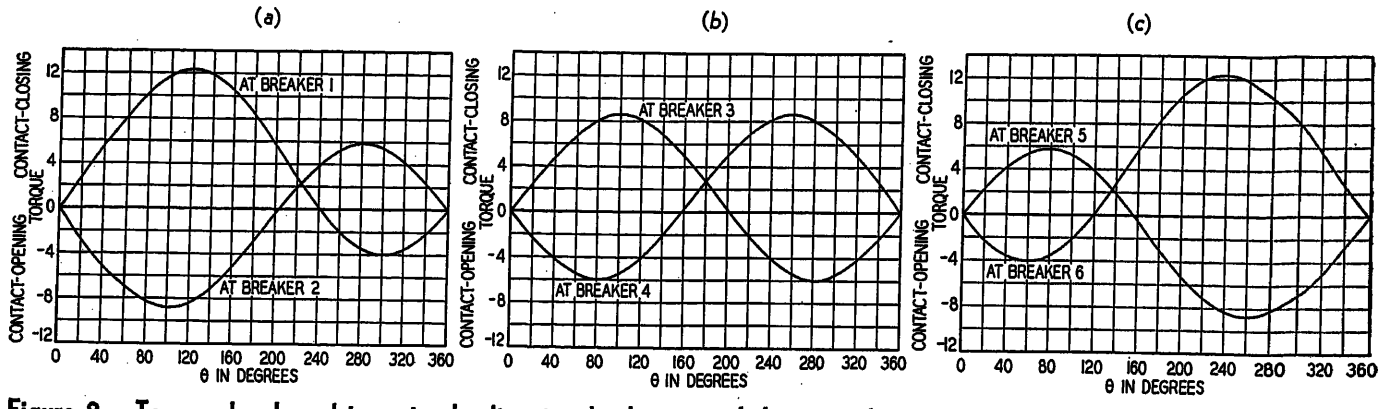



**Figure 8. Torque developed in a simple directional relay at each location during one complete slip cycle according to equation 4 with the following assumptions:**

$(\tau - \phi) = -45$ degrees. In other words, the angle of maximum torque is 45 degrees leading the natural system phase angle

$I_{MAX} = 20$ amperes $I_{MIN} = 0.1$ ampere

$K_1 V_A = 1.0$. This value has no effect on the direction of the torque, but merely on its magnitude

## Operation of Directional Relays With Voltage Restraint

A directional relay with voltage restraint is a simple directional relay which is given an impedance characteristic, or a voltage restraint, for current flow in its tripping direction. The operating characteristics of such a relay are shown in figure 9. It will be noted that the minimum pick-up current $I'_{MIN}$ is a maximum at normal, or rated, voltage, and as the voltage decreases the pick-up current decreases. However, at very low voltages where the restraint becomes negligible, the pick-up current increases the same as for a simple directional relay; to avoid confusion, this is not shown on figure 9.

The superposition of this operating characteristic on the curves of figure 6 would have much the same appearance as for the simple directional relay. It is obvious, however, that the voltage restraint will render this relay less sensitive to oscillations.

An analysis of the operating tendencies of a directional relay with voltage restraint provides the following torque equation:

$$T = K_1 V_A \left\{ \pm I_{MAX} \left[ (2n-1)\cos(\tau-\phi)\sin^2\frac{\theta}{2} - \sin(\tau-\phi) \times \sin\frac{\theta}{2}\cos\frac{\theta}{2} \right] - I_{MIN} - (I'_{MIN} - I_{MIN}) \left[ (1-2n)^2 \sin^2\frac{\theta}{2} + \cos^2\frac{\theta}{2} \right] \right\} \quad (5)$$

where $T$ and $K_1$ have the same meanings as for equation (4) and where:

$I_{MIN}$ = the minimum pick-up current of the relay if the voltage restraint is removed

$I'_{MIN}$ = the minimum pick-up current of the relay with voltage restraint

The significance of the $\pm$ sign before the first term of equation 5 is the same as for equation 4.

Curves illustrating relay operation according to equation 5 are given in figures 10*a*, *b*, and *c* The effect of the voltage restraint is largely to move the curves of a simple directional relay bodily toward the nontripping region. This effect is more pronounced for small displacement angles for which the voltage restraint is relatively high. As the voltage decreases with increasing displacement, the curves approach those of the simple directional relay more closely the nearer the relay is to the impedance center of the system. The curve for a voltage-restrained directional relay at the impedance center would converge to the curve of a simple directional relay at $\theta = 180$ degrees.

The voltage restraint chosen for the curves of figure 10*a*, *b*, and *c* does not prevent incorrect relay operation for the assumed conditions during out-of-step system oscillations. It is natural to inquire if, by a better choice of the restraint, operation can be prevented. If we revert to figures 8*a*, *b*, and *c* and read the contact closing torque of a relay without restraint for any given displacement angle, we can equate this torque to the last term of equation 5 which gives the voltage-restraint torque, and hence find a value of $I'_{MIN}$ to reduce the total torque to zero. This value of $I'_{MIN}$ will vary with the displacement angle, and several trials will be necessary to find the proper value so that at no angle does the curve go positive.

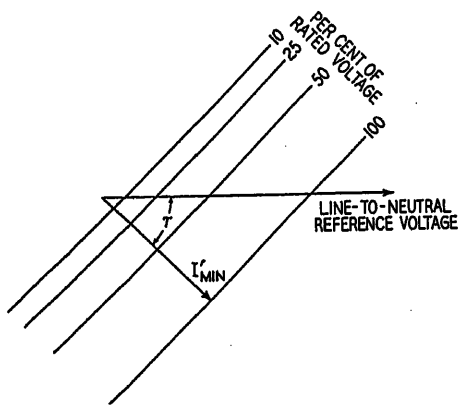



**Figure 9. Operating characteristic of a directional relay with voltage restraint, referred to its line-to-neutral voltage, for various voltage magnitudes**

The result of such a study is tabulated below:

| For No Operation During System Oscillations | | | Relay Current and Voltage for a Fault at Distant End of Line | | | Relay Pick-up for the Fault |
|---|---|---|---|---|---|---|
| For the Relay at Breaker | $I'_{MIN}$ | Must Be | I | | V | $I_{p.u.}$ |
| 1 | 28.2 amperes | 25 amperes | 0.5 | $V_A$ | 20 amperes | |
| 2 | 13.7 amperes | 12.5 amperes | 0.25 | $V_A$ | 4.9 amperes | |
| 3 | 79.0 amperes | 16.7 amperes | 0.33 | $V_A$ | 37 amperes | |
| 4 | 79.0 amperes | 16.7 amperes | 0.33 | $V_A$ | 37 amperes | |
| 5 | 13.7 amperes | 12.5 amperes | 0.25 | $V_A$ | 4.9 amperes | |
| 6 | 28.2 amperes | 25.0 amperes | 0.5 | $V_A$ | 20 amperes | |

The crucial test of the adjustment is that a relay must operate for faults in the line it protects. Hence, the tabulation lists also the fault current and voltage each relay will have for a fault at the distant end of its line, together with the pick-up current of the relay for the fault voltage. This pick-up current is obtained as follows:

$$I_{p.u.} = \frac{(I'_{MIN})\ (\text{per cent } V_A)}{100}\left[\frac{1}{\cos(\tau - \phi)}\right]$$

where we have assumed $\cos(\tau - \phi) = \cos(-45) = 0.707$.

The tabulation shows that if $I'_{MIN}$ is made large enough, all but the relays at breakers 3 and 4 can be prevented from operating during oscillations without preventing operation for faults because, except for the relays at breakers 3 and 4, $I_{p.u.}$ is always less than the fault current. It is impossible to correct for the misoperation of the relays at breakers 3 and 4 because the line they protect spans the impedance center of the system. When the 2 oscillating sources are 180 degrees out of phase, conditions at these relays are the same as for a dead 3-phase fault at the impedance center of the system which falls in the line between breakers 3 and 4. Hence, if the relays there are to operate for a 3-phase fault in the middle of their line, they cannot be prevented from operating when the oscillating

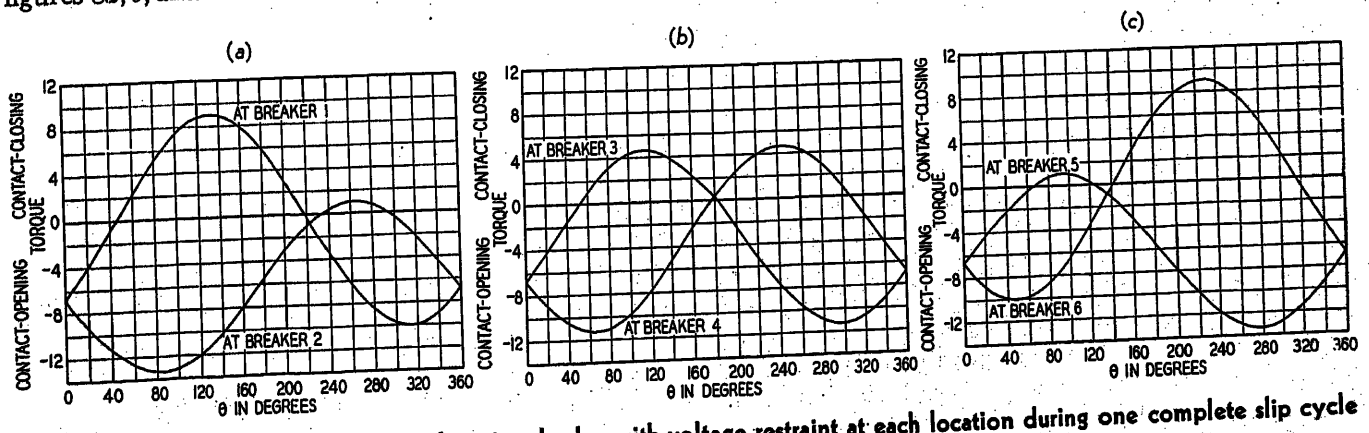



**Figure 10. Torque developed in a directional relay with voltage restraint at each location during one complete slip cycle according to equation 5 with the following assumptions:**

$(\tau - \phi) = -45$ degrees $\quad I_{MAX} = 20$ amperes $\quad I_{MIN} = 0.1$ ampere $\quad I'_{MIN} = 7.0$ amperes $\quad K_1 V_A = 1.0$

sources go through the 180-degree-out-of-phase position.

Since the angle of maximum torque also affects the operation of the relay, let us examine the effect of varying it. Was the choice of $(\tau - \phi) = -45$ the best possible? Considering only the relay at breaker 1, an analysis of its operation provides the following typical data concerning the value of $I'_{MIN}$ necessary to prevent operating during oscillations, and the pick-up current of the relay for faults at the distant end of its line, for values of $(\tau - \phi)$ either side of 45 degrees:

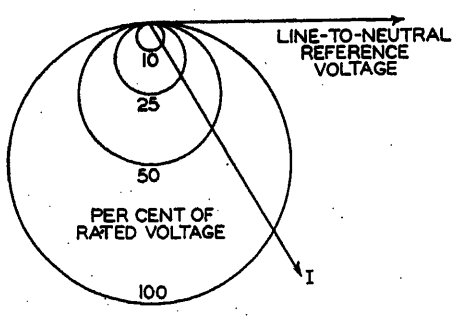



**Figure 11. Operating characteristic of a reactance element, with respect to its line-to-neutral voltage for various voltage magnitudes**

| $(\tau-\phi)$ | $I'_{MIN}$ | $I_{p.u.}$ |
|---|---|---|
| −35.0 deg | 30.0 amp | 18.3 amp |
| −45.0 deg | 28.2 amp | 20.0 amp |
| −55.0 deg | 26.1 amp | 22.7 amp |

These data indicate that as $(\tau - \phi)$ is reduced, the required $I'_{MIN}$ increases, and the pick-up current for the fault decreases. However, the particular fault considered provides highly lagging current. If the fault current should be more nearly in phase with the relay voltage, the pick-up current for that type of fault would increase when $(\tau - \phi)$ is reduced below −45 degrees. Similarly, as $(\tau - \phi)$ is increased, $I_{p.u.}$ for the highly lagging fault increases. The optimum value of $\tau$ is midway between the extreme angular positions which can be taken for the fault at the distant end of the line. For most lines this value of $\tau$ will probably lie between 45 and 85 degrees.

In the foregoing discussions concerning the choice of $I'_{MAX}$ and $(\tau - \phi)$, the attempt was made to prevent operation when the oscillating sources went out of step. The problem is obviously simpler if hunting only is considered. It is probable that, by proper adjustment, even the relays protecting a line which spans the impedance center could be restrained against operating during hunting.

These are not general conclusions, but they provide an indication of a possible solution to the problem for some cases. Where a long line exists whose impedance is a more sizeable portion of the total system impedance, it may be found impossible to adjust the relays to select between faults and severe oscillations. Similarly, it may be impossible to use a relay for back-up protection in the case of faults in adjoining lines if the relay is too highly restrained against improper operation during oscillations. And finally, we do not always have the ideal system setup, assumed for the purpose of analysis, where the location of the impedance center never changes, and where the oscillation is not accompanied by the short circuit which causes it. A general conclusion is that while in most cases the majority of voltage-restrained directional relays can probably be adjusted to improve their selectivity between faults and system oscillations, such adjustment is a satisfactory palliative, but not a complete cure.

## Operation of a Reactance Relay[2]

This discussion will be confined to the reactance element of a distance relay. Such an element responds properly only to lagging current in a given direction, and consequently it is always used in conjunction with a voltage-restrained directional element which prevents tripping except when a short circuit in the proper direction is indicated.

The operating characteristics of a reactance element are shown in figure 11. For a given voltage magnitude, such as 100 per cent, any current vector $I$, whose head lies outside of the characteristic circle for the chosen voltage, will cause the element to close its tripping contacts; the element will not operate for any current vector which falls within the circle.

The superposition of this characteristic on each of the curves of figure 6 will indicate that the element is more than likely to operate. In order completely to determine the appearance of an oscillation to a reactance element, the following equation has been derived:

$$X = \pm \frac{Z'}{2}\left[ (2n - 1) \sin \phi - \cot \frac{\theta}{2} \cos \phi \right] \qquad (6)$$

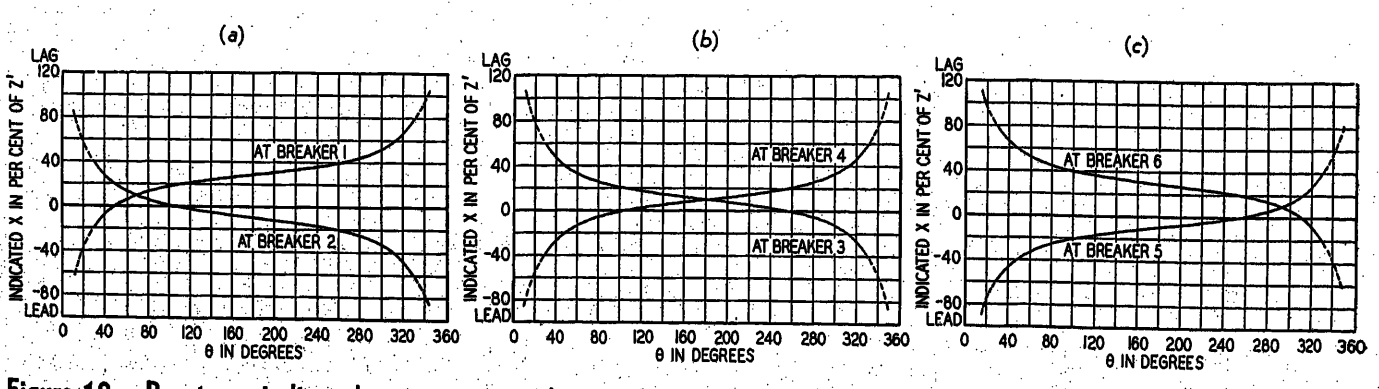



**Figure 12. Reactance indicated to a reactance element during one complete slip cycle. The element operates when the indicated reactance is less than a given positive value for which it is adjusted**

where $X$ = the reactance indicated to a relay; positive reactance means lagging current; negative reactance means leading current.

The + sign before the right-hand side of equation 6 is to be used for the relays at breakers 1, 3, and 5; the negative sign is for the relays at breakers 2, 4, and 6.

Curves according to equation 6 are shown in figure 12*a*, *b*, and *c*, for which it was assumed that $\phi = 75$ degrees.

In order to use figure 12 to determine relay operation, it is first necessary to establish a value of reactance for which the relay shall operate for faults. A distance relay having a stepped distance-time characteristic is adjusted to operate instantly on its lowest reactance setting for faults up to about 90 per cent of the length of the protected line; the second reactance setting is to provide operation for faults up to about 50 per cent of the length of an adjoining line; the reach of the relay on its third time step is determined solely by the reach of the directional unit.

Each line section of the system shown in figure 1 has a reactance of 20 per cent of the total system reactance. With $\phi$ assumed to be 75 degrees, 20 per cent of the system reactance is 19 per cent of the system impedance. The setting of the first reactance step will be approximately 17 per cent, and the second step 26 per cent, of the system impedance. This is equivalent to drawing horizontal lines on figure 12*a*, *b*, and *c* at heights of +17 per cent $Z'$ and +28 per cent $Z'$. The reactance elements will operate for all portions of the curves below these horizontal lines.

Figure 12 shows that the reactance elements at one end, and possibly both ends, of any line are likely to operate on hunting oscillations and that if out-of-step occurs, all elements will operate. It is evident, therefore, that the operation of the voltage restrained directional element will largely determine if tripping will occur. The time, or the reactance step, responsible for tripping would depend on the relay location and on the period and severity of the oscillation. The longer the time delay setting for the second and third steps, the less likelihood there is of operation. It is impossible to generalize except on the basis that if the voltage restrained directional element operates, tripping is possible.

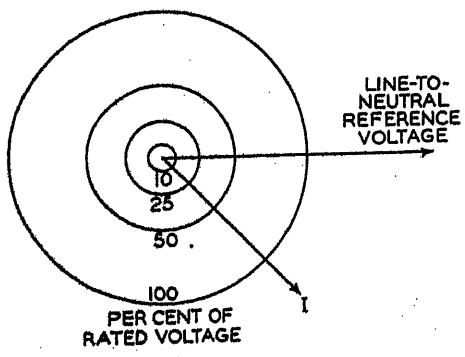



**Figure 13. Operating characteristic of an impedance relay, with respect to its line-to-neutral voltage for various voltage magnitudes**

## Operation of an Impedance Relay[2]

The operating characteristics of an impedance relay are illustrated in figure 13. This relay operates to close its tripping contacts when the head of the current vector lies outside of the circle for any given voltage, such as the current $I$ for 100 per cent of rated voltage. The superposition of this characteristic on the curves of figure 6 will indicate an increasing tendency to operate as the system displacement approaches 180 degrees.

More definite conclusions are possible based on the following equation:

$$Z = \frac{Z'}{2}\sqrt{(1-2n)^2 + \cot^2\frac{\theta}{2}} \qquad (7)$$

where $Z$ = the impedance indicated to a relay.

The operation of an impedance relay according to equation 7 is illustrated in figure 14. Conventional distance relays employing impedance elements have 3 such elements, one for each of the 3 distance-time steps. The first step covers about 90 per cent of the protected line, the second step reaches to about 50 per cent of the next adjoining line, and the third step extends to about 25 per cent of the third line section. For use with figure 14, these 3 adjustments may be taken, respectively, as 18 per cent, 30 per cent, and 45 per cent, of $Z'$, the total system impedance. Horizontal lines through these impedance values reveal the operating tendency of the elements.

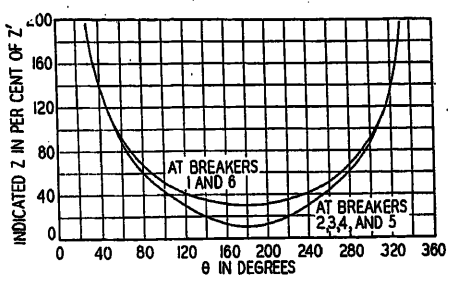



**Figure 14. Impedance indicated to an impedance relay during one complete slip cycle. The relay operates when the impedance is less than a given value for which it is adjusted**

For the assumed system, figure 14 indicates that operation of only the third step impedance elements at the end stations is likely to occur. All 3 impedance elements at the other stations will function depending on the amount of displacement. Here, as in the case of the reactance relay, a determination of which elements can cause tripping depends on their time settings and on the magnitude and the period of the oscillation. Since conventional distance relays having impedance elements employ an unrestrained directional element, the probable operation of such relays is almost solely determined by the operation of their impedance elements.

## Operation of Current and Voltage Relays

The curves of figure 3 are suitable for determining the operating tendencies of simple current or voltage relays. Only the use of time delay in the operation of such a relay can prevent it from closing contacts when its operating point is reached during an oscillation. It is desirable that the resetting time of such relays be as short as possible, else there will be a tendency for the contacts to "notch"

closed during continued oscillations. Incidentally, this quick resetting characteristic is desirable in any relay.

## Preventing Tripping During System Oscillations

The preceding analyses show that conventional relays are not individually endowed with enough discriminative ability to distinguish infallibly between any short circuit and any system oscillation. At various instants during oscillations, the electrical quantities affecting relay operation are identical to those existing during short circuits. Are there any differences between the characteristics of oscillations and of short circuits whereby discrimination can be made?

Fortunately, relays commonly used for protecting against ground faults are not affected by system oscillations. Such relays are energized with zero-phase-sequence current and voltage which are not produced by system oscillations. On the other hand, interphase faults not involving ground do not produce zero-phase-sequence quantities. Consequently, ground relays alone will not solve the problem unless protection only against faults involving ground is considered sufficient as a first line of defense.

The consideration of ground relays and the zero-phase-sequence quantities suggests the possibility of using the negative phase sequence current and voltage. System oscillations of the type considered are balanced 3-phase phenomena and hence contain only positive-phase-sequence current and voltage. Since interphase faults, except those which are balanced 3-phase, produce negative-phase-sequence quantities, this characteristic could be used for discrimination. However, there are those who will consider it heresy in view of the fact that balanced 3-phase faults have been known to occur. Barring the accidental closing in of a line on protective grounding devices which lineman have forgotten to remove, there are exceedingly few substantiated cases of short circuits originating in the balanced 3-phase state. Present-day high-speed relays would require an unbalance for only a short time in order to cause tripping. The protection against faults due to failure to remove grounding devices, however, is an easily solvable problem since these faults originate the instant the line breaker is closed. Auxiliary means could be used during that period to permit tripping even though the fault were balanced 3-phase.

The requirement that there be an unbalance in current between the 3 phases in order to permit tripping has been used as a first line of defense measure against short circuits for several years by one large power company with apparently satisfactory results.[3] This method is somewhat different from using negative-phase-sequence quantities since it employs the line currents directly, but it is a simpler and easier method to apply. Its additional shortcoming is that it may in some cases permit tripping for oscillations which accompany external faults. When an unbalance is required for tripping, the remote possibility of balanced 3-phase faults is anticipated by the use of back-up relays having long enough time settings to prevent operation on oscillations alone.

The use of time delay in a relay's operation is perhaps an obvious way to prevent tripping during oscillations. This solution will apply to a back-up relay particularly if the resetting time of the relay is short.

But there are other uses which can be made of the time variable. An important difference between faults and oscillations is that whereas the electrical quantities present during an oscillation may reach proportions identical to those during short circuits, the approach to, and the departure from, the identical state during an oscillation is different on a time basis from that accompanying short circuits. The earliest known appreciation of the possibilities residing in this fact is recorded in a proposed method[4] to prevent the operation of distance relays during hunting following the occurrence of a distant short circuit. There, the distance relay operated very sensitively for a limited time after the occurrence of the short circuit, but before the oscillation could progress far enough to cause false operation, the relay changed its sensitivity so as to be inoperative during the ensuing hunting.

An extension of the principles involved led to making present-day carrier-current pilot relaying immune to any type of system oscillation whether it be accompanied by a short circuit or not.[5] This method of protection uses directional and associated relays at the ends of a line and a simple carrier-current telegraph channel to apprise one end of what is happening at the other. During any system disturbance, if current flows *out* of one end of the line as to an external short circuit, the directional relay at that end permits a carrier-current signal to be impressed on the line which prevents tripping at the other end where the current flow is in the tripping direction.

Reverting to the description of operation of directional relays, it will be recalled that a system oscillation first has the appearance of an external short circuit beyond one end, followed by the appearance of an internal short circuit, and still later appearing again as an external short circuit. This sequence of events in the cycle of an oscillation before and after it resembles an internal fault is used to prevent tripping during that limited period when an internal fault seems to exist. This is accomplished by prolonging the carrier-current signal once it has started during a 3-phase disturbance, for a definite time after the directional relay attempts to stop it, thereby temporarily taking control from the directional relays until they have passed through the period of delusion and once more regain their sense of direction.

This solution to the problem is particularly significant because it is achieved with equipment which is both faster and more selective than any other type having comparable application. The irony of the solution is that we have not bettered the vision of a single relay, but have actually introduced a blinder against its seeing that which it should not.

## Conclusions

The content of this paper cannot be fairly revealed by a set of conclusions. The paper was written to be read and studied by those who wish to understand better why

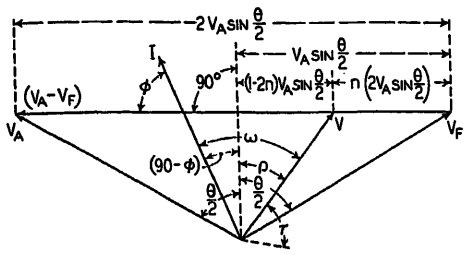



**Figure 15**

conventional relays operate as they do during system oscillations. An attempt has been made to present the analysis in an easily understandable form which has been found in actual practice to give a better insight into the apparent vagaries of relay operation.

Certain definite conclusions can be drawn (probably more or less obvious without the preceding analyses):

1. Any of the conventional relays except the zero-phase-sequence type is apt to operate in an undesirable manner during system oscillations. This is no reflection on the relay in so far as it reacts as it is intended under definite imposed conditions. The difficulty is that the conditions imposed by oscillations are the same to a single relay's perception as those during short circuits

2. It is possible to adjust some relays to better their discrimination between faults and oscillations depending on a relay's location and on the severity of the oscillation

3. Time delay and quick resetting in a relay's operation are aids toward preventing incorrect operation during oscillations

4. The problem is easily solvable if the best possible protection against balanced 3-phase faults is not required

5. Pilot protection using a wired pilot or carrier current can be made immune to the effects of system oscillations

## Appendix

### Derivation of Equation 1

If $Z'$ = total system line-to-neutral impedance,

$$I = \frac{(V_A - V_F)}{Z'}$$

From an inspection of figure 15,

$$(V_A - V_F) = 2V_A \sin\frac{\theta}{2}$$

Therefore,

$$I = \frac{2V_A}{Z'} \sin\frac{\theta}{2} \tag{1}$$

### Derivation of Equation 2

From an inspection of figure 15,

$$V \cos\rho = V_A \cos\frac{\theta}{2}$$

$$V \sin\rho = (1 - 2n)\, V_A \sin\frac{\theta}{2}$$

Squaring both sides of these equations and adding,

$$V^2 = V_A^2\left[\cos^2\frac{\theta}{2} + (1 - 2n)^2 \sin^2\frac{\theta}{2}\right]$$

Therefore,

$$V = V_A\sqrt{\cos^2\frac{\theta}{2} + (1 - 2n)^2 \sin^2\frac{\theta}{2}} \tag{2}$$

### Derivation of Equation 3

In figure 15,

$$\omega = (90 - \phi) + \rho$$

From inspection,

$$\tan\rho = \frac{(1 - 2n)\, V_A \sin\frac{\theta}{2}}{V_A \cos\frac{\theta}{2}} = (1 - 2n)\tan\frac{\theta}{2}$$

Therefore,

$$\omega = (90 - \phi) + \tan^{-1}\left[(1 - 2n)\tan\frac{\theta}{2}\right] \tag{3}$$

### Derivation of Equation 4

Referring to figure 15, and neglecting the effects of saturation in magnetic circuits of a directional relay, its torque may be expressed as

$$T = K_1 IV \cos(\tau + \omega) - K_2$$

where $K_1$ is a constant for the production of electrical torque, and $K_2$ is a constant representing the torque of the control spring.

At minimum pick-up the torque is zero.

$$0 = K_1 I_{MIN} V_A - K_2 \qquad K_2 = K_1 I_{MIN} V_A$$

$$T = K_1[IV \cos(\tau + \omega) - I_{MIN} V_A]$$

Developing this equation,

$$T = K_1\{-IV[\sin(\tau - \phi)\cos\rho + \cos(\tau - \phi)\sin\rho] - I_{MIN} V_A\}$$

But

$$I = \frac{2V_A}{Z'} \sin\frac{\theta}{2} = I_{MAX} \sin\frac{\theta}{2} \qquad V\cos\rho = V_A \cos\frac{\theta}{2}$$

and

$$V \sin\rho = (1 - 2n)\, V_A \sin\frac{\theta}{2}$$

Substituting in the torque equation,

$$T = KV_A\left\{I_{MAX}\left[(2n - 1)\cos(\tau - \phi)\sin^2\frac{\theta}{2} - \sin(\tau - \phi)\sin\frac{\theta}{2}\cos\frac{\theta}{2}\right] - I_{MIN}\right\} \tag{4}$$

### Derivation of Equation 5

The torque of a directional relay with voltage restraint may be expressed:

$$T = K_1[IV \cos(\tau + \omega) - I_{MIN} V_A] - K_3 V^2$$

At minimum pick-up the torque is zero.

$$0 = K_1 V_A (I'_{MIN} - I_{MIN}) - K_3 V_A^2$$

$$K_3 = K_1 \frac{(I'_{MIN} - I_{MIN})}{V_A}$$

$$T = K_1\left[IV \cos(\tau + \omega) - I_{MIN} V_A - \frac{(I'_{MIN} - I_{MIN})V^2}{V_A}\right]$$

Developing this equation,

$$T = K_1 \left\{ -IV[\sin(\tau - \phi)\cos\rho + \cos(\tau - \phi)\sin\rho] - I_{MIN} V_A - \frac{(I_{MIN}' - I_{MIN})V^2}{V_A} \right\}$$

But

$$I = I_{MAX} \sin\frac{\theta}{2} \qquad V\cos\rho = V_A \cos\frac{\theta}{2}$$

$$V\sin\rho = (1 - 2n)V_A \sin\frac{\theta}{2}$$

and from equation 2

$$V^2 = V_A^2\left[\cos^2\frac{\theta}{2} + (1 - 2n)^2 \sin^2\frac{\theta}{2}\right]$$

Substituting in the torque equation,

$$T = K_1 V_A \left\{ I_{MAX}\left[ (2n - 1)\cos(\tau - \phi)\sin^2\frac{\theta}{2} - \sin(\tau - \phi) \times \sin\frac{\theta}{2}\cos\frac{\theta}{2}\right] - I_{MIN} - (I'_{MIN} - I_{MIN})\left[(1 - 2n)^2 \sin^2\frac{\theta}{2} + \cos^2\frac{\theta}{2}\right]\right\} \quad (5)$$

## Derivation of Equation 6

Referring to figure 15,

$$X = -\frac{V}{I}\sin\omega = -\frac{V}{I}\sin(\rho + 90 - \phi)$$

$$= -\frac{V}{I}\cos(\rho - \phi)$$

$$= -\frac{V}{I}[\cos\rho\cos\phi + \sin\rho\sin\phi]$$

But $V\cos\rho = V_A\cos\frac{\theta}{2}$ $\qquad V\sin\rho = (1 - 2n)\,V_A\sin\frac{\theta}{2}$

Therefore,

$$X = \frac{V_A}{I}\left[(2n - 1)\sin\frac{\theta}{2}\sin\phi - \cos\frac{\theta}{2}\cos\phi\right]$$

But

$$I = \frac{2V_A}{Z'}\sin\frac{\theta}{2}$$

Therefore,

$$X = \frac{Z'}{2}\left[(2n - 1)\sin\phi - \cot\frac{\theta}{2}\cos\phi\right] \quad (6)$$

## Derivation of Equation 7

Referring to figure 15,

$$Z = \frac{V}{I}$$

But

$$V = V_A\sqrt{(1 - 2n)^2\sin^2\frac{\theta}{2} + \cos^2\frac{\theta}{2}}$$

and

$$I = \frac{2V_A}{Z'}\sin\frac{\theta}{2}$$

Therefore

$$Z = \frac{Z'}{2}\sqrt{(1 - 2n)^2 + \cot^2\frac{\theta}{2}} \quad (7)$$

## Symbols

- $V_A$ $V_F$ = line-to-neutral root-mean-square secondary voltage behind transient reactance at source $A$ and at source $F$
- $V_B$, $V_C$, $V_D$, and $V_E$ = line-to-neutral root-mean-square secondary voltage at substations $B$, $C$, $D$, and $E$
- $V$ = line-to-neutral root-mean-square secondary voltage at any location
- $I$ = root-mean-square secondary current at any location
- $I_{MIN}$ = minimum root-mean-square pick-up current of a directional relay
- $I_{MIN}'$ = minimum root-mean-square pick-up current of a directional relay with voltage restraint
- $I_{MAX}$ = maximum root-mean-square secondary current during an oscillation
- $I_{p.u.}$ = root-mean-square pick-up current of a relay
- $\theta$ = displacement angle
- $\phi$ = natural system phase angle
- $\omega$ = angle between $V$ and $I$
- $\tau$ = angle of maximum torque of a directional relay with or without voltage restraint
- $\rho$ = angle used in construction for derivation of equations
- $T$ = relay torque
- $n$ = per-unit impedance
- $Z'$ = total system secondary line-to-neutral impedance
- $Z$ = secondary line-to-neutral impedance indicated to an impedance relay
- $X$ = secondary line-to-neutral reactance indicated to a reactance relay
- $K_1$, $K_2$, and $K_3$ = constants

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# A Comprehensive Method of Determining the Performance of Distance Relays

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## Introduction

DURING the past few years rapid progress has been made in the development of distance relay protective schemes, and there are now available a number of various types of distance measuring and directional elements which may be utilized in various combinations to afford the protection desired. In determining the performance of these elements under various fault conditions it would be of great benefit to be able to express the performance of each type of element under a given fault condition in terms of a simple quantity such as the effective line impedance between the relay and the point of fault. Unfortunately it will be found that the performance of certain elements, notably those connected to the unfaulted phases will be affected by changes in system setup and in system capacity. Lewis and Tippet have provided an excellent theoretical treatment of this problem[1] which Calabrese has supplemented by a study of the effect of wye-delta and delta-wye transformers interposed between the relay and the fault.[2]

Fundamentally, the performance of any distance element is a function of the current and voltage applied to the relay and of the vector angle between them. Unless this relationship becomes equal to a definite impedance which is present in the system network, the practice heretofore has been to determine the performance of the element for a given fault condition by the calculation of the current, voltage, and vector angle involved.

The calculation of these currents, voltages, and angles involves the use of certain fundamental impedances and current distribution factors which are characteristic of the system set-up, fault and relay location; but which are independent of the type of fault. By expressing the performance of the relay directly in terms of these fundamental quantities for any type of fault, the labor involved in the determination of the relay performance for any specific case will be reduced to a minimum.

The determination of these fundamental quantities may present considerable difficulty, and in the case of the complicated system networks commonly met with in practice, their accurate determination is practically impossible without the use of an a-c calculating table. An approximate determination is possible, however, by the use of a d-c calculating table, and the general expressions for relay performance will be presented in such a form that the approximate values thus obtained for the fundamental quantities may be used instead of the more accurate values. The accuracy of the results obtained will, of course, be dependent upon the accuracy of the fundamental assumption necessary in the use of the d-c calculating table; i.e., that all of the impedances appearing in the system networks have the same power factor angles.

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1. For all numbered references, see list at end of paper.

## Summary

This paper presents a comprehensive method of determining the performance of distance relays along the lines indicated above which may be summarized as follows:

1. A general method by which the performance of any of the types of distance elements in common use may be determined from the effective impedance presented to the element.

2. A tabulation from which the effective impedance presented to any type of distance element under any condition of fault may be obtained in terms of the effective line impedance between the relay and the fault and 4 quantities which are characteristic of the system setup and location of the fault with reference to the relay. These quantities may be determined approximately by the use of a d-c calculating table setup.

3. A method for including the effect of fault resistance in the determination of the effective impedance presented to the relay.

4. Methods by which the performance of standard directional elements under fault conditions may be determined.

5. An extension of the general method to enable the expression of the operating time of *CZ* relays in terms of the effective impedance presented to the relay.

6. An extension of the general method to include the performance of distance relays connected for protection against single-phase-to-ground faults.

## Types of Distance Relays Considered

While the method outlined in this paper is primarly intended to encompass all forms of distance relays operative on interphase faults, i.e., those relays which are connected to phase-to-phase potentials, it nevertheless is also applicable to the case of relays connected to phase-to-neutral-potentials with or without current compensation, which are intended to protect against single-phase-to-ground faults only Since this connection may be regarded as a special application, it will be treated subsequent to the general method.

With the exception of the *CZ* relay, the time of operation of which varies with the effective impedance presented to the relay, all of the distance relays in general use in the United States are either of the instantaneous

type or are composed of elements which are of that type. The method of solution will, therefore, be indicated on the basis of instantaneous elements with no further reference as to their time of operation. The *CZ* relay will be subsequently treated as a special case.

For purposes of treatment, distance elements may be classified both as to function and as to connections. Under the former classification the following types are evident:

(*a*) Impedance elements (types *CZ, HZ, IGX, IJX*)

(*b*) Reactance elements (type *HX*, ohm units of types *GAX, GCX*)

(*c*) Modified reactance elements (type *HY*)

(*d*) Directional elements with voltage restraint (starting units of types *GAX* and *GCX*, polyphase types *CHV-3, IDP, CBP*)

In regard to classification as to connections, the following distinctions may be drawn:

(*a*) One current and one voltage (types *CZ, HZ, IGX, IJX, HY, HX*, ohm units of type *GAX, GCX*, starting unit of type *GAX*)
1. Star-connected current transformers
2. Delta-connected current transformers

(*b*) One current and 2 voltages (starting unit of type *GCX*)

(*c*) Three currents and 3 voltages (type *CHV-3, IDP, CBP*)

In the above classification, the first group of elements is indicated as being operative from either star-or delta-connected current transformers. Actually the effect of delta-connected current transformers may be obtained by the delta connection of the main current transformer secondaries, the use of auxiliary secondary current transformers, or by the use of double coil elements. For simplicity, the problem will be treated as if the first method were employed. The use of any other method will not affect the theory and will merely change the value of the constant indicative of the relay setting.

## Distance Relay Equations

The operation of any simple relay element involves the resultant torque produced in the element by the application of a current and/or a voltage. This torque may be made up of torques produced by the current alone, the voltage alone, and the interaction of the current and the voltage. In the case of a distance measuring element, the resultant torque at the balance point must equal zero and the following general equation may be written to express this fact

$$K_v V^2 - K_i I^2 - K_{iv} IV \cos(\phi_V - \phi_I - \psi) = 0 \qquad (1)$$

in which the first term is indicative of the torque produced by the voltage alone tending to open the contacts, the second term is indicative of the torque produced by the current alone tending to close the contacts, and the third term indicates the interaction torque in which the angle $\psi$ is the vector angle between current and voltage at which this interaction torque is a maximum.

Equation 1 may be expressed in terms of $\mathcal{Z}$ the effective impedance presented to the relay by dividing by $K_v I^2$.

$$\mathcal{Z}^2 - \frac{K_{iv}}{K_v}\mathcal{Z}\cos(\phi_z - \psi) = \frac{K_i}{K_v} \qquad (2)$$

Equation 2 may be transformed into the following form by the addition of $(K_{iv}/2K_v)^2$ to both sides.

$$\mathcal{Z}^2 + \left(\frac{K_{iv}}{2K_v}\right)^2 - \frac{K_{iv}}{K_v}\mathcal{Z}\cos(\phi_z - \psi) = \left(\frac{\sqrt{K_{iv}^2 + 4K_iK_v}}{2K_v}\right)^2 \qquad (3)$$

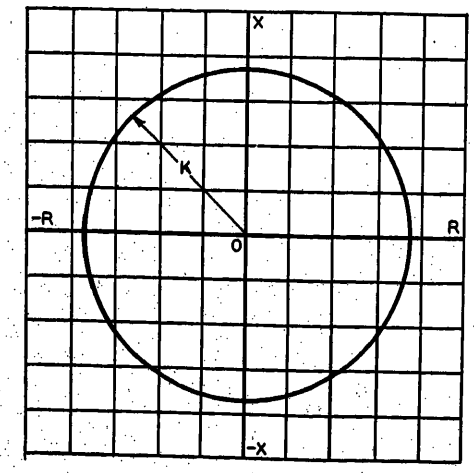
Equation 3 will be recognized as the equation of a circle expressed in terms of the polar co-ordinates $\mathcal{Z}$ and $\phi_z$. The radius of this circle is $(K_{iv}^2 + 4K_iK_v)/2K_v$ and its center is located at a distance $K_{iv}/2K_v$ from the origin at the angle $\psi$ from the reference vector.

It is therefore apparent that the balance point of any distance element may be expressed graphically on an impedance diagram as a characteristic circle and in order to determine whether or not the element will operate under a given fault condition, it is merely necessary to determine the effective impedance presented to the relay under that fault condition and to locate it on the diagram. If it falls within the circle the relay will operate, and the relay will not operate if it falls outside of the circle.

Equation 2 is a quadratic and may be solved for $\mathcal{Z}$ giving the following expression

$$\left[\frac{K_{iv}}{2K_v}\cos(\phi_z - \psi) \pm \frac{\sqrt{K_{iv}^2\cos^2(\phi_z - \psi) + 4K_iK_v}}{2K_v}\right] \angle\phi_z = \mathcal{Z}\angle\phi_z \qquad (4)$$

**Figure 1. Characteristic figure for an impedance relay**



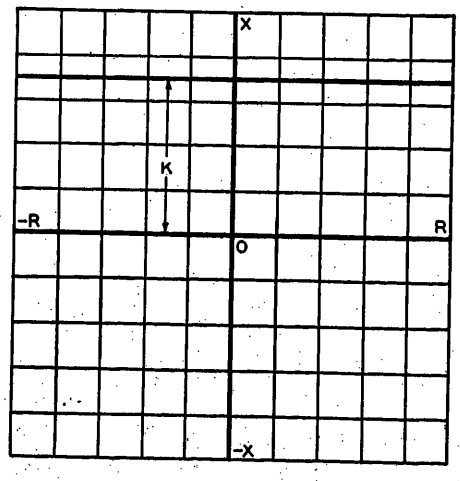
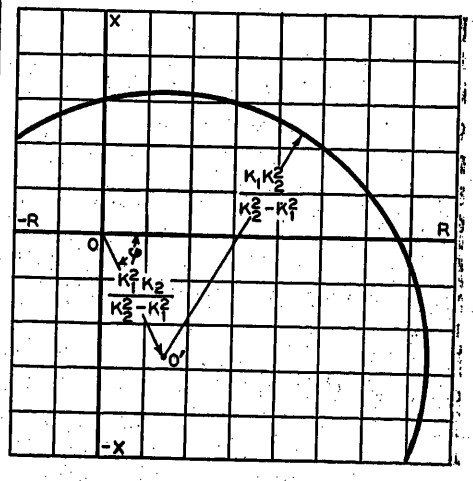




**Figure 2. Characteristic figure for a reactance relay**

**Figure 3. Characteristic figure for a modified reactance relay**



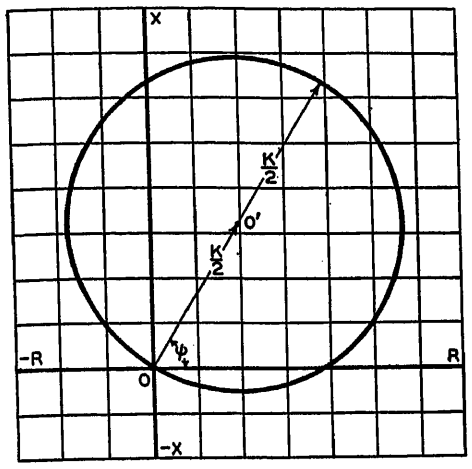



**Figure 4. Characteristic figure for a directional relay with voltage restraint**

Both sides of equation 4 have been multiplied by $\epsilon^{j\phi_z}$ (herein indicated as $\angle\phi_z$) in order to indicate that the effective impedance presented to the element is to be used as a vector quantity in determining its performance. As previously indicated the left-hand side of the equation when plotted for all possible values of $\phi_z$ will be a circle.

By the proper evaluation of the constants, equation 4 may be made to assume the following forms which are characteristic of the various types of distance elements previously classified. The derivation of these equations in the conventional manner is given in appendix $A$.

(*a*) IMPEDANCE ELEMENT

$$K_{tv} = 0; \qquad \sqrt{K_t/K_v} = K \tag{5}$$

$$K\angle\phi_z = \mathcal{Z}\angle\phi_z = \frac{V}{I}\angle\phi_V - \phi_I \tag{6}$$

The characteristic circle for this element shown in figure 1 has a radius equal to $K$ with its center at the origin.

(*b*) REACTANCE ELEMENT

$$K_v = 0; \qquad K_t/K_{tv} = K; \qquad \psi = -90° \tag{7}$$

$$\frac{K\angle\phi_z}{\sin\ \phi_z} = \mathcal{Z}\angle\phi_z = \frac{V}{I}\angle(\phi_V - \phi_I) \tag{8}$$

The characteristic circle for the element shown in figure 2 has a radius equal to infinity with its center located at infinity. It is therefore a straight line and has a minimum distance of $K$ from the origin.

(*c*) MODIFIED REACTANCE ELEMENT

In this element all of the torque terms are utilized.

$$K_1 = 1; \qquad K_v = \frac{1}{K_1^2} - \frac{1}{K_2^2}; \qquad K_{tv} = \frac{2}{K_2} \tag{9}$$

$$\angle\phi_z = \mathcal{Z}\angle\phi_z = \frac{V}{I}\angle(\phi_V - \phi_I) \tag{10}$$

The characteristic circle for this element shown in figure 3 has a radius of $K_1K_2^2/(K_2^2-K_1^2)$ with its center located $K_1^2K_2/(K_2^2-K_1^2)$ distant from the origin.

(*d*) DIRECTIONAL ELEMENT WITH VOLTAGE RESTRAINT

$$K_1 = 0; \qquad K_{tv}/K_v = K \tag{11}$$

1. *GAX Type*

$$K\cos(\phi_z - \psi)\angle\phi_z = \frac{1}{S}\mathcal{Z}\angle\phi_z = \frac{1}{S}\frac{V}{I}\angle\phi_V - \phi_I \tag{12}$$

2. *GCX Type*

$$K\cos(\phi_z - \psi)\angle\phi_z = \mathcal{Z}\angle\phi_z = \frac{V}{I}\angle(\phi_V - \phi_I) \times \frac{2}{\sqrt{3}}\sin(\phi_V - \phi_{Vq})\angle(90° + \phi_{Vq} - \phi_V) \tag{13}$$

3. *Polyphase Type*

$$K\cos(\phi_z - \psi)\angle\phi_z = \mathcal{Z}\angle\phi_z = \frac{3}{\frac{1}{\mathcal{Z}_a\angle\phi_{za}} + \frac{1}{\mathcal{Z}_b\angle\phi_{zb}} + \frac{1}{\mathcal{Z}_c\angle\phi_{zc}}} \tag{14}$$

The characteristic circle for these elements shown in figure 4 has a radius equal to $K/2$ with its center located at the same distance from the origin.

In equation 12, $S$ is a factor indicative of the variation in range of the unit with variation of the applied potential. This is discussed in appendix $A$.

In the equation 14, the quantities $\mathcal{Z}_a$, $\mathcal{Z}_b$, and $\mathcal{Z}_c$ are the effective impedances presented to the respective phase *GCX* type units as determined from equation 13.

In view of the above equations, it is evident that the performance of all of the above mentioned types of elements for a given fault can be completely expressed by 4 characteristic graphical figures (3 circles and a straight line) and the solution of the requisite equivalent expressions for $\mathcal{Z}\angle\phi_z$. Actually in the case of relays connected for protection against interphase faults, since 3 individual phase relays are involved in all but the last type and since the first 3 types of elements may or may not employ delta-connected current transformers (or their equivalent) 10 such solutions must be made. These solutions may be summarized in tabular form by the equations given below.

Since the expression $\mathcal{Z}\angle\phi_z$ and its equivalents are vectors we will be dealing hereafter entirely with vectors, which will be indicated by bold-face type.

(*a*) ONE CURRENT AND ONE VOLTAGE

(Impedance, reactance, modified reactance, *GAX* starting unit)

1. *Star-Connected Current Transformers*

$$Z_a = \frac{V_{ba}}{I_a} \tag{15}$$

$$Z_b = \frac{V_{ab}}{I_b} \tag{16}$$

$$Z_c = \frac{V_{ac}}{I_c} \tag{17}$$

2. *Delta-Connected Current Transformers*

$$Z_a' = \frac{V_{ba}}{I_a'} \tag{18}$$

$$Z_b' = \frac{V_{cb}}{I_b'} \tag{19}$$

$$Z_c' = \frac{V_{ac}}{I_c'} \tag{20}$$

## Table I. Relay Voltages and Currents in Terms of Fundamental Quantities for Various Fault Conditions

| | | Three-Phase Fault | No Phase Shift in Voltage Between Relay and Fault | | |
|---|---|---|---|---|---|
| | | | Phase-Phase Fault | Phase-Ground Fault | Two-Phase-Ground Fault |
| Voltages | $V_{ba}$ | $\sqrt{3}\frac{c_1}{Z_1} z E\angle 30°$ | $1.5\left(1+\frac{c_1 z}{\sqrt{3}Z_1}\angle 90°\right)E$ | $\frac{\sqrt{3}}{2}\left(\sqrt{3}\frac{2c_1 z+Z_0}{2Z_1+Z_0}+1\angle 90°\right)E$ | $1.5\left(\frac{c_1 z+2Z_0}{Z_1+2Z_0}+\frac{c_1 z}{\sqrt{3}\,Z_1}\angle 90°\right)E$ |
| | | $=\frac{\sqrt{3}}{2}\frac{c_1 z}{Z_1}A\,E\angle 90°$ | $=\frac{\sqrt{3}}{2}\frac{c_1 z}{Z_1}A\,E\angle 90°$ | $=\frac{\sqrt{3}}{2}AE\angle 90°$ | $=\frac{\sqrt{3}}{2}\frac{c_1 z}{Z_1}AE\angle 90°$ |
| | $V_{cb}$ | $\sqrt{3}\frac{c_1}{Z_1} z E\angle -90°$ | $\sqrt{3}\frac{c_1 z}{Z_1}E\angle -90°$ | $\sqrt{3}\,E\ \angle -90°$ | $\sqrt{3}\frac{c_1 z}{Z_1}E\angle -90°$ |
| | $V_{ac}$ | $\sqrt{3}\frac{c_1}{Z_1} z E\angle 150°$ | $1.5\left(-1+\frac{c_1 z}{\sqrt{3}Z_1}\angle 90°\right)E$ | $\frac{\sqrt{3}}{2}\left(-\sqrt{3}\frac{2c_1 z+Z_0}{2Z_1+Z_0}+1\angle 90°\right)E$ | $1.5\left(-\frac{c_1 z+2Z_0}{Z_1+2Z_0}+\frac{c_1 z}{\sqrt{3}\,Z_1}\angle 90°\right)E$ |
| | | $=\frac{\sqrt{3}}{2}\frac{c_1 z}{Z_1}BE\angle 90°$ | $=\frac{\sqrt{3}}{2}\frac{c_1 z}{Z_1}BE\angle 90°$ | $=\frac{\sqrt{3}}{2}BE\angle 90°$ | $=\frac{\sqrt{3}}{2}\frac{c_1 z}{Z_1}BE\angle 90°$ |
| Currents — Star-Connected Current Transformers | $I_a$ | $\frac{c_1}{Z_1}E$ | 0 | $\frac{2c_1+c_0}{2Z_1+Z_0}E$ | $\frac{c_1-c_0}{Z_1+2Z_0}E$ |
| | $I_b$ | $\frac{c_1}{Z_1}E\angle -120°$ | $\frac{\sqrt{3}c_1}{2Z_1}E\angle -90°$ | $-\frac{c_1-c_0}{2Z_1+Z_0}E$ | $\frac{1}{2}\left(-\frac{c_1+2c_0}{Z_1+2Z_0}-\sqrt{3}\frac{c_1}{Z_1}\angle 90°\right)E$ |
| | | | | | $=\frac{\sqrt{3}}{2}\frac{c_1}{Z_1}CE\angle -90°$ |
| | $I_c$ | $\frac{c_1}{Z_1}E\angle 120°$ | $\frac{\sqrt{3}\,c_1}{2Z_1}E\angle 90°$ | $-\frac{c_1-c_0}{2Z_1+Z_0}E$ | $\frac{1}{2}\left(-\frac{c_1+2c_0}{Z_1+2\,Z_0}+\sqrt{3}\frac{c_1}{Z_1}\angle 90°\right)E$ |
| | | | | | $=\frac{\sqrt{3}}{2}\frac{c_1}{Z_1}DE\angle 90°$ |
| Delta-Connected Current Transformers | $I_a'$ | $\sqrt{3}\frac{c_1}{Z_1}E\angle 30°$ | $\frac{\sqrt{3}c_1}{2Z_1}E\angle 90°$ | $\frac{3\,c_1}{2Z_1+Z_0}E$ | $1.5c_1\left(\frac{1}{Z_1+2Z_0}+\frac{1}{\sqrt{3}\,Z_1}\angle 90°\right)E$ |
| | | | | | $=\frac{\sqrt{3}}{2}\frac{c_1}{Z_1}C'E\angle 90°$ |
| | $I_b'$ | $\sqrt{3}\frac{c_1}{Z_1}E\angle -90°$ | $\frac{\sqrt{3}c_1}{Z_1}E\angle -90°$ | 0 | $\sqrt{3}\frac{c_1}{Z_1}E\angle -90°$ |
| | $I_c'$ | $\sqrt{3}\frac{c_1}{Z_1}E\angle 150°$ | $\frac{\sqrt{3}c_1}{2Z_1}E\angle 90°$ | $-\frac{3\,c_1}{2\,Z_1+Z_0}E$ | $1.5c_1\left(-\frac{1}{Z_1+2Z_0}+\frac{1}{\sqrt{3}\,Z_1}\angle 90°\right)E$ |
| | | | | | $=\frac{\sqrt{3}}{2}\frac{c_1}{Z_1}D'E\angle 90°$ |

(*b*) One Current and 2 Voltages

Star-connected current transformers (*GCX* starting unit)

$$Z_a'' = Z_a \times \frac{2}{\sqrt{3}} \sin(\phi_{Vba} - \phi_{Vcb}) \angle (90° + \phi_{Vcb} - \phi_{Vba}) \quad (21)$$

$$Z_b'' = Z_b \times \frac{2}{\sqrt{3}} \sin(\phi_{Vcb} - \phi_{Vac}) \angle (90° + \phi_{Vac} - \phi_{Vcb}) \quad (22)$$

$$Z_c'' = Z_c \times \frac{2}{\sqrt{3}} \sin(\phi_{Vac} - \phi_{Vba}) \angle (90° + \phi_{Vba} - \phi_{Vac}) \quad (23)$$

(*c*) Three Currents and 3 Voltages

Star-connected current transformers (polyphase directional with voltage restraint)

$$Z_p = \frac{3}{\frac{1}{Z_a''} + \frac{1}{Z_b''} + \frac{1}{Z_c''}} \quad (24)$$

## Solution of $Z$

The solution of $Z$ from equations 15–24 will be effected by the application of the method of symmetrical components to the determination of the various currents and voltages involved in these equations. It will be evident that these currents and voltages may be completely expressed in terms of the following quantities, all of which are to be considered as vectors.

$E$ = the normal primary phase to neutral voltage at the relay

$Z_1, Z_2, Z_0$ = the equivalent impedances of the positive-, negative-, and zero-phase sequence networks, respectively, expressed at the voltage $E$

$c_1, c_2, c_0$ = the respective ratios of the positive-, negative-, and zero-phase-sequence currents at the relay to the corresponding total phase sequence currents at the point of fault

$z$ = the *effective* (positive- or negative-phase sequence) impedance between the relay and the point of fault

## Table I (Continued). Relay Voltages and Currents in Terms of Fundamental Quantities for Various Fault Conditions

**Thirty-Degree Phase Shift in Voltage Between Relay and Fault**

| | | Phase-Phase Fault | Phase-Ground Fault | Two-Phase-Ground Fault |
|---|---|---|---|---|
| Voltages | | $\frac{\sqrt{3}}{2}\left(\sqrt{3}\frac{c_1 z}{Z_1}+1\angle 90^\circ\right)E$ | $1.5\left(1+\frac{1}{\sqrt{3}}\frac{2c_1z+Z_0}{2Z_1+Z_0}\angle 90^\circ\right)E$ | $\frac{\sqrt{3}}{2}\left(\sqrt{3}\frac{c_1 z}{Z_1}+\frac{c_1z+2Z_0}{Z_1+2Z_0}\angle 90^\circ\right)E$ |
| | | $=\frac{\sqrt{3}}{2}AE\angle 90^\circ$ | $=\frac{\sqrt{3}}{2}\frac{2c_1z+Z_0}{2Z_1+Z_0}AE\angle 90^\circ$ | $=\frac{\sqrt{3}}{2}\frac{c_1z+2Z_0}{Z_1+2Z_0}AE\angle 90^\circ$ |
| | | $\sqrt{3}\,E\angle -90^\circ$ | $\sqrt{3}\frac{2c_1z+Z_0}{2Z_1+Z_0}E\angle -90^\circ$ | $\sqrt{3}\frac{c_1z+2Z_0}{Z_1+2Z_0}E\angle -90^\circ$ |
| | | $\frac{\sqrt{3}}{2}\left(-\sqrt{3}\frac{c_1z}{Z_1}+1\angle 90^\circ\right)E$ | $1.5\left(-1+\frac{1}{\sqrt{3}}\frac{2c_1z+Z_0}{2Z_1+Z_0}\angle 90^\circ\right)E$ | $\frac{\sqrt{3}}{2}\left(-\sqrt{3}\frac{c_1z}{Z_1}+\frac{c_1z+2Z_0}{Z_1+2Z_0}\angle 90^\circ\right)E$ |
| | | $=\frac{\sqrt{3}}{2}BE\angle 90^\circ$ | $=\frac{\sqrt{3}}{2}\frac{2c_1z+Z_0}{2Z_1+Z_0}BE\angle 90^\circ$ | $=\frac{\sqrt{3}}{2}\frac{c_1z+2Z_0}{Z_1+2Z_0}BE\angle 90^\circ$ |
| Currents | Star-Connected Current Transformers | $\frac{c_1}{Z_1}E$ | 0 | $\frac{c_1}{Z_1}E$ |
| | | $-\frac{c_1}{2Z_1}E$ | $\frac{\sqrt{3}c_1}{2Z_1+Z_0}E\angle -90^\circ$ | $\frac{c_1}{2}\left(-\frac{1}{Z_1}-\frac{\sqrt{3}}{Z_1+2Z_0}\angle 90^\circ\right)E$ |
| | | | | $=\frac{\sqrt{3}}{2}\frac{c_1}{Z_1+2Z_0}CE\angle -90^\circ$ |
| | | $-\frac{c_1}{2Z_1}E$ | $\frac{\sqrt{3}\,c_1}{2Z_1+Z_0}E\angle 90^\circ$ | $\frac{c_1}{2}\left(-\frac{1}{Z_1}+\frac{\sqrt{3}}{Z_1+2Z_0}\angle 90^\circ\right)E$ |
| | | | | $=\frac{\sqrt{3}}{2}\frac{c_1}{Z_1+2Z_0}DE\angle 90^\circ$ |
| | Delta-Connected Current Transformers | $1.5\frac{c_1}{Z_1}E$ | $\frac{\sqrt{3}\,c_1}{2Z_1+Z_0}E\angle 90^\circ$ | $\frac{\sqrt{3}}{2}c_1\left(\frac{\sqrt{3}}{Z_1}+\frac{1}{Z_1+2Z_0}\angle 90^\circ\right)E$ |
| | | | | $=\frac{\sqrt{3}}{2}\frac{c_1}{Z_1+2Z_0}C'E\angle 90^\circ$ |
| | | 0 | $\frac{2\sqrt{3}\,c_1}{2Z_1+Z_0}E\angle -90^\circ$ | $\frac{\sqrt{3}\,c_1}{Z_1+2Z_0}E\angle -90^\circ$ |
| | | $-1.5\frac{c_1}{Z_1}E$ | $\frac{\sqrt{3}\,c_1}{2Z_1+Z_0}E\angle 90^\circ$ | $\frac{\sqrt{3}}{2}c_1\left(-\frac{\sqrt{3}}{Z_1}+\frac{1}{Z_1+2Z_0}\angle 90^\circ\right)E$ |
| | | | | $=\frac{\sqrt{3}}{2}\frac{c_1}{Z_1+2Z_0}D'E\angle 90^\circ$ |

It is important to notice that $z$ is the *effective* impedance between the relay and the point of fault and take into account not only the impedances of the lines and equipment in this path, but the relative current distribution as well. For instance, if the path comprises the impedances $z$, $z'$, and $z''$, etc., with the corresponding current distribution factors $c$, $c'$, and $c''$, then

$$z=\frac{cz+c'z'+c''z''\ldots.}{c} \tag{25}$$

With relay elements not employing phase-to-neutral voltages the corresponding effective zero-phase-sequence impedance $z_0$ will not be needed since the phase-to-phase voltages are not dependent upon the voltage distribution through the zero-phase-sequence network.

In order to simplify the expressions to follow, the assumption has been made that the positive- and negative-phase-sequence networks are identical. This assumption is felt to be justifiable in work of this kind and considerably reduces the amount of calculation necessary to obtain the desired results. On this basis all currents and voltages may be expressed in terms of the fundamental quantities $E$, $Z_1$, $Z_0$, $c_1$, $c_0$, and $z$.

In considering the effect of the type of fault, 7 distinct types of faults must be recognized, since in addition to the symmetrical case of a 3-phase fault and the 3 unsymmetrical cases of phase-to-phase, phase-to-ground, and 2-phase-ground faults, these unsymmetrical faults occurring beyond a transformer bank which produces a phase shift in voltage constitute 3 more different cases.

If a wye-delta or delta-wye transformer bank is interposed between the relay and the fault, the positive-phase-sequence currents and voltages will be displaced 30 degrees in one direction (depending upon the bank connections)

and the negative-phase-sequence currents and voltages will be displaced 30 degrees in the other direction when passing through the bank. The effect of this upon the vector diagrams at the relay is such that they will be similar for a given type of fault irrespective of the direction of phase shift and may be made identical by choosing the phases to be involved in the fault with reference to the direction of the phase shift.

Three-phase faults produce no negative-phase-sequence components so that the presence of a bank between the point and the fault has no effect upon the vector diagram. Similarly delta-delta or wye-delta-wye banks produce no net phase shift and do not affect the vector diagram.

To summarize, the 7 distinct cases of faults must be recognized which are as follows:

1. Three-phase fault under any condition.
2. *B* phase — *C* phase fault with no voltage phase shift between the relay and the point of fault. This includes faults beyond a delta-delta or wye-delta-wye transformer bank.
3. *A* phase — ground fault under the conditions outlined in 2.
4. *B* phase — *C* phase — ground fault under the conditions outlined in 2.

5*a*. *A* phase — *B* phase — fault beyond a transformer bank connected so that the voltage on the fault side lags the voltage on the relay side by 30 degrees.

5*b*. *C* phase — *A* phase fault beyond a transformer bank connected so that the voltage on the fault side leads the voltage on the relay side by 30 degrees.

6*a*. *C* phase — ground fault under the conditions outlined in 5*a*.

6*b*. *B* phase — ground fault under the conditions outlined in 5*b*.

7*a*. *A* phase — *B* phase — ground fault under the conditions outlined in 5*a*.

7*b*. *C* phase — *A* phase — ground fault under the conditions outlined in 5*b*.

The values of the phase currents and voltages at the relay for each of these 7 cases in terms of the fundamental quantities are given in table I. Currents applicable to relays fed from delta-connected current transformers are indicated by a prime mark ($'$). The derivation of these expressions is given in appendix *B*.

The expressions for currents and voltages given in table I when substituted in equations 15–24 give the solutions of $\boldsymbol{Z}$ sought for each of the 7 cases of fault. These expressions are given in table II. In order to simplify the expressions thus obtained factors have been introduced in certain cases as indicated. These factors are, of course, vectors, and in the case of the factors applied to the simplification of the voltage expressions, their vector angles are indicative of certain of the angles of the voltage triangle. This fact permits the formulation of the expressions for $\boldsymbol{Z}''$ in terms of the vector angles of the factors.

In utilizing the expressions given in tables I and II it is very important to realize that the quantities $\boldsymbol{c}_1$ and $\boldsymbol{c}_0$ which are vectors should be formulated on the basis of the direction of phase sequence current flow in the line under consideration with respect to the fault and not with respect to the direction of connection of the relay for which the effective impedance presented to it is desired. If the fault lies behind the relay the vector expression obtained for the impedance presented to the relay should be rotated 180 degrees.

## Effect of Fault Resistance Upon $\boldsymbol{Z}$

In dealing with the problem of fault resistance, it should be realized that the fundamental quantity to be considered in the usual case of an arc fault is the voltage drop across the arc. This is essentially dependent upon the length of the arc and independent of the fault current. Since we have chosen to express the performance of the relay in terms of a quantity having the dimensions of impedance, it is desirable to express the effect of the fault arc in terms of a resistance, realizing that this resistance, unlike the fundamental quantities dealt with heretofore, is a function of the actual fault. Futhermore, this fault resistance will affect the value of all of these fundamental quantities except $\boldsymbol{E}$.

In formulating the effective fault resistance, the quantity $\boldsymbol{R}_f$ is to be treated as a phase sequence resistance at the point of fault which is in series with $Z_1$, $Z_2$, and $Z_0$ in the respective phase sequence networks. The values of $\boldsymbol{R}_f$ introduced into each network are all equal for any given type of fault, but are different for different types of faults. In order to determine the actual value of $\boldsymbol{R}_f$ for the various types of faults, a 3-phase fault will be assumed to consist of 3 simultaneous single-phase-to-ground arcs of equal length and a 2-phase-to-ground fault to consist of 2 simultaneous phase-to-ground faults of equal length. The magnitude of $\boldsymbol{R}_f$ will then be equal to $\boldsymbol{V}_A$, the voltage drop across the arc divided by the total faulted phase current for 3-phase, phase-to-ground, and 2-phase-to-ground faults, and equal to half the arc voltage divided by the faulted phase current for a phase-to-phase fault. If we assume that the magnitude of the total faulted phase current is unaffected by the presence of $\boldsymbol{R}_f$ the following relationships are evident.

(*a*) *Three Simultaneous Phase-to-Ground Faults*

$$\boldsymbol{R}_f = \frac{\boldsymbol{V}_A}{\boldsymbol{E}}\, Z_1 \tag{26}$$

(*b*) *Phase-to-Phase Fault (not involving ground)*

$$\boldsymbol{R}_f = \frac{\boldsymbol{V}_A}{\boldsymbol{E}}\,\frac{Z_1}{\sqrt{3}} \tag{27}$$

(*c*) *Single Phase-to-Ground Fault*

$$\boldsymbol{R}_f = \frac{\boldsymbol{V}_A}{\boldsymbol{E}}\,\frac{2Z_1 + Z_0}{3} \tag{28}$$

(*d*) *Two Simultaneous Phase-to-Ground Faults*

$$\boldsymbol{R}_f = \frac{\boldsymbol{V}_A}{\boldsymbol{E}}\,\frac{2Z_1}{\sqrt{3}C'} \tag{29}$$

The value of $\boldsymbol{C}'$ to be used in equation 29 is that for the case of a 2-phase-to-ground fault without phase shift in voltage between the relay and the fault. Equations 26–29 yield the magnitude of $\boldsymbol{R}_f$, and the vector angle which results from their solution has no significance. $\boldsymbol{R}_f$ thus determined should be used as a resistance vector and

## Table II. Effective Impedances in Terms of Fundamental Quantities Presented to Distance Relay Elements for Various Fault Conditions

| | | | No Phase Shift in Voltage Between Relay and Fault | | | Thirty-Degree Phase Shift in Voltage Between Relay and Fault | | |
|---|---|---|---|---|---|---|---|---|
| | | Three-Phase Fault | Phase-Phase Fault | Phase-Ground Fault | Two-Phase-Ground Fault | Phase-Phase Fault | Phase-Ground Fault | Two-Phase-Ground Fault |
| Factors | $A$ | $2\angle -60°$ | $1-\frac{\sqrt{3}Z_1}{c_1 z}\angle 90°$ | $1-\sqrt{3}\frac{2c_1 z+Z_0}{2Z_1+Z_0}\angle 90°$ | $1-\frac{\sqrt{3}\,Z_1}{c_1 z}\left(\frac{c_1 z+2Z_0}{Z_1+2Z_0}\right)\angle 90°$ | $1-\sqrt{3}\frac{c_1 z}{Z_1}\angle 90°$ | $1-\sqrt{3}\frac{2Z_1+Z_0}{2c_1+Z_0}\angle 90°$ | $1-\sqrt{3}\frac{c_1 z}{Z_1}\left(\frac{Z_1+2Z_0}{c_1 z+2Z_0}\right)\angle 90°$ |
| | $B$ | $2\angle 60°$ | $1+\frac{\sqrt{3}Z_1}{c_1 z}\angle 90°$ | $1+\sqrt{3}\frac{2c_1 z+Z_0}{2Z_1+Z_0}\angle 90°$ | $1+\frac{\sqrt{3}\,Z_1}{c_1 z}\left(\frac{c_1 z+2Z_0}{Z_1+2Z_0}\right)\angle 90°$ | $1+\sqrt{3}\frac{c_1 z}{Z_1}\angle 90°$ | $1+\sqrt{3}\frac{2Z_1+Z_0}{2c_1+Z_0}\angle 90°$ | $1+\sqrt{3}\frac{c_1 z}{Z_1}\left(\frac{Z_1+2Z_0}{c_1 z+2Z_0}\right)\angle 90°$ |
| | $C$ | | | | $1-\frac{Z_1}{\sqrt{3}\,c_1}\left(\frac{c_1+2c_0}{Z_1+2Z_0}\right)\angle 90°$ | | | $1-\frac{Z_1+2Z_0}{\sqrt{3}\,Z_1}\angle 90°$ |
| | $D$ | | | | $1+\frac{Z_1}{\sqrt{3}\,c_1}\left(\frac{c_1+2c_0}{Z_1+2Z_0}\right)\angle 90°$ | | | $1+\frac{Z_1+2Z_0}{\sqrt{3}\,Z_1}\angle 90°$ |
| | $C'$ | | | | $1-\frac{\sqrt{3}\,Z_1}{Z_1+2Z_0}\angle 90°$ | | | $1-\sqrt{3}\frac{Z_1+2Z_0}{Z_1}\angle 90°$ |
| | $D'$ | | | | $1+\frac{\sqrt{3}\,Z_1}{Z_1+2Z_0}\angle 90°$ | | | $1+\sqrt{3}\frac{Z_1+2Z_0}{Z_1}\angle 90°$ |
| Elements With One Current and One Voltage — Star-Connected Cts. | $Z_a=\frac{V_{ba}}{I_a}$ | $\sqrt{3}z\angle 30°$ | $\infty$ | $\frac{\sqrt{3}}{2}A\frac{2Z_1+Z_0}{2c_1+c_0}\angle 90°$ | $\frac{\sqrt{3}}{2}A\frac{c_1 z}{Z_1}\left(\frac{Z_1+2Z_0}{c_1-c_0}\right)\angle 90°$ | $\frac{\sqrt{3}}{2}A\frac{Z_1}{c_1}\angle 90°$ | $\infty$ | $\frac{\sqrt{3}}{2}A\frac{Z_1}{c_1}\left(\frac{c_1 z+2Z_0}{Z_1+2Z_0}\right)\angle 90°$ |
| | $Z_b=\frac{V_{cb}}{I_b}$ | $\sqrt{3}z\angle 30°$ | $2z$ | $\sqrt{3}\frac{2Z_1+Z_2}{c_1-c_0}\angle 90°$ | $\frac{2}{c}z$ | $2\sqrt{3}\frac{Z_1}{c_1}\angle 90°$ | $\frac{2c_1 z+Z_0}{c_1}$ | $\frac{2}{c}\frac{c_1 z+Z_0}{c_1}$ |
| | $Z_c=\frac{V_{ac}}{I_c}$ | $\sqrt{3}z\angle 30°$ | $Bz$ | $\frac{\sqrt{3}}{2}B\frac{2Z_1+Z_0}{c_1-c_0}\angle -90°$ | $\frac{B}{D}z$ | $\sqrt{3}B\frac{Z_1}{c_1}\angle -90°$ | $\frac{B}{2}\frac{2c_1 z+Z_0}{c_1}$ | $\frac{B}{D}\frac{c_1 z+2Z_0}{c_1}$ |
| Elements With One Current and One Voltage — Delta-Connected Cts. | $Z_a'=\frac{V_{ba}}{I_a'}$ | $z$ | $Az$ | $\frac{A}{2\sqrt{3}}\frac{2Z_1+Z_0}{c_1}\angle 90°$ | $\frac{A}{c'}z$ | $\frac{A}{\sqrt{3}}\frac{Z_1}{c_1}\angle 90°$ | $\frac{A}{2}\frac{2c_1 z+Z_0}{c_1}$ | $\frac{A}{c'}\frac{c_1 z+2Z_0}{c_1}$ |
| | $Z_b'=\frac{V_{cb}}{I_b'}$ | $z$ | $z$ | $\infty$ | $z$ | $\infty$ | $\frac{1}{2}\frac{2c_1 z+Z_0}{c_1}$ | $\frac{c_1 z+2Z_0}{c_1}$ |
| | $Z_c'=\frac{V_{ac}}{I_c'}$ | $z$ | $Bz$ | $\frac{B}{2\sqrt{3}}\frac{2Z_1+Z_0}{c_1}\angle -90°$ | $\frac{B}{D'}z$ | $\frac{B}{\sqrt{3}}\frac{Z_1}{c_1}\angle -90°$ | $\frac{B}{2}\frac{2c_1 z+Z_0}{c_1}$ | $\frac{B}{D'}\frac{c_1 z+2Z_0}{c_1}$ |

**Elements With One Current and 2 Voltages—Star-Connected Current Transformers**

$$Z_a''=Z_a\times\frac{2}{\sqrt{3}}\sin(-\phi_A)\angle(-90°-\phi_A) \qquad Z_b''=Z_b\times\frac{2}{\sqrt{3}}\sin\phi_B\angle(\phi_B-90°) \qquad Z_c''=Z_c\times\frac{2}{\sqrt{3}}\sin(\phi_B-\phi_A)\angle(90°+\phi_A-\phi_B)$$

**Element With 3 Currents and 3 Voltages—Star-Connected Current Transformers—90-Degree Potential Connection**

$$Z_p=\frac{3}{\frac{1}{Z_a''}+\frac{1}{Z_b''}+\frac{1}{Z_c''}}$$

should be applied if necessary in the correction of the fundamental quantities.

$R_f$ must be included in the determination of $z$ and equation 25 may be rewritten as follows

$$z = \frac{cz + c'z' + c''z'' \ldots + R_f}{c} \tag{30}$$

## Use of a D-C Calculating Table

If a d-c calculating table is employed to obtain the fundamental quantities mentioned above, it is of course impossible to treat them as vectors with different vector angles. If the usual practice of setting up the calculating table on the basis of the reactive components of impedance is followed, then the vector angles of $c_1$ and $\doteq c_0$ will be zero and the vector angles of $Z_1$ and $Z_0$ will be 90 degrees. It is still possible to synthesize $z$ with a fair degree of accuracy from equations 25 or 30 and a knowledge of the impedances of the branches in the path between the relay and the fault. The effect of arc resistance is included only in the computation of $z$.

The results obtained by this procedure will usually be sufficiently accurate for most purposes, but it must be realized that in the case of a fault on the end of a line having a relatively large resistive component and fed by a system which is highly reactive, the impedances thus determined for the unfaulted phase relays may be subject to an appreciable error. The limitations introduced are, of course, due to the use of the d-c calculating table and not to the expressions given in tables I and II which are rigorous except for the assumption that the positive- and negative-phase-sequence networks are identical.

Under the assumptions necessitated by the use of the d-c calculating table the solution for $Z_p$ the effective impedance presented to the polyphase unit is greatly simplified and the following expressions may be used in place of equation 24.

*Three-Phase Fault*

$$Z_p = \sqrt{3}z \tag{31}$$

*Phase-to-Phase Fault*

$$Z_p = 2\sqrt{3}z \tag{32}$$

*Phase-to-Ground Fault*

$$Z_p = \sqrt{3}\left(\frac{2c_1z + Z_0}{c_1}\right) \tag{33}$$

*Two-Phase-to-Ground Fault*

$$Z_p = \sqrt{3}\left(\frac{c_1z + 2Z_0}{c_1z + Z_0}\right)z \tag{34}$$

Equations 31–34 apply whether or not there is a phase shift in voltage between the relay and the fault.

## Performance of Directional Elements Without Voltage Restraint

Distance relays are almost invariably of the directional type. The type *GAX* and *GCX* reactance relays are given directional characteristics by means of the starting units discussed above. The *CZ*, *HZ*, *HY*, and *IGX* types are made directional by the use of a conventional directional element suitably connected to the circuit. In interpreting the performance of such relays, it is necessary to know whether or not the various phase distance elements will be released by their associated directional elements.

In the case of *CZ*, *HZ*, and *HY* relays a true wattmetric type of element is used with a 30 degree connection. That is the *A*-phase relay is connected to the current $I_a$ and the voltage $V_{ac}$ reversed and so on. It will be evident, therefore, that the vector angle between the voltage and current applied to the directional element is equal to the vector angle of the impedance presented to the distance element minus the corresponding internal angle of the voltage triangle. The directional element will operate if the angle thus obtained lies between $\doteq$ 90 degrees. Solutions of the following expressions are therefore required.

*A* phase: $\phi z_a - 180° + \phi_{Vac} - \phi_{Vba}$ (35)

*B* phase: $\phi z_b - 180° + \phi_{Vba} - \phi_{Vcb}$ (36)

*C* phase: $\phi z_c - 180° + \phi_{Vcb} - \phi_{Vac}$ (37)

In view of the angular relationships developed in appendix *B* expressions 35–37 become:

*A* phase: $\phi z_a - 180° + \phi_B - \phi_A$ (38)

*B* phase: $\phi z_b + \phi_A$ (39)

*C* phase: $\phi z_c - \phi_B$ (40)

If delta connected current transformers are employed for the directional elements, $\phi_z'$ should be substituted for $\phi_z$ in expressions 35–40.

In the case of the *IGX* relay, a 90 degree connection is used for the directional element. (*A*-phase relay is connected to the current $I_a$ and the voltage $V_{bc}$ and so on) and the angle of maximum torque of the element is variable within certain limits. The angular range of operation of this element is therefore similar to that ot the type *GCX* starting unit and therefore the element will operate if the vector angle of $Z''$ lies within $\doteq$90 degrees of $\psi$ where $\psi$ is now to be interpreted as the angle of maximum torque of the directional element.

If delta-connected current transformers are used with the directional element of *IGX* relay, $Z''$ should be formulated from $Z'$ rather than from $Z$.

It should be noted, however, that by the use of auxiliary current transformers it is possible to obtain the effect of delta-connected current transformers on the distance elements and at the same time maintain the more desirable effect of star-connected current transformers on any type of directional element.

## Determination of CZ Relay Operating Times

Unlike the instantaneous distance elements previously discussed which either do or do not operate according to the value of $Z$ presented to the element, the *CZ* relay operates in a time which is more or less a direct function of the magnitude of $Z$. The characteristic time curves for this relay have usually been expressed as a set of current-

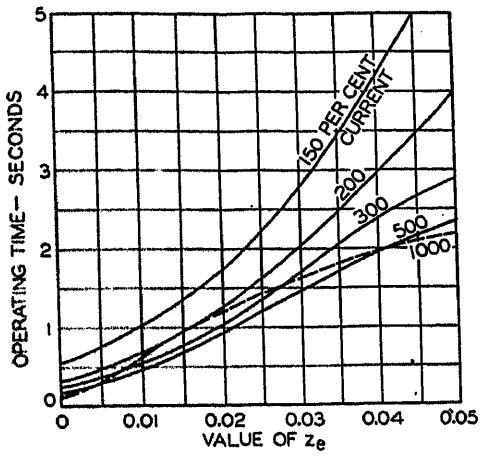



**Figure 5. Time-impedance characteristics of CZ relays**

time curves, each curve being for a constant voltage maintained at the relay terminals. This method is unsatisfactory because it fails to bring out the constant time-impedance relationship which is the inherent principle of operation for which the relay is designed. This may be done by plotting a set of time-impedance curves, each curve being for a constant current applied to the relay. Figure 5 shows such a set of curves plotted in terms of an impedance parameter $z_e$ for various values of current expressed in per cent of current tap setting. The parameter $z_e$ is so constituted that it bears the following relationship to $Z$

$$z_e = \frac{T_c R_c}{T_p R_p} Z \tag{41}$$

in which:

$T_c$ = the current tap setting of the relay
$T_p$ = the voltage tap setting of the relay
$R_c$ = the current transformer ratio
$R_p$ = the potential transformer ratio

The derivation of equation 41 and the curves of figure 5 is given in appendix $A$. Having determined the value of $Z$ in exactly the same manner as for the case of an instantaneous impedance element, equation 41 and the use of the curves of figure 5 permit the determination of the relay operating time. Unfortunately, as is evident from the curves of figure 5, this operating time is a function of the current in the relay. It will, therefore, be necessary to solve the proper expression for current given in table I and express this value as a percentage of $T_c R_c$ in order to determine which curve of figure 5 applies.

## Distance Relays for Ground Faults

The application of distance relays for protection against single-phase-to-ground faults has been discussed by Lewis and Tippett,[1] A. R. van C. Warrington,[3] and Goldsborough and Smith.[4] From these discussions it appears that a reactance type of element is indicated, connected to the the phase-to-neutral potential of the phase at fault and supplied with the faulted phase current compensated by a certain amount of residual current dependent upon the ratio of the effective zero-phase-sequence impedance between the relay and the fault to the effective positive-phase-sequence impedance between the same points. Further it is generally agreed that the relay so connected must be rendered inoperative in case more than one phase is involved in the fault. On this basis the effective impedance presented to the relay in the case of a single-phase-to-ground fault will be:

$$Z_{a0} = \frac{V_{oa}}{I_a + \frac{M-1}{3} I_n} \tag{42}$$

This becomes:

$$Z_{a0} = \frac{2c_1 z + c_0 z_0}{2c_1 + M c_0} = z \tag{43}$$

If

$$M = \frac{z_0}{z} \tag{44}$$

It should be remembered that $z_0$ in the above expression is an *effective* value and takes into account not only the zero-phase-sequence impedances of the lines and equipment in the path between the relay and the fault, but also the relative current distribution and, most important, the effect of mutual induction of zero-phase-sequence currents flowing in parallel circuits.

## Appendix A—Derivation of Distance Element Equations

In an instantaneous distance element 2 torques, an operating torque and a restraining torque are placed in opposition. The relay will be assumed to operate under conditions such that the operating torque is equal to or greater than the restraining torque and to be balanced when these torques are equal. These torques are functions of the fluxes produced in the relay coils and the angles between them. Since these fluxes are proportional to and have angles equal to the currents in the relay coils, the following balance equations will be derived from the currents themselves without further reference to the fluxes produced by them. The following nomenclature will be used.

$I$ = current in the current coil
$V$, $V_q$ = voltages applied to the potential coils
$z_p$, $z_p'$ = impedances of the potential coil circuits
$k$, $k'$ = balance constants
$K$, $K_1$, $K_2$ = derived constants indicative of the distance setting or range of the element
$S$ = a factor indicative of the variation of the range of the $GAX$ starting unit with applied voltage
$\psi$ = an angle characteristic of the element at which the operating torque is a maximum

(*a*) Impedance Element

$$kI^2 = \left(\frac{V}{z_p}\right)^2 \tag{A1}$$

$$K = z_p\sqrt{k} \tag{A2}$$

$$K = \frac{V}{I} \tag{A3}$$

$$K\angle\phi_z = Z\angle\phi_z = \frac{V}{I}\angle(\phi_V - \phi_I) \tag{A4) (6}$$

(*b*) REACTANCE ELEMENT

$$kI^2 = I\frac{V}{z_p}\sin(\phi_V - \phi_I - \phi_{zp}) \tag{A5}$$

In order for this element to indicate reactance $\phi_{zp}$ must be made $= 0$. If this is done

$$K = kz_p; \qquad \phi_{zp} = 0 \tag{A6}$$

$$\frac{K}{\sin(\phi_V - \phi_I)} = \frac{V}{I} \tag{A7}$$

$$\frac{K}{\sin\phi_z}\angle\phi_z = \mathcal{Z}\angle\phi_z = \frac{V}{I}\angle(\phi_V - \phi_I) \tag{A8) (8}$$

(*c*) MODIFIED REACTANCE ELEMENT

The construction and principle of operation of this relay is fully described in reference 5 to which the reader is referred.

$$I^2 + \left(\frac{V}{k'z_p'}\right)^2 + 2I\frac{V}{k'z_p'}\cos(\phi_V - \phi_I - \phi_{zp}) = \left(\frac{V}{kz_p}\right)^2 \tag{A9}$$

$$K_1 = kz_p; \quad K_2 = k'z_p'; \quad \psi = \phi_{zp}' \tag{A10}$$

Substitute equations $A10$ in equation $A9$ and divide by $I^2$

$$1 = \left(\frac{1}{K_1^2} - \frac{1}{K_2^2}\right)\left(\frac{V}{I}\right)^2 - \left(\frac{2}{K_2}\cos(\phi_V - \phi_I - \psi)\right)\left(\frac{V}{I}\right) \tag{A11}$$

Equation $A11$ is a quadratic which may be solved for $V/I$ and the solution expressed in the polar form yields equation 10 given in the text.

(*d*) DIRECTIONAL ELEMENTS WITH VOLTAGE RESTRAINT

Two types of single-phase elements must be distinguished, the *GAX* starting unit type which employs a single voltage and current, and the *GCX* starting unit type which employs 2 voltages and a current.

1. *GAX Type.* In this element the operating torque is obtained from the current $I$ in the current coil and the current in a potential coil which is connected to the source of potential $V$ through a condenser (to obtain the desired phase shift) and a Thyrite stack in order to give the current in the potential coil an amplified value at low values of $V$. The impedance of this potential circuit $z_p'$ is, therefore, not a constant, but is dependent upon the value of $V$. The power factor angle of this circuit $\phi_{zp}'$, however, is substantially a constant. The restraining torque is obtained from a second potential coil operating from $V$ without amplification.

$$kI\frac{V}{z_p'}\sin(\phi_I - \phi_V + \phi_{zp}') = \left(\frac{V}{z_p}\right)^2 \tag{A12}$$

$$KS = \frac{kz_p^2}{z_p'}; \; 90° + \psi = \phi_z'_p \tag{A13}$$

$$K\cos(\phi_V - \phi_I - \psi) = \frac{1}{S}\frac{V}{I} \tag{A14}$$

$$K\cos(\phi_z - \psi)\angle\phi_z = \frac{1}{S}\mathcal{Z}\angle\phi_z = \frac{1}{S}\frac{V}{I}\angle(\phi_V - \phi_I) \tag{A15) (12}$$

In the above equations $K$ is a constant indicative of the relay range at normal voltage. $S$ is a function of $V$ and represents the ratio of the range of the relay at any given value of $V$ to the range at normal voltage. Figure 6 shows the relationship between $S$ and $V$ for the standard *GAX* relay starting unit. For a given fault condition the value of $V$ is readily determined from the proper expression given in table I.

2. *GCX Type.* In this element the operating torque is obtained by the interaction of the current $I$ in the current coil and the current in a potential coil which is connected to a second source of potential $V_q$ which is in quadrature to $I$ at unity power factor. No Thyrite stack is employed so that the impedance of this potential circuit is a constant. The restraining torque is obtained by the interaction of the current in the above mentioned potential coil and the current in a second potential coil connected to the potential $V$.

$$kI\frac{V_q}{z_p'}\sin(\phi_I - \phi_V - \phi_{z'p}) = \frac{V_q}{z_p'}\frac{V}{z_p}\sin(\phi_V - \phi_{Vq}) \tag{A16}$$

$$K = \frac{2}{\sqrt{3}}kz_p; \; \psi = \phi_{z'p} \tag{A17}$$

$$K\cos(90° + \phi_{Vq} - \phi_I - \psi) = \frac{2}{\sqrt{3}}\frac{V}{I}\sin(\phi_V - \phi_{Vq}) \tag{A18}$$

$$K\cos(\phi_z - \psi)\angle\phi_z = \mathcal{Z}\angle\phi_z \tag{A19) (13}$$

$$= \frac{2}{\sqrt{3}}\frac{V}{I}\sin(\phi_V - \phi_{Vq})\angle 90° + \phi_{Vq} - \phi_I$$

$$= \frac{V}{I}\angle(\phi_V - \phi_I) \times \frac{2}{\sqrt{3}}\sin(\phi_V - \phi_{Vq})\angle(90° + \phi_{Vq} - \phi_V)$$

3. *Polyphase Element.* This element has 2 restraining potential coils mechanically balanced against the torque produced by a conventional polyphase directional element. The equations will be derived on the basis of the usual quadrature connections to the operating potential coils. Since we are to deal with 3 phase currents and 3 phase-to-phase voltages, these currents and voltages will be given the usual phase notation.

$$k\Big[I_a\frac{V_{cb}}{z_p'}\sin(\phi_{Ia} - \phi_{Vcb} + \phi_{z'p}) +$$

$$I_b\frac{V_{ac}}{z'_p}\sin(\phi_{Ib} - \phi_{Vac} + \phi_{z'p}) + \tag{A20}$$

$$I_c\frac{V_{ba}}{z_p'}\sin(\phi_{Ic} - \phi_{Vba} + \phi_{z'p})\Big]$$

$$= \frac{V_{cb}}{z_p}\frac{V_{ba}}{z_p}\sin(\phi_{Vba} - \phi_{Vcb})$$

$$= \frac{V_{ac}}{z_p}\frac{V_{cb}}{z_p}\sin(\phi_{Vcb} - \phi_{Vac})$$

$$= \frac{V_{ba}}{z_p}\frac{V_{ac}}{z_p}\sin(\phi_{Vac} - \phi_{Vba})$$

By making the substitution

$$K = 2\sqrt{3}\,k\frac{z_p^2}{z_p'}; \quad \psi = \phi_{z'p} \tag{A21}$$

and transposing the terms, the following equation is obtained.

$$\frac{K\cos(90° + \phi_{Vcb} - \phi_{Ia} - \psi)}{\frac{2}{\sqrt{3}}\frac{V_{ba}}{I_a}\sin(\phi_{Vba} - \phi_{Vcb})} +$$

$$\frac{K\cos(90° + \phi_{Vac} - \phi_{Ib} - \psi)}{\frac{2}{\sqrt{3}}\frac{V_{cb}}{I_b}\sin(\phi_{Vcb} - \phi_{Vac})} +$$

$$\frac{K\cos(90° + \phi_{Vba} - \phi_{Ic} - \psi)}{\frac{2}{\sqrt{3}}\frac{V_{ac}}{I_c}\sin(\phi_{Vac} - \phi_{Vba})} = 3 \tag{A22}$$

It will be noted that the 3 left-hand terms of equation $A22$ are composed of terms identical with the terms of equation $A18$ for the *GCX* unit. Substituting their equivalents from equation $A19$ the following equation is obtained:

$$\frac{K\cos(\phi_{za} - \psi)\angle\phi_{za}}{\mathcal{Z}_a\angle\phi_{za}} + \frac{K\cos(\phi_{zb} - \psi)}{\mathcal{Z}_b\angle\phi_{zb}}\angle\phi_{zb} +$$

$$\frac{K\cos(\phi_{zc} - \psi)\angle\phi_{zc}}{\mathcal{Z}_c\angle\phi_{zc}} = 3 \tag{A23}$$

Equation *A*23 may be reduced to the following form

$$K\cos(\phi_z - \psi)\angle\phi_z = \mathcal{Z}\angle\phi_z = \frac{3}{\frac{1}{\mathcal{Z}_a\angle\phi_{za}} + \frac{1}{\mathcal{Z}_b\angle\phi_{zb}} + \frac{1}{\mathcal{Z}_c\angle\phi_{zc}}} \qquad \text{(A24) (14)}$$

(*e*) TYPE *CZ* IMPEDANCE RELAY

In this type of relay the operating torque is balanced against the restraining torque through what may be considered as an ideal spring. It is apparent, therefore, that the effect of the operating torque in opposing the restraining torque is a function of the extension of the spring which in turn is a function not only of the current, but also of $T$, the time of application of the current. The restraining torque is produced by a voltage solenoid so constructed that the torque produced is proportional to the first power and not to the square of current in it.

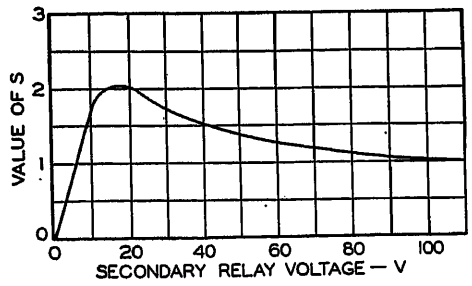



**Figure 6. Variation in range of GAX starting unit with applied voltage**

The relay operates when:

$$kTI = \frac{V}{z_p} \qquad \text{(A25)}$$

$$K = \frac{I}{kz_p} \qquad \text{(A26)}$$

$$T = K\frac{V}{I} = K\mathcal{Z} \qquad \text{(A27)}$$

Unfortunately, equation *A*27 is not satisfactory for the accurate determination of $T$ from $\mathcal{Z}$ due to the fact that $k$ and, therefore, $K$ is not an exact constant but is affected by variations in $V$ and $I$. In order to best express this variation it is desirable to write the following equations.

$$T = f\left(z_e, \frac{I}{T_c}\right) \qquad \text{(A28)}$$

$$z_e = \frac{T_c}{T_v}\mathcal{Z} \qquad \text{(A29)}$$

where

$T_c$ = the current tap setting of the relay
$T_v$ = the voltage tap setting of the relay
$z_e$ = an impedance which would have to be applied to the relay terminals if the relay were connected on the 1-ampere current tap and the 1-volt voltage tap to produce equivalent results

The above relationships assumed that $I$ is a secondary current and that $\mathcal{Z}$ is a secondary impedance. For primary values equation *A*29 will become

$$z_e = \frac{T_cR_c}{T_vR_v}\mathcal{Z} \qquad \text{(A30) (41)}$$

where:

$R_c$ = the current transformer ratio
$R_v$ = the potential transformer ratio

The relationship between $T$ and $z_e$ for various values of $I/T_cR_c$ can be readily determined and plotted as a family of curves. If a set of conventional *CZ* relay curves are available in which $T$ is plotted against current in per cent of tap setting for various voltages applied to the relay on a given voltage tap, then the $T - z_e$ curve may be determined for a given per cent current by making use of the relationship

$$z_e = \frac{\text{voltage applied}}{T_v} \times \frac{100}{\text{per cent current}}$$

$T$ = the time shown by the voltage curve for the given per cent current

## Appendix B—Derivation of Expressions for Voltages and Currents

The expressions for voltages and currents will be derived on the basis that the positive- and negative-phase-sequence networks are identical. The following nomenclature will be used.

$E$ = the normal primary phase to neutral voltage at the relay in the reference phase
$v_1, v_2, v_0$ = the respective positive-, negative-, and zero-phase-sequence voltages at the relay in the reference phase
$V_{0a}, V_{ba}, V_{ab}, V_{ac}$ = phase-to-neutral and phase-to-phase voltage at the relay as indicated
$Z_1$ = the equivalent impedance of the positive- (or negative) phase-sequence network expressed at the voltage $E$
$Z_0$ = the equivalent impedance of the zero-phase-sequence network expressed at the voltage $E$
$z$ = the effective positive- or negative-phase-sequence impedance between the relay and point of fault expressed at the voltage $E$
$z_0$ = the effective zero-phase-sequence impedance between the relay and point of fault expressed at the voltage $E$
$z_1'$ = the effective positive- (or negative) phase-sequence impedance behind the relay expressed at the voltage $E$
$z_0'$ = the effective zero-phase-sequence impedance behind the relay expressed at the voltage $E$
$I_1, I_2, I_0$ = the respective total positive-, negative-, and zero-phase-sequence currents at the point of fault transferred to the relay and in the reference phase at the relay
$i_1, i_2, i_0$ = the respective positive-, negative-, and zero-phase-sequence currents at the relay in the reference phase flowing in $z$ or $z_0$
$i_1', i_2', i_0'$ = the respective positive-, negative-, and zero-phase-sequence currents behind the relay in the reference phase flowing through $z_1'$ or $z_0'$
$I_a, I_b, I_c, I_n$ = primary phase and neutral currents flowing through the relay with star-connected current transformers
$I_a', I_b', I_c'$ = primary phase currents flowing through the relay with delta-connected current transformers
$c_1 = i_1/I_1 = i_2/I_2$ = the positive- (or negative) phase-sequence current distribution factor at the relay
$c_0 = i_0/I_0$ = the zero-phase-sequence current distribution factor
$A, B$ = factors used to simplify the expressions for the voltages $V_{ba}$ and $V_{ac}$

$C, D$ = factors used to simplify the expressions for the currents $I_b$ and $I_c$ in the case of 2 phase-ground faults

$C', D'$ = factors used to simplify the expressions for the currents $I_a'$ and $I_c'$ in the case of 2 phase-ground faults

The following equations express the phase sequence voltages at the relay in the reference phase.

$$v_1 = E - i_1'z_1' = E - (I_1Z_1 - i_1z) \quad \text{(B1)}$$

$$v_2 = -i_2'z_1' = -(I_2Z_1 - i_2z) \quad \text{(B2)}$$

$$v_0 = -i_0'z_0' = -(I_0Z_0 - i_0z_0) \quad \text{(B3)}$$

From these the following equations are derived to express the phase-to-neutral and phase-to-phase voltages at the relay.

$$V_{0a} = v_1 + v_2 + v_0 = E - (I_1 + I_2)Z_1 - I_0Z_0 + (i_1 + i_2)z + i_0z_0 \quad \text{(B4)}$$

$$V_{ba} = \sqrt{3}(v_1\angle 30° + v_2\angle -30°) = \sqrt{3}[E\angle 30° - (I_1\angle 30° + I_2\angle -30°)Z_1 + (i_1\angle 30° + i_2\angle -30°)z] \quad \text{(B5)}$$

$$V_{cb} = \sqrt{3}(v_1 - v_2)\angle -90° = \sqrt{3}[E - (I_1 - I_2)Z_1 + (i_1 - i_2)z]\angle -90° \quad \text{(B6)}$$

$$V_{ac} = \sqrt{3}(v_1\angle 150° + v_2\angle -150°) = \sqrt{3}[E\angle 150° - (I_1\angle 150° + I_2\angle -150°)Z_1 + (i_1\angle 150° + i_2\angle -150°)z] \quad \text{(B7)}$$

The phase and neutral currents in the relay may be expressed in terms of the phase sequence components in the reference phase as follows:

$$I_a = i_1 + i_2 + i_0 \quad \text{(B8)}$$

$$I_b = i_1\angle -120° + i_2\angle 120° + i_0 \quad \text{(B9)}$$

$$I_c = i_1\angle 120° + i_2\angle -120° + i_0 \quad \text{(B10)}$$

$$I_n = 3i_0 \quad \text{(B11)}$$

$$I_a' = \sqrt{3}(i_1\angle 30° + i_2\angle -30°) \quad \text{(B12)}$$

$$I_b' = \sqrt{3}(i_1\angle -90° + i_2\angle 90°) \quad \text{(B13)}$$

$$I_c' = \sqrt{3}(i_1\angle 150° + i_2\angle -150°) \quad \text{(B14)}$$

The above equations are general and apply for any type of fault. The following relationships apply for the particular case of fault under consideration.

1. *Three-Phase Fault*

$$E = I_1Z_1; \quad I_2 = 0; \quad I_0 = 0 \quad \text{(B15)}$$

$$i_1 = c_1\frac{E}{Z_1}; \; i_2 = 0; \; i_0 = 0 \quad \text{(B16)}$$

2. *Phase-Phase Fault (no phase shift in voltage between relay and fault)*

$$E = 2I_1Z_1; \quad I_2 = -I_1; \quad I_0 = 0 \quad \text{(B17)}$$

$$i_1\frac{c_1E}{2Z_1}; \quad i_2 = -i_1; \quad i_0 = 0 \quad \text{(B18)}$$

3. *Phase-Ground Fault (no phase shift in voltage between relay and fault)*

$$E = I_1(2Z_1 + Z_0); \quad I_2 = I_1; \quad I_0 = I_1 \quad \text{(B19)}$$

$$i_1 = \frac{c_1E}{2Z_1 + Z_0}; \; i_2 = i_1; \; i_0 = \frac{c_0E}{2Z_1 + Z_0} \quad \text{(B20)}$$

4. *Two Phase-Ground Fault (no phase shift in voltage between relay and fault)*

$$E = (I_1 - I_2)Z_1;$$

$$I_2 = -\frac{Z_0}{Z_1 + Z_0}I_1; \quad I_0 = -\frac{Z_1}{Z_1 + Z_0}I_1 \quad \text{(B21)}$$

$$i_1 = \frac{c_1(Z_1 + Z_0)}{Z_1(Z_1 + 2Z_0)}E;$$

$$i_2 = -\frac{c_1Z_0}{Z_1(Z_1 + 2Z_0)}E; \quad i_0 = -\frac{c_0}{Z_1 + 2Z_0}E \quad \text{(B22)}$$

5. *Phase-Phase Fault (30-degree phase shift in voltage between relay and fault)*

$$E = 2I_1Z_1; \quad I_2 = I_1; \quad I_0 = 0 \quad \text{(B23)}$$

$$i_1 = \frac{c_1E}{2Z_1}; \quad i_2 = i_1; \quad i_0 = 0 \quad \text{(B24)}$$

6. *Phase-Ground Fault (30-degree phase shift in voltage between relay and fault)*

$$E = I_1(2Z_1 + Z_0); \quad I_2 = -I_1; \quad I_0 = 0 \quad \text{(B25)}$$

$$i_1 = \frac{c_1E}{2Z_1 + Z_0}; \quad i_2 = -i_1; \quad i_0 = 0 \quad \text{(B26)}$$

7. *Two Phase-Ground Fault (30-degree phase shift in voltage between relay and fault)*

$$E = (I_1 + I_2)Z_1; \quad I_2 = \frac{Z_0}{Z_1 + Z_0}I_1; \quad I_0 = 0 \quad \text{(B27)}$$

$$i_1 = \frac{c_1(Z_1 + Z_0)}{Z_1(Z_1 + 2Z_0)}E; \; i_2 = \frac{c_1Z_0}{Z_1(Z_1 + 2Z_0)}E; \; i_0 = 0 \quad \text{(B28)}$$

Equations *B*15–*B*28 when substituted in equation *B*5–*B*7 and *B*8–*B*14 yield the expressions for voltages and currents given in table I.

Equations *B*14 and *B*20 when substituted in equations *B*4, *B*8, and *B*11 give rise to equation 43 in the text.

The vector angles between the voltages are obtained by division of the voltage expressions given in table I. In all cases:

$$\frac{V_{ba}}{V_{cb}} = -\frac{A}{2} \quad \text{(B29)}$$

$$\phi_{Vba} - \phi_{Vcb} = 180° + \phi_A \quad \text{(B30)}$$

$$\frac{V_{cb}}{V_{ac}} = -\frac{2}{B} \quad \text{(B31)}$$

$$\phi_{Vcb} - \phi_{Vac} = 180° - \phi_B \quad \text{(B32)}$$

$$\frac{V_{ac}}{V_{ba}} = \frac{B}{A} \quad \text{(B33)}$$

$$\phi_{Vac} - \phi_{Vba} = \phi_B - \phi_A \quad \text{(B34)}$$

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# Tests on Oil-Impregnated Paper—II

## Effects of Gas Pressure

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## Synopsis

In 1934 tests were started to investigate the important factors influencing the life of oil-impregnated paper at high voltage. Last year we described the techniques developed to date in this investigation. The present paper presents all data taken on specimens tested under a gas pressure of 200 pounds per square inch and compared all results obtained with one commercial mineral oil and one commercial wood-pulp paper for 3 conditions of gas pressure. The results indicate that under the conditions of these tests *there is no correlation between dielectric loss and electrical life* and that *gas-free specimens are superior to any specimens saturated with gas up to 200 pounds per square inch pressure.*

## A. Introduction

THE TECHNIQUE developed in our laboratories for studying the causes of electrical failure in oil-impregnated paper using miniature specimens has been described in an earlier paper.[1] Three types of cells were developed to allow life tests to be made under 3 conditions of gas pressure; namely, gas saturated at atmospheric pressure (figure 2), gas saturated at 200 pounds per square inch pressure (figure 4), and gas free (figure 3). This paper also showed the results obtained with 23 specimens which were saturated with gas at atmospheric pressure. It is the object of the present paper to present the data obtained on all the specimens which we have saturated with gas at 200 pounds per square inch pressure, and to compare the data obtained using one commercial mineral oil (oil *A*) and one commercial wood-pulp paper (paper *D*) for 3 conditions of gas pressure in the specimen.

The most general criticism of the work presented in the previous paper was the lack of check tests. The same criticism can be applied to the data presented in this paper since all specimens listed were made in 1934 during the preliminary stages of this investigation. Our subsequent efforts have been directed toward studying *gas-free* specimens and no check tests on the gas saturated or gas pressure specimens have been attempted. Also, we exhausted our supply of oil *A* so that no check tests with identical samples of oil and paper are now possible. However, I believe that the marked differences in life shown by figure 1 are significant and worthy of publication.

The important characteristics of oil *A* and paper *D* are shown in tables I and II.

## B. Specimens Saturated With Gas at Atmospheric Pressure

Table III gives a summary of the life-test data for specimens containing oil *A* and paper *D* and maintained during life under a gas pressure of one atmosphere. All but one of these specimens failed at 22 kv in less than 150 days. Number 165, however, was raised to 30 kv at the end of 150 days and failed immediately. The power factor life history of all specimens is shown in figure 1.

## C. Specimens Saturated With Gas at 200 Pounds Per Square Inch Pressure

Table IV gives a summary of the life-test data for all specimens made with 10 layers of paper *D* and maintained during life under a gas pressure of 200 pounds per square inch. Specimens numbers 182*B* and 300 were dried, impregnated and immersed with degasified oil in the pressure vessel, and then charged with gas to 200 pounds per square inch pressure. The other specimens were dried and impregnated in a glass cell and then allowed to drain while still under good vacuum. After draining, they were transferred as quickly as possible to the pressure vessel and charged with gas at 200 pounds per square inch pressure. Specimens numbers 184, 185, and 186 were drained hot while the oil-impregnated samples were drained cold so that they would retain the maximum volume of oil. The drained samples were made up so as to simulate the worst possible conditions of a high-pressure-gas cable, such as a high spot in the line from which the impregnant would gradually drain away because of temperature cycles during operation. Specimen number 188 was made to see whether 200 pounds per square inch gas pressure was sufficient to prevent ionization in unimpregnated paper. The result was quite conclusive. It was unfortunate that the pressure cell containing specimen number 300 developed a leak which was not detected until the sample had failed electrically because this specimen would probably have had the longest life of any of this series.

One very interesting observation in connection with the preparation of these specimens was the difference in absorption of $N_2$ and $CO_2$. The oil and paper became saturated with $N_2$ in about one hour whereas several days were

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HUBERT H. RACE is a research engineer for the General Electric Company, Schenectady, N. Y. The information reported in this paper is obviously the result of the co-operative efforts of many individuals. In particular, the author wishes to express appreciation to those who have been responsible for important phases of the work, namely: S. I. Reynolds, for preparation of specimens, preliminary and post-mortem electrical measurements; H. M. Bousman, for life tests; and Doctor E. H. Winslow, for acid and metal determinations.

1. For all numbered references, see list at end of paper.

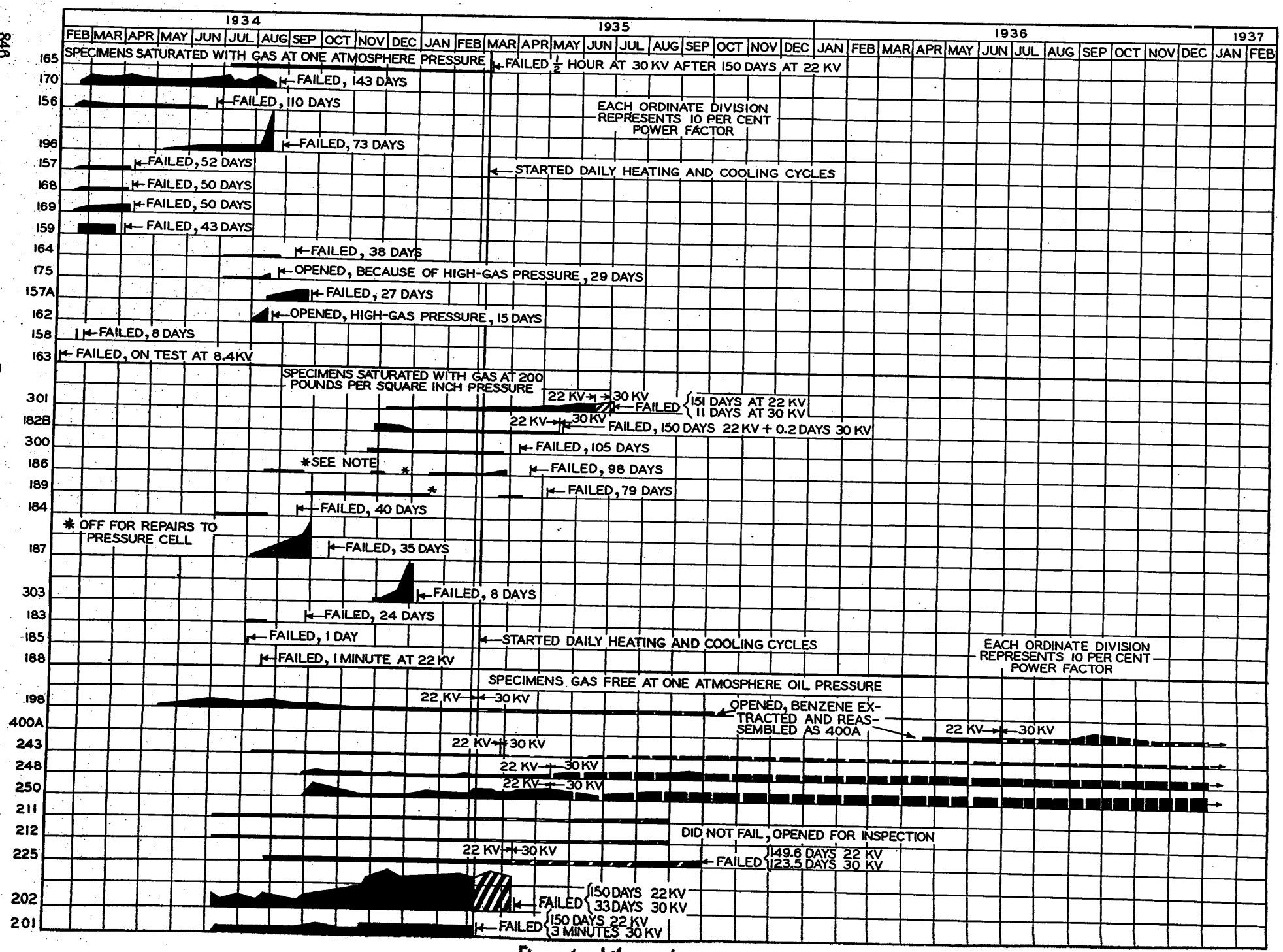



Figure 1. Life-test data

required to completely saturate the specimens with $CO_2$. Also the quantity of $CO_2$ absorbed was correspondingly very much greater.

Table V gives the data obtained by post-mortem examination of the 3 high-pressure specimens having longest life.

After specimens numbers 300 and 301 were prepared it was found that the tank $N_2$ used to charge them may have contained up to 1 per cent $O_2$. This may account for the high values of power factor, acid number, hydrophil number, and lead in solution in the oil from the latter specimen.

### Table I. Properties of Oil A

| | |
|---|---|
| Flash point | about 165 degrees centigrade |
| Fire point | about 185 degrees centigrade |
| Pour point | about −40 degrees centigrade |
| Specific gravity at 15.6 degrees centigrade | about 0.904 |
| Viscosity (Univ. Saybolt) at 37.8 degrees centigrade | about 105 sec. |
| Iodine unsaturation number (grams per 100 grams) | about 15 |
| Slight oxidation number | about 15 |
| Neutralization number (milligrams KOH per gram) | ≤0.015 |
| Chlorides | None |
| Free sulphur | None |
| Power Factor at 60 cycles per second and 60 degrees centigrade | ≤0.0002 |

### Table II. Properties of Paper D

| | |
|---|---|
| Type | 100 per cent sulphate kraft |
| Thickness | 0.0065 inch ± 0.0005 inch |
| Apparent density | 0.75 |
| Ash content | 1.2 per cent |
| Alkalinity (milligrams $H_2SO_4$ per gram) | 0.1 |
| Tensile strength strip one inch wide (machine direction) | 80 pounds |
| Tensile strength strip one inch wide (cross direction) | 22 pounds |
| Tearing strength (Elmendorf) machine direction | 140 pounds |
| Tearing strength (Elmendorf) cross direction | 280 pounds |

By contrast, note the low values for all these quantities for the oil removed from specimen number 182*B*, which was charged with dry $CO_2$.

## D. Specimens, Gas Free, at One Atmosphere Hydraulic Pressure

Table VI summarizes the life histories of all gas-free specimens that have been made with oil *A* and paper *D*. Specimen number 198 was the first gas-free specimen made. After it had been on high-voltage test for a total of 355 days it was taken out of its glass cell without disturbing the electrodes or the wrapping of the paper, extracted in benzene vapor for 24 hours, remounted in a new glass cell, reimpregnated and returned to test as number 400*A*. This was done to determine whether extraction of free oil with benzene and reimpregnation with new oil would improve the power factor. Since no improvement was obtained, we conclude that the materials responsible for dielectric loss in this specimen either are not benzene-soluble or are bound so tightly to the paper fibers that they cannot be washed out with benzene.

Specimens numbers 211 and 212 did not fail but were removed from test after a total life of 295 days, dissembled and examined by the micro methods described in the previous paper.[1] These are the only specimens which have been removed from test for examination before failure has started and therefore they have been included in this comparison. The papers used in these specimens had the same physical characteristics as paper *D*, the only difference being that they had been given special treatment to lower the ash content. There was no sign of incipient failures although there were dark brown stress marks on the inside of the inner layer showing the pattern of the edges of the copper threads on the inner electrode and light gray marks on the outside of the outer layer at the edge of the lead electrode. The results of the microanalyses on these specimens are given in table VIII.

Specimen number 225 has been included in this comparison because it was impregnated with oil similar to oil *A* but removed from the joint of an oil-filled cable in service and delivered to our laboratory in a standard reser-

### Table III. Summary of Data for Specimens Saturated With Gas at Atmospheric Pressure

| Specimen | Gas | Special Treatment† | Days Life 22 Kv | Days Life 30 Kv |
|---|---|---|---|---|
| 165 | Carbon dioxide | 0.01 per cent *G*† | 150+ | 0.02 |
| 170 | Oxygen | 0.1 per cent *H*† | 143 | |
| 156 | Oxygen | New oil | 110 | |
| 196 | Oxygen | 0.1 per cent *F*† | 75 | |
| 157 | Carbon dioxide | New oil | 52 | |
| 168 | Nitrogen | New oil | 50 | |
| 169 | Carbon dioxide | 0.1 per cent *H*† | 50 | |
| 159 | Oxygen | 0.5 per cent *H*† | 49 | |
| 164 | Carbon dioxide | 0.1 per cent *G*† | 38 | |
| 175* | Carbon dioxide | Paper washed 24 hours | 29 | |
| 157*A* | Carbon dioxide | New oil | 26 | |
| 162* | Nitrogen | 0.1 per cent *F*† | 15 | |
| 158 | Carbon dioxide | 1 per cent *H*† | 8 | |
| 163 | Oxygen | 1 per cent *G*† | 0 | |

* These specimens indicated a gas pressure exceeding 2 atmospheres and were removed before failure and opened

† Special characters *F*, *G*, *H*, and *I* indicate polar substances of undisclosed nature used in the laboratory experiments

### Table IV. Specimens Saturated With Gas at 200 Pounds per Square Inch Pressure

| Specimen Number | Gas | Paper | Oil | Treatment | Days Life 22 Kv | Days Life 30 Kv |
|---|---|---|---|---|---|---|
| 301 | $N_2$ | *D* | *A* | Drained | 151+ | 11 |
| 182*B* | $CO_2$ | *D* | *A* | Immersed | 150+ | 0.2 |
| 300 | $N_2$ | *D* | *A* | Immersed | 105* | |
| 186 | $CO_2$ | *D* | Paraffin | Drained | 98 | |
| 189 | $CO_2$ | *D* | *B* | Drained | 79 | |
| 184 | $CO_2$ | *D* | Ceresin and beeswax | Drained | 40 | |
| 187 | $CO_2$ | *D* | *E* | Drained | 35 | |
| 303 | $N_2$ | *D* | *E* | Drained | 35 | |
| 183 | $CO_2$ | *D* | *A* | Drained | 21 | |
| 185 | $CO_2$ | *D* | Petrolatum and 20 per cent rosin | Drained | 0.9 | |
| 188 | $CO_2$ | *D* | None | | <1 minute | |

* Cell leaked so that pressure dropped to 30 pounds per square inch. This probably caused failure

Specimen number 225 has been included in this comparison because it was impregnated with oil similar to oil *A* but removed from the joint of an oil-filled cable in service and delivered to our laboratory in a standard reser-

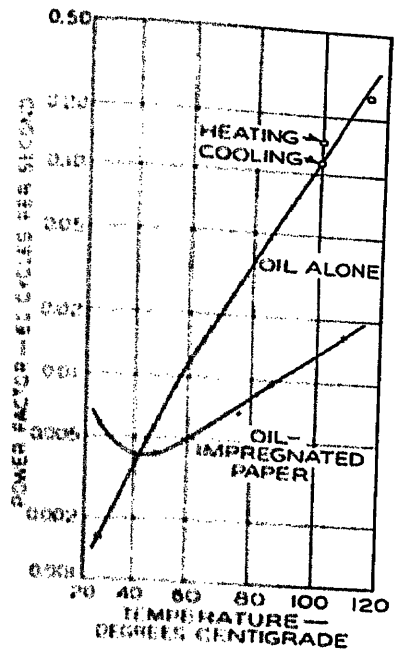



**Figure 2. Comparison of power factor of used cable oil alone and cable paper impregnated with this oil under vacuum**

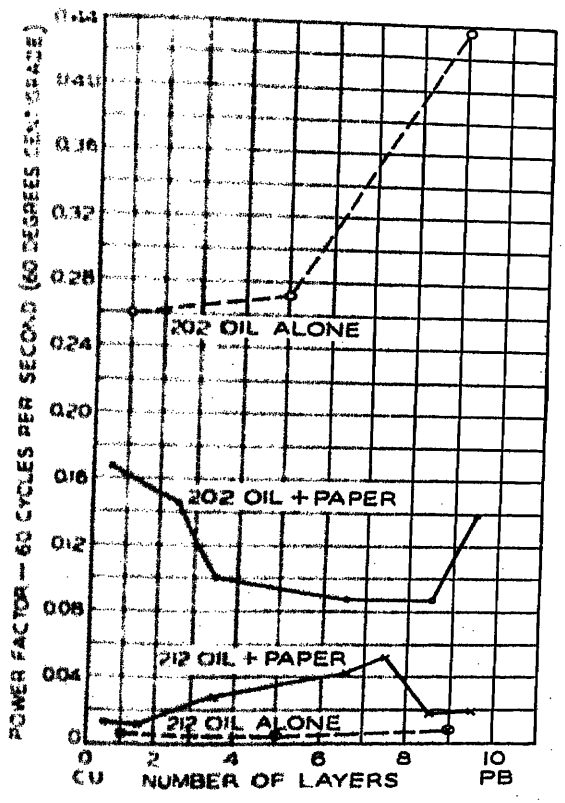



**Figure 3. Radial power measurements of oil alone and oil-soaked paper from specimens 202 and 212**

voir without exposure to air. The important properties of this oil which were different from those of new oil are shown in table VII. These were probably caused by contact with limited amounts of oxygen and black varnished cambric tape in the joint. The important observations from this test are the stability, relatively long life, and relatively low power factor of the specimen impregnated with this oil. That high power factor of oil does not mean correspondingly high power factor of oil-impregnated paper is shown by the life history of specimen number 225 shown in figure 1 and the comparison of oil alone and oil-impregnated paper shown in figure 2.

Specimens numbers 201 and 202 are particularly interesting in that they were impregnated with portions of oil *A*, one without and one with 0.1 per cent of a commercial oxidation inhibitor and preoxidized 96 hours at 115 degrees centigrade in a standard aging oven used by cable manufacturers for making oil-oxidation control tests. The specimen without an oxidation inhibitor gradually developed considerably higher power factor but had a longer life than the specimen containing the inhibitor (see figure 1). Neither had a life comparable with unoxidized speci-

**Table V. Data From Examination of Specimens Saturated With Gas at 200 Pounds Per Square Inch Pressure**

| | | | | | | |
|---|---|---|---|---|---|---|
| Specimen | | 182 *B* | | 300 | | 301 |
| Days life | 22 kv | 150+ | | 105 | | 151+ |
| | 30 kv | 0.2 | | 0 | | 11 |
| Oil | | A | | A | | A |
| Paper | | D | | D | | D |
| Gas | | $CO_2$ | | $N_2$ | | $N_2$ |
| Pressure (pounds per square inch) at 60 degrees centigrade | | 250 | | 215 | | 225 |
| | Portion | ε′ | P. F. | ε′ | P. F. | ε′ | P. F. |
| Test 1. Paper plus oil. Dielectric constant (ε′) and power factor (P. F.) | 1 | 2.78 | 0.097 | 2.49 | 0.068 | 3.67 | 0.200 |
| | 2 | 2.13 | 0.039 | 2.79 | 0.053 | 3.46 | 0.175 |
| | 3 | 2.69 | 0.020 | | 0.040 | 3.37 | 0.132 |
| | 4 | 2.65 | 0.025 | 2.79 | 0.057 | 3.46 | 0.160 |
| | 7 | 2.56 | 0.012 | | | 3.54 | 0.152 |
| | 8 | | 0.017 | | | 3.47 | 0.104 |
| | 9 | 2.84 | 0.010 | | | 3.50 | 0.190 |
| | 10 | 3.12 | 0.055 | | | 3.62 | 0.205 |
| Test 2. Oil. Dielectric constant (ε′) and power factor (P. F.) | 1 | 2.16 | 0.0036 | 2.18 | | 2.07 | 0.250 |
| | 2 | 2.16 | 0.0019 | 2.16 | 0.045 | 2.06 | 0.237 |
| | 3 | 2.17 | 0.0019 | 2.16 | 0.042 | 2.07 | 0.278 |
| Test 3. Acid (Milligram per gram) | 1 | | 0.1 | | 0.3 | | 0.5 |
| | 2 | | <0.1 | | 0.1 | | 0.3 |
| | 3 | | <0.1 | | | | 0.3 |
| Test 4. Hydrophil (Square centimeters per milligram) | 1 | | 30 | | 83 | | 276 |
| | 2 | | 23 | | 68 | | 261 |
| | 3 | | 26 | | 81 | | 253 |
| Test 5. Molecular weight (Grams per mol) | 1 | 335 | 275 | 270 | 256 | 332 | 256 |
| | 2 | 270 | 304 | 184 | 314 | 294 | 284 |
| | 3 | 313 | 303 | 309 | 313 | 265 | 208 |
| Test 6. Unsaturation (Grams per 100 grams) | 1 | | 0 | | 9 | | 8 |
| | 2 | | 0 | | 9 | | 4 |
| | 3 | | 0 | | 15 | | 7 |
| | | Cu | Pb | | | Cu | Pb |
| Test 7. Copper and lead ($10^{-6}$ grams per gram) | 1 | * | * | | | * | 30 |
| | 2 | * | * | | | * | 50 |
| | 3 | * | * | | | * | 380 |

* Less than minimup detectable concentration.

**Table VI. Specimens, Gas Free, at One Atmosphere Hydraulic Pressure Containing Oil A and Paper D**

| Specimen Number | Special Treatment | Days Life 22 Kv | Days Life 30 Kv |
|---|---|---|---|
| 198 | (First gas-free specimen made) | 186+ | 169+ |
| 400*A* | Number 198 extracted with $C_6H_6$ and re-impregnated | 31+ | 151+ |
| 243 | Paper washed 24 hours in tap water | 149+ | 446+ |
| 248 | Oil filtered through fullers' earth | 156+ | 418+ |
| 250 | Same as number 248 | 156+ | 418+ |
| 211 | Special-low-ash paper | 149+ | 146* |
| 212 | Special low ash paper | 149+ | 146* |
| 225 | Used oil from oil-filled cable in service | 150+ | 123 |
| 202 | Oil *A* oxidized 96 hours at 115 degrees centigrade | 149+ | 33 |
| 201 | Oil *A* + 0.1 per cent oxidized 96 hours at 115 degrees centigrade | 149+ | 3 minutes |

* Opened for inspection—did not fail

mens (198, 401, 211, 243, 248, 250). Apparently, although a cable may contain no free oxygen, if the oil has been oxidized before it is used to impregnate a cable, chemical reactions thus started continue during the life of the cable to the detriment of its electrical properties.

Table VIII shows the results of micro examinations which were made on gas-free specimens shown in table VI. Specimens for which no analysis is given are still running. Tests 4–7 are not reported because the measurements were made several days after the specimens were opened and the results are questionable. It is interesting to note that the specimens containing preoxidized oil showed measurable neutralization numbers concentrated at the electrodes whereas the unoxidized oils had neutralization numbers below our ability to measure them when these specimens were opened. Since these measurements were made the sensitivity of the acid and soluble metal measurements has been considerably improved. The technique will be described in later papers when more experience has been gained with the new methods.

The major difference between specimens 202 and 212 is that the oil used in number 202 was preoxidized before degasification and filling. Therefore, it is very interesting

**Table VII. Measurements on Sample of Oil Removed From Cable Joint in Service and Used to Impregnate Specimen Number 225**

| | |
|---|---|
| Power factor at 26 degrees centigrade | 0.0017 |
| Power factor at 100 degrees centigrade | 0.115 |
| Power factor at 115 degrees centigrade | 0.245 |
| Neutralization number (grams KOH per milligram oil) | 0.037 |
| Hydrophil number (square centimeters per milligram oil) | 6.1 |

a power factor curve similar to that observed in commercial cables,[2] being higher in the layers closest to the copper core and lead sheath and lowest in the center layers away from the metal electrodes. These data indicate that oxidized oil is the cause of this type of results observed in tests on commercial cable.

## E. Conclusions

The following general conclusions seem justified by the data presented in this paper.

1. At high electric stress, *gas-free*, oil-impregnated paper at one atmosphere oil pressure (oil and paper having properties like the components of oil-filled cable) should have longer life and less tendency to fail by gaseous ionization than similar cable under $N_2$ or $CO_2$ gas pressure up to at least 200 pounds per square inch gas pressure

2. High power factor of oil-impregnated paper does not necessarily mean short life as long as temperature equilibrium is maintained

3. The presence of oxidized oil will cause high dielectric losses, particularly in the layers of paper near the metal electrodes

**Table VIII. Data From Examination of Gas-Free Specimens**

| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Specimen | | 201 | | 202 | | 211 | | 212 | | 225 |
| Days life | 22 kv | 149+ | | 149+ | | 149+ | | 149+ | | 150+ |
| | 30 kv | 3 minutes | | 33 | | 146+ | | 146+ | | 123 |
| Oil | | A + F | | A | | A | | A | | Used oil |
| Paper | | D | | D | | J | | K | | D |
| | | oil oxidized 96 hours at 115 degrees centigrade | | | | | | | | |
| Test 1 | Portion | ε′ | P. F. | ε′ | P. F. | ε′ | P. F. | ε′ | P. F. | ε′ | P. F. |
| Paper plus oil (ε′ and power factor) | 1 | 3.23 | 0.168 | 2.98 | 0.017 | 3.29 | 0.013 | 3.01 | 0.048 | | |
| | 2 | | | 3.03 | 0.020 | 3.30 | 0.012 | 2.91 | 0.040 | | |
| | 3 | 3.36 | 0.146 | 3.03 | 0.017 | 3.22 | 0.020 | 3.29 | 0.047 | | |
| | 4 | 3.21 | 0.101 | 2.97 | 0.011 | 2.99 | 0.028 | 3.37 | 0.047 | | |
| | 7 | 3.02 | 0.088 | 3.06 | 0.018 | 3.08 | 0.043 | 3.27 | 0.048 | | |
| | 8 | | | 3.13 | 0.044 | 3.16 | 0.053 | 3.21 | 0.046 | | |
| | 9 | 3.68 | 0.087 | 3.03 | 0.039 | 3.20 | 0.018 | 3.23 | 0.044 | | |
| | 10 | 3.42 | 0.138 | 2.88 | 0.018 | 3.11 | 0.020 | 3.05 | 0.044 | | |
| Test 2 Oil (ε′ and power factor) | 1 | 2.18 | 0.260 | 2.18 | 0.018 | 2.16 | 0.006 | 2.18 | 0.047 | | |
| | 2 | 2.17 | 0.274 | 2.18 | 0.016 | 2.16 | 0.004 | 2.20 | 0.046 | | |
| | 3 | 2.17 | 0.436 | 2.18 | 0.011 | 2.16 | 0.008 | 2.20 | 0.047 | | |
| Test 3 Acid (milligrams per gram) | 1 | 0.1 | | 0.2 | | <0.1 | | <0.1 | | 0.02* | |
| | 2 | <0.1 | | <0.1 | | <0.1 | | <0.1 | | 0.02* | |
| | 3 | 0.2 | | 0.1 | | <0.1 | | <0.1 | | 0.01* | |

* These measurements were made with a recently developed, more sensitive neutralization number technique.

to compare the electrical data shown in figure 3 taken after these 2 specimens were opened.

The oil removed from specimen number 212 showed low losses throughout. The oil-soaked paper from specimen number 212 showed higher losses in the center and lowest at both the copper and lead ends. A plausible explanation for this variation is that *in the absence of oxygen or oxidation products* there was negligible chemical action at the 2 electrodes but that some thermal deterioration occurred in the center layers where the temperature would be highest because of dielectric losses. Now considering specimen number 202 the findings are entirely different. The oil extracted from the paper shows very high losses, particularly at the lead end. The oil-soaked paper gives

## References


1. Tests on Oil Impregnated Paper, H. H. Race. Electrical Engineering, volume 55, June 1936, page 590.

2. A Criterion of Quality of Cable Insulation, K. S. Wyatt and E. W. Spring. Electrical Engineering, volume 54, April 1935, page 417.

# Distortion of Traveling Waves by Corona

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## Synopsis

In order to make possible the prediction of the attenuation and distortion of lightning waves on transmission lines an equation is proposed that relates the change of shape of a traveling wave to the corona loss on the line at normal operating frequency. Results obtained by computation from this formula are compared with experimental results of various investigators.

THE ATTENUATION of high-voltage traveling waves by corona is of importance because of the protection it affords to terminal equipment when lightning strikes a transmission line at some distance from the nearest transformer station. The traveling wave that results from the lightning discharge has been found by many observers to lose energy quite rapidly as long as its crest voltage is well above the corona-forming voltage of the line on which it travels. A line of several miles length may usually be depended upon, therefore, to reduce the initial voltage of the lightning wave to a safe value.

Various equations have been proposed to express the rate of attenuation of the wave. These are reviewed by Bewley.[3] All of them, including an equation proposed by one of the present authors,[2] are purely empirical and have one or more adjustable constants which cannot be predetermined. It is now proposed to relate the distortion and attenuation of a traveling wave to the loss of power in corona at the line's normal operating frequency.

## The Mechanism of Corona Loss

The energy loss that accompanies corona is due to motion of free electric charge in the space surrounding conductors at high potential. This was pointed out by Ryan and Henline[4] in 1924, and the study of space charge which has since been carried on leads to the following conclusions:

1. There is a critical electric gradient for air that cannot be exceeded. Any attempt to increase the gradient above the critical value results in profuse ionization of the air, and the charges liberated by ionization take up such positions in space that the gradient is maintained at (or below) the critical value

2. Shortly after its formation space charge becomes relatively immobile. This is doubtless due to the formation of relatively heavy ions, for which the mobility is almost negligible as compared to electrons

3. The supply of space charge to the region about a conductor commences when the critical gradient is reached, and continues as long thereafter as the applied voltage continues to increase. During this time there is loss of energy from the conductor

4. After the crest of a voltage wave is reached, and the voltage begins to decrease, the space charge remains (approximately) constant in magnitude and fixed in position. During this time there is little loss of energy from the conductor, what loss there is being due to diffusion of the ions in the electric field at a slow rate. This interval ends when the critical gradient of opposite sign is reached and a new interval of active ionization commences

Space charge may be considered as forming a protective sheath about a conductor—a sheath that receives and terminates much of the incoming dielectric flux, so that no part of the air about the conductor is subjected to electric stress greater than the critical value. If voltage were raised so that the electric stress at any point exceeded the critical value, the gradient at the overstressed point would immediately be reduced by further ionization and the production of additional protective space charge. The action is analogous to the relief of mechanical stress in a piece of overstressed steel by inelastic deformation of the material.

When the voltage applied to a conductor is alternating it is necessary to locate a protective sheath of space charge about the conductor as the voltage rises to a crest, and then to neutralize that charge and replace it with one of opposite sign as the voltage changes to a crest of opposite polarity. Energy is consumed in the production of the space charge; the amount of energy consumed per cycle depends on the crest voltage of the wave but, as the amount of space charge required is independent of the duration of a cycle, the energy per cycle consumed in its production is independent of the frequency of the applied voltage. The power, consequently, or energy per second, is proportional to frequency. But this is not the total loss.

There is another kind of loss that is due to migration of the ions of space charge in the electric field. The protective sheath of space charge can never be stationary, for it is at all times acted upon by the electric field of the applied voltage and that of other parts of the space charge. When space charge moves in response to the electric field of the applied voltage it consumes power. So there is a continuous drain of power due to the *motion* of the space charge, quite apart from that due to its *formation*. Both are dependent upon the amount of applied voltage, but the loss due to migration differs from that due to formation by being a nearly constant loss that (at low frequency) is independent of the frequency. At moderately high fre-

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The analytical work reported in this paper is by H. H. Skilling. The experimental work was done by P. de K. Dykes, while a graduate student at the Ryan Laboratory, Stanford University. The aid of Doctor J. S. Carroll, director of the Ryan Laboratory, is gratefully acknowledged.

1. For all numbered references, see list at end of paper.

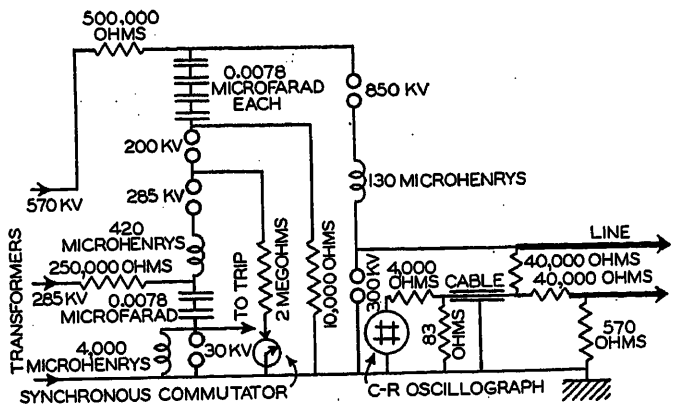



**Figure 1. Impulse generator and oscillograph**

quencies it becomes a negligible part of the total loss, while at 60 cycles per second it is about one-third of the total.[5]

The energy required to produce a protective sheath of space charge about a conductor is dependent upon the height to which the applied voltage rises. Each increase of voltage requires an increase of space charge, with a corresponding consumption of energy. As the applied voltage is raised from $e$ to $e + \Delta e$ the energy which has been used to produce space charge increases from $E$ to $E + \Delta E$. The ratio of the increments is (for very small increments) $dE/de$, which may be found by differentiation. The loss corresponding to a given increment of voltage is of course not constant, but is in general greater when the increase of voltage takes place at a high voltage than when the same increase takes place at a low voltage.

In developing the above concept of corona loss the mechanism of corona formation has been greatly idealized, and many small factors have been entirely neglected. One of these is a difference in loss on the positive and negative half-cycles of corona. This particular factor requires special mention, for it will arise again in the discussion of traveling waves.

## Loss From a Traveling Wave

A wave of electric energy traveling along a transmission line will necessarily produce ionization about the line as it passes and, since the only source of energy is the wave itself, it will lose energy as it travels. There is ample direct evidence of corona produced by traveling waves, for it may be both seen and heard.

Moreover, the voltage of a wave is related to its energy, although the relationship is not at all simple in a wave which is changing in shape as it travels. On a line without loss, or a distortionless line, energy is proportional to the square of the voltage for each element of the wave. This simple relationship is an approximation when applied to waves that are producing corona, but under any circumstances the voltage of a wave becomes less as its energy is decreased. And oscillographic measurements and sphere-gap measurements both show a rapid reduction of the voltage of traveling waves as long as their voltage exceeds the corona-forming voltage of the line.

## Analysis of Oscillograms

Oscillograms of waves attenuated by corona are shown in figure 2. The figure shows at the top, left, the record of a 320-kv wave impressed upon a line of number 10 copper wire, and at the top, right, the record of the same wave as it was received after traveling 836 feet along the line. Below this is a similar record of a wave of negative polarity, with an equal initial voltage but showing rather less attenuation as received. The time scale of the record is given by the 5-million-cycle wave at the bottom of the figure; the initial waves rise from zero to maximum voltage in 0.3 microseconds, the wave fronts being practically straight lines. These are typical of a collection[1] of several dozen of such oscillograms.

The network shown in figure 1 was used in obtaining these records. In producing a wave, the sphere gap set to flash at 285 kv is first to trip, the polarity of discharge being determined by a synchronous commutator. This immediately actuates the trip circuit of the cathode-ray oscillograph, and then, with a slight time delay, because of inductance, the gap set for 200-kv sparks. One set of condensers is charged by the transformers to 285 kv, and the other set to 570 kv; operation of the first 2 sphere gaps connects the condensers in series and so trips the main gap which is set at 850 kv. The condensers now commence to discharge into the line, producing the test surge, but when the voltage across the line has risen to 300 kv the surge is "chopped" by a sphere gap, and the surge voltage drops almost immediately to zero.

By adjusting the values of inductance, waves were produced having wave fronts of 0.3 to 1.63 microseconds duration. All waves were substantially triangular in shape. The oscillograms show a superimposed ripple, but this originated in the oscillograph circuit; it could be removed by introduction of damping resistance in the oscillograph circuit, but it was found best not to do so because of resulting loss of accuracy of the record.

The generated surge was sent out as a traveling wave on the test line. The line was laid out as a large loop, returning to the laboratory, and terminated in a resistor having the surge resistance of the line. Both outgoing and returning waves were recorded on a cathode-ray oscillograph.

Examination of the oscillograms yields the following information. The received wave has a wave front that is less steep than was that of the initial wave. The time re-

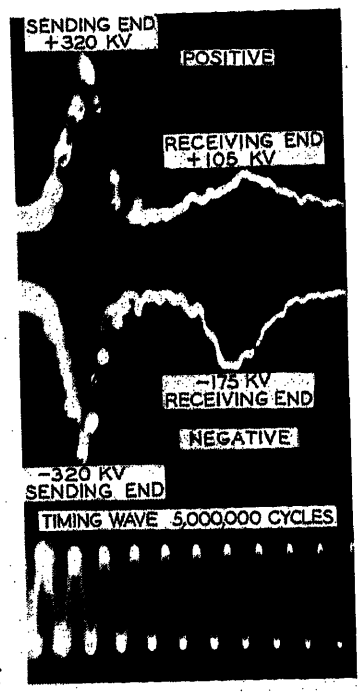



**Figure 2. Oscillograms of traveling waves, showing distortion by corona**

quired for the received voltage to rise from zero to maximum is equal to the time required for the initial voltage to rise from zero to maximum and then to descend to a value equal to the maximum received voltage. In other words, if the received wave were superimposed on the initial wave its crest would fall upon the "tail" of the initial wave, as shown in figure 3. At the same time the received wave has acquired a longer tail than was possessed by the initial wave. The appearance of the whole is as if the wave front had been cut down to a gentler slope as a result of having traveled along the line, so that the front and crest of the wave have been reduced, while the tail has somewhat gained.

Various attempts to deduce a law of action by *a posteriori* reasoning from the oscillograms failed, but they served at least to indicate the nature of the differential equation from which the law would have to be derived. It was seen to be related to the "quadratic law" of corona loss as promulgated by Peek,[5] and so the quadratic law was adopted as a starting point for the *a priori* deduction of a law of distortion by corona.

## Deduction of a Law of Action

Power loss from the experimental transmission line was determined by measurement, and is shown in figure 4. By plotting on a logarithmic scale it was found that the curve may well be expressed analytically as

$$\text{Loss} = k'(e - e_0)^2 \qquad (1)$$

in which $e$ is voltage, and $e_0$ and $k'$ are constants. The constants as so determined are in good agreement with those computed from the coefficients of Peek's law.

Corona loss is measured as power; that is, as energy per second. After that part of the power loss which is not proportional to frequency has been subtracted, the remainder may be divided by the number of voltage crests per second, and by the length of the line. The result, loss per unit length per half cycle, is expressed by an equation similar to equation 1 but with a different value for the coefficient which (for reasons that will appear later) may be written as $k/n$:

$$(\text{Loss as voltage rises to } e) = \frac{k}{n}(e - e_0)^2 \qquad (2)$$

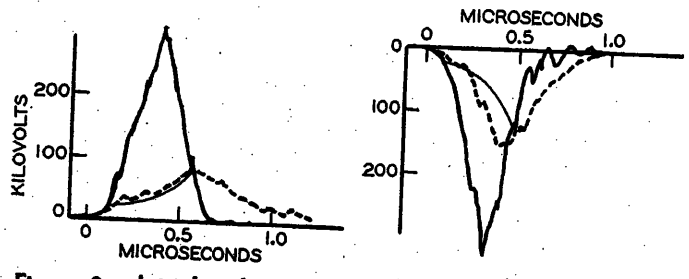



**Figure 3. Initial and received waves of oscillograms, superimposed. Computed curves are also shown**

The rate of energy loss as voltage increases is then found by differentiating equation 2:

$$\frac{dE}{de} = 2\frac{k}{n}(e - e_0) \qquad (3)$$

so that for a differential increase of voltage the loss is

$$dE = 2(k/n)(e - e_0)de \qquad (4)$$

When an electric wave is traveling on a line the voltage at a point of the line rises as the front of the wave passes. During the passage of the wave front, space charge is placed about the conductor, and energy is lost from the wave. Consider a specific point of the line $P$ at a distance which may be called $s$ from some stationary reference axis. (See figure 5.) Consider a short section of the traveling wave at the point $P$, which section of the wave may be specified as being at a distance $x$ from a reference axis which is moving along the line at the speed of the traveling wave. It follows that for a given point on the line $s$ is constant, while for a given section of the wave $x$ is constant. The 2 systems of co-ordinates are related by $s = x + y$. By definition, then, $y$ is the distance between the reference axes, so $y = vt$ wherein $v$ is the velocity of propagation of the wave (practically that of light) and $t$ is the time that has elapsed since $y$ was zero.

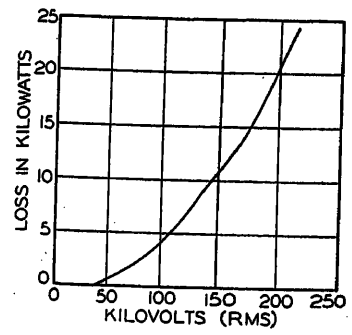



**Figure 4. Corona loss from a number 10 American wire gauge copper conductor, 836 feet long, 12.5 feet above ground. Voltage: 60-cycle sine-wave, wire to ground**

The energy loss at the point $P$ from a section of wave of length $dx$ while the wave is traveling a short distance $dy$ is

$$\text{Loss} = 2\frac{k}{n}\,dx\,(e - e_0)\,de \qquad (5)$$

in which $de$, the change of voltage at the point $P$, is

$$de = \frac{\partial e}{\partial x}dx + \frac{\partial e}{\partial y}dy$$

But since at a fixed point $s$ is constant, $dx = -dy$ and

$$\text{Loss} = 2\frac{k}{n}\,dx\,(e - e_0)\left(-\frac{\partial e}{\partial x}dy + \frac{\partial e}{\partial y}dy\right) \qquad (6)$$

It is now necessary to express energy of a section of traveling wave in terms of voltage. In the absence of distortion the energy of a section of wave of length $dx$ would be

$$E = c\,dx\,e^2 \qquad (7)$$

$c$ being the capacitance per unit length of line. Half of the energy is in the electric field, and half in the magnetic.[13] When distortion of the wave is taking place this equation

becomes an approximation only. Although of uncertain accuracy in the presence of corona, it will nevertheless be used in the following discussion, for it must be of the right order of magnitude.

Differentiation of equation 7 gives the rate of change of energy of a section of wave as its voltage changes, so the change of energy corresponding to a differential change of voltage is

$$dE = 2\,c\,dx\,e\,de \tag{8}$$

But loss due to corona, as expressed in equation 6, must be supplied from the energy of the wave, so

$$2\,c\,dx\,e\,de = 2\,\frac{k}{n}\,dx\,(e - e_0)\left(\frac{\partial e}{\partial x} - \frac{\partial e}{\partial y}\right)dy \tag{9}$$

Since $de$ of equations 8 and 9 is the change of voltage of a section of the wave it is the partial differential with constant $x$, and is equal to $(\partial e/\partial y)\,dy$. Introducing this into equation 9, and performing obvious simplifications,

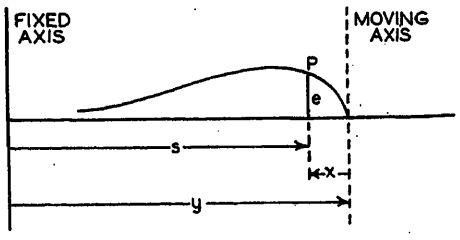



**Figure 5. Coordinates of traveling wave**

$$c\,e\,\frac{\partial e}{\partial y} = \frac{k}{n}\,(e - e_0)\left(\frac{\partial e}{\partial x} - \frac{\partial e}{\partial y}\right) \tag{10}$$

Rearrangement gives the partial differential equation

$$-\frac{k(e - e_0)}{k(e - e_0) + nce}\,\frac{\partial e}{\partial x} + \frac{\partial e}{\partial y} = 0 \tag{11}$$

for which the solution is an arbitrary function

$$f\left(t - \frac{k(e - e_0) + nce}{ncve}\,s\,,\,e\right) = 0 \tag{12}$$

(Elimination of $x$ and $y$ between equations 11 and 12 has been accomplished by use of the expressions defining $s$ and $y$.)

The form of function to be used in equation 12 is determined by some known relationship between $e$ and $t$ at some known value of $s$; for example, at the point where the voltage wave is applied to the line. If the initial wave is the function of time $e = f_0(t)$, it follows from equation 12 that at a distance $s$ the wave will have become

$$e = f_0\left(t - \frac{k(e - e_0) + nce}{ncve}\,s\right) \tag{13}$$

The initial voltage as a function of time may also be expressed $t = F_0(e)$, and corresponding to this is the equation (derived from equation 13) which applies at distance $s$:

$$t = F_0(e) + \frac{k}{ncv}\,\frac{(e - e_0)}{e}\,s + \frac{s}{v} \tag{14}$$

## Use of Derived Equation

This form of the equation is easily applied to any traveling wave. The only information regarding the wave that is needed is a curve of voltage and time; an oscillogram, that is, of the initial voltage (or if this is not available, of the voltage at any point on the line). There is no necessity to express $f_0(t)$ or $F_0(e)$ analytically, for the equation has been arranged to allow a graphical solution. The equation gives the information that at a point at distance $s$ there will correspond to each value of voltage $e$ a value of time $t$. This will differ from the value of time that corresponded to the same voltage at the initial point on the line by the last term of equation 14, which is merely the time required for the wave to travel the distance $s$, and by the next-to-last term which alone describes the distortion of the wave due to corona.

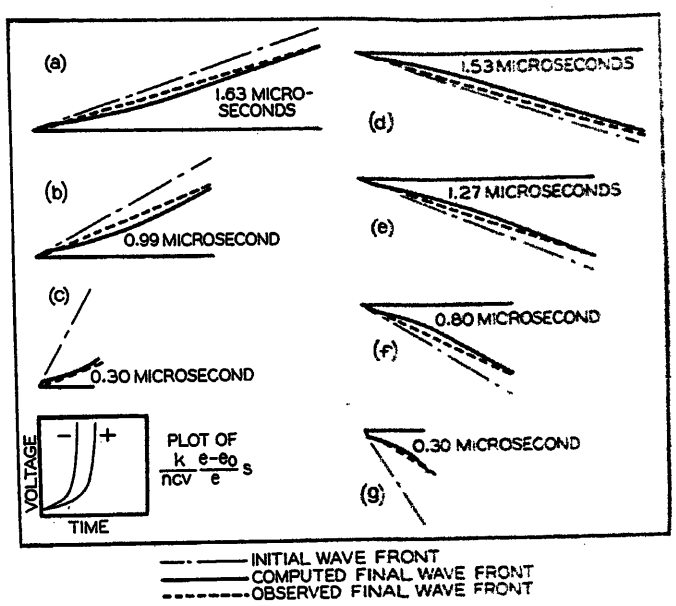



**Figure 6. Comparison of computed and recorded waves after attenuation and distortion by corona. All initial waves have crest voltage approximately 310 kv**

To determine the shape of the wave at distance $s$, plot the initial voltage-time curve. Then, at each value of voltage increase the value of time by an amount $Ks(e - e_0)/e$. The result is the wave as distorted by corona. (It must be noted, however, that this procedure applies only on the front of the wave, while the voltage is rising to a higher value than it has before attained. In the absence of further information it must be assumed that the tail of a wave is not affected by corona. This will be discussed in a later paragraph.) Reference to equation 14 gives a value of $k/ncv$ for $K$.

Symbols have the following meanings:

$t$ = time in seconds
$e$ = voltage in volts
$e_0$ = corona-starting voltage in volts (crest)
$c$ = capacitance of the line in farads per foot
$v$ = velocity of the wave in feet per second (practically $0.985 \times 10^9$)

$s$ = distance of travel in feet
$k$ = the constant of equation 2 which relates crest voltage in volts to energy loss in joules per foot per half cycle, and which may be found from Peek's quadratic law or otherwise
$n$ = a factor which differs for positive and negative waves, and as discussed below

## The Factor n

The factor $n$ is a more or less constant factor which is needed to account for 3 differences between the corona of traveling waves and the corona at power frequency. These are (1) the effect of mobility of charge, (2) the fact that when voltage is alternating there is space charge left over from one half cycle to the next, and (3) the difference between positive and negative corona.

The effect of mobility of charge has already been mentioned; at power frequency there is considerable loss due to mobility that is essentially constant regardless of frequency. Peek[5] shows that this is 25/85 of the 60-cycle loss. Other investigators give a slightly higher value, and it will be approximately correct to consider that the loss at 60 cycles due to cyclic reversal of space charge is 2/3 of the total loss. It was partly to take care of the division of power loss into cyclic and constant parts that the factor $n$ was introduced, and this consideration alone gives $n$ a value of 3/2. (See equation 2.) But this value of $n$ may be altered to take care of other considerations also.

Each crest of alternating voltage leaves the conductor surrounded by a sheath of space charge. Some of this returns to the conductor from which it came, some reaches the other conductor or is lost in space, but most remains until it is cancelled by a discharge of opposite sign as the applied voltage is reversed. During each half cycle of voltage, therefore, it is necessary not only to supply space charge of the same polarity as the voltage, but also to remove (or cancel) space charge of the opposite polarity. Consequently the total loss per half cycle is greater than would be the loss if there had been no previous opposite charge by a factor of uncertain magnitude that is something between 1 and 2. The use of $n$ may be extended to care for this factor, and the value of $n$ therefore becomes approximately 3.

Moreover, it is found that the loss of energy from a positive conductor is greater than that from a negative conductor. This is observed even with alternating voltage, although in the steady state the loss is largely equalized by the production of a rectified space charge. It is impossible for the charge that escapes from a conductor in corona to be continuously unbalanced, for the resulting excess of charge of one sign will accumulate until the voltage gradient about the conductor is so adjusted that the production of charge on alternate half cycles is equalized. But many observers of impulse voltages and traveling waves have found that the loss is greater from a positive conductor. It is, of course, natural that there should be a difference due to polarity because of different details of action of positive and negative ions. The ratio of loss from a positive wave to loss from a negative wave appears to be about 3 to 2. It is helpful, therefore, to assign different values to $n$ for positive and negative waves; $n^+$ (for positive waves) would on this basis be about $2^1/_2$, while $n^-$ (for negative waves) would be about 4.

## Comparison With Oscillograms of Waves

In figures 3, 6, 8, and 9 a comparison is shown of distortion as predicted by equation 14 and actual oscillographic voltage records. The oscillographic curves of figure 3 have been described above; superimposed on them are computed curves based on equation 14. The values of $n$ used in making the computations were $2^1/_2$ and 4 for positive and negative waves, respectively. These are the predicted values of $n$, and they give reasonably good agreement.

Figure 6 shows a comparison with the fronts of the same waves and with longer ones also. Each curve shows the average of data from several oscillograms; in most cases 5 or 6 photographic records were averaged. The term from equation 14 that expresses wave distortion due to corona is plotted in the lower left corner of the figure: in computing the shape of the distorted wave the abscissas of the appropriate curve are added to the values of time of the initial wave front, at the corresponding value of voltage.

It will be seen that agreement with measured waves is within the probable experimental error. However, computation for this figure was done with $n^+ = 4$ and $n^- = 6$, which values are about 50 per cent higher that the predicted ones.

It was also possible to compare the results of computation with equation 14 to data obtained some years ago.[2] A series of measurements with sphere gaps gave crest values of very short traveling waves as they were attenuated by corona. Only maximum voltages were measured, so the comparison must necessarily be with computed maximum values. It is known that the waves employed in the experimental work had practically uniform rise of voltage from zero to maximum, at which point they were "chopped," so that they were essentially triangular waves without tails. The slope of the impressed wave front was of the order of 2,000 kv per microsecond, and the crest voltage varied from 100 to 220 kv, so the duration of the wave is computed to be from $^1/_{20}$ microsecond for the short waves to $^1/_{10}$ microsecond for the longer ones. It will be seen that these are of a shorter order of magnitude than the waves of figure 6. Comparison of experimental and computed results is shown in figure 7; the agreement is surprisingly good. The value of $n$ used for the computed curves was 5, but the polarity of the experimental waves is not known.

The line used for the data of figure 7 was similar in size and height to that used later, so its loss at 60 cycles was taken from figure 4. Its total length was 1,000 feet but the first 500 feet were most significant and data for that part of the line only are shown in figure 7. The complete experimental curves appear in figure 1 of a previous paper,[2] and agreement with computed values is good throughout.

For comparison with completely independent experi-

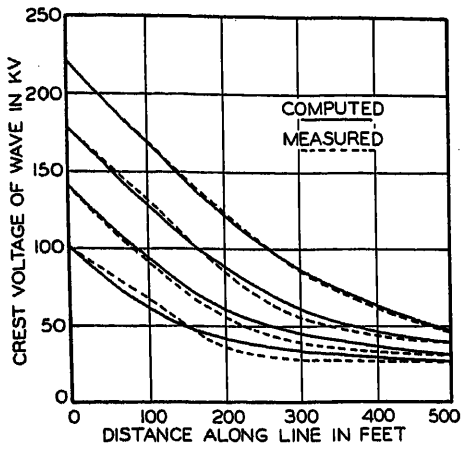



**Figure 7. Comparison of computed and measured wave crests as traveling waves are attenuated by corona**

mental work, computations were made of the change of shape to be expected in waves on one wire of the *S*-19 line of the Consumers Power Company (Michigan). Dimensions of the line are given in a paper[8] by McEachron, Hemstreet, and Rudge; corona loss on the line was computed according to the quadratic law, and the change of shape as predicted for traveling waves by equation 14 was determined on that basis. The experimentally recorded distortion of waves on the *S*-19 line is shown in a paper[7] by Brune and Eaton, and one set of their oscillograms is particularly fitted for comparison with computed distortion. Experimental and computed waves are shown in figure 8. The initial wave is shown, and also the received waves at 3 different distances along the line.

In computing distortion of the negative wave of figure 8*a*, a value of 4 was used for $n^-$, and for the positive wave of figure 8*b* a value of $2^1/_4$ was taken for $n^+$. See table I.

The general form of the computed and observed wave fronts of figure 8 is quite comparable. It is not at all surprising that there is difference of detail, for the computed curves consider only the effect of an ideal distribution of corona and completely neglect resistance of line and ground, the presence of other conductors, insulators and towers, variation of ground level, and other irregularities of the line. It is natural that the shorter the distance of travel, and the more rapid the attenuation by corona, the better is the agreement.

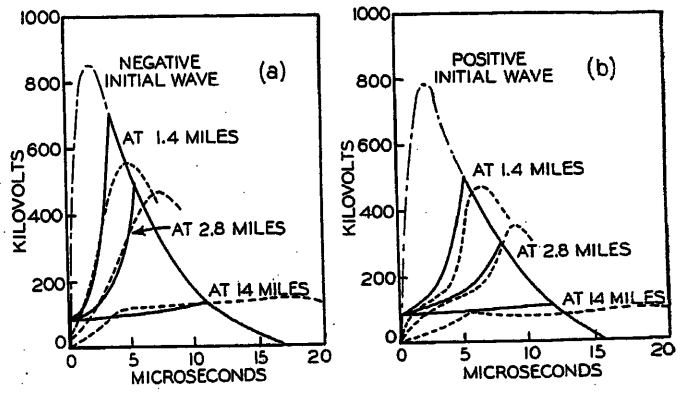
Several of the other curves shown by Brune and Eaton offer further interesting comparisons, but will not be reproduced here.

A study of the change of shape of traveling waves on the Bushkill-Roseland line of the Public Service Electric and Gas Company (New Jersey) is reported by Cox and Beck[9] and by Conwell and Fortescue.[10] The latter paper gives data that make possible the computation of corona loss at power frequency (using the quadratic law) and both papers show a number of oscillograms of waves affected by corona. Comparison of a wave from the latter paper with a curve of wave form computed from line dimensions appears in figure 9. The agreement is seen to be satisfactory. The value of $n^+$ used in computation was $2^1/_2$. There are several other sets of oscillograms of waves in these papers for comparison with computed distortion, but unfortunately there are no records of waves of negative polarity.

Behavior of waves on the Bushkill-Roseland line is of particular interest because it is typical of 220-kv lines in general dimensions, and therefore in corona loss. The conductors are 795,000-circular-mil-steel-reinforced aluminum cables, some 60 feet above ground. Conductors are spaced 28 feet, 6 inches, in a horizontal plane.

It will be noted that in all cases of comparison the agreement of recorded and computed distortion is good, but that different values of the factor $n$ have been employed. The values used for $n$ are shown in table I.

It is not improbable that the apparent variation of $n$ with duration of wave front is entirely fictitious, being due to experimental difficulty. On the other hand, it may be due to an actual decrease of loss when the duration of the wave front under consideration is very short. If the decrease of loss is real it may be due to inability of ions to move with great enough speed, although this is improbable because the motion required for the formation of space charge is largely electronic and electrons in a critical field travel several meters per microsecond; it may more probably be attributed to ground resistance




**Figures 8a (left) and 8b (right). Comparison of computed waves (solid lines) with oscillograms by Brune and Eaton (dash lines) as a traveling wave is distorted and attenuated by corona**

and a consequent decrease of gradient about the conductor due to what may be loosely spoken of as a lowered equivalent ground plane.

Imperfect agreement of the values determined for $n^+$, and for $n^-$, is not at all surprising when it is remembered that the duration of the waves varies from about 10 microseconds for Brune and Eaton's waves to less than $^1/_{20}$ microsecond for Skilling's, or a factor of over 100 to 1, and that a half cycle at 60-cycle frequency is nearly 1,000 times the duration of the waves of Brune and Eaton. It appears, on the contrary, that there must be some element of truth in the theory proposed since the discrepancy in $n$ is less than a factor of 2 over a time range of 1 to 100,000, particularly considering that the crest voltage varied from 100 kv (Skilling) to 900 (Conwell and Fortescue), the line from a number 10 wire (Dykes and Skilling) to a one-inch aluminum cable (Conwell and Fortescue), and the distance of travel from 50 feet (Skilling) to 2.8

miles (the greatest distance for really significant comparison with Brune and Eaton).

## The "Tail" of the Wave

While the front of a wave is passing a short section of line it is surrounding that section with a sheath of space charge. This reduces the potential gradient in the immediate vicinity of the conductor. But after the crest of the traveling wave has passed, and the line voltage has dropped to well below its instantaneous maximum, there will be some return of space charge to the conductor. Because of the presence of space charge, the gradient about the conductor will be reversed in polarity even before the wave has completely passed, and it is this that will return some of the inner part of the charge to the conductor. As the charge returns, the tail of the passing wave is built up and lengthened. This effect is visible in all oscillograms. (See figures 3, 8, and 9.) Whether an important part of the energy of the wave is thus regained depends on the shape of the wave and the relation of its maximum voltage to corona-forming voltage of the line. In general the tail of the wave is not *greatly* altered from point to point of the line. It will be seen from any of the oscillograms that voltage at a given point on the tail is continuously but slowly increasing, but that the total increase is small compared to the crest voltage of the initial wave. It seems entirely practicable, therefore, to neglect any change of the tail in computing the change of shape of a traveling wave.

This is done in figures 3, 6, 8, and 9. It will be seen that the wave form at any point of the line is determined by

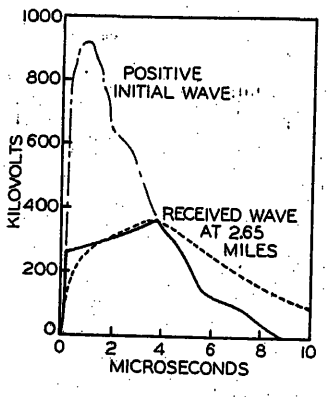



**Figure 9. Comparison of computed wave (solid line) with oscillogram by Conwell and Fortescue (dash line) as a traveling wave is distorted and attenuated by corona**

extending the computed curve (based on equation 14) until it intersects the initial wave, and thereafter following the tail of the initial wave. This does not give an accurate representation of the tail of the distorted wave, but it does give a satisfactory curve for the front of the wave and a good approximation of the wave's maximum voltage. It is this last value that is usually of greatest practical importance.

The shape of the computed wave will usually more nearly approach the shape of the actual wave if its sharp corners are slightly rounded. Physically this is due to the resistance of the line and ground, particularly as influenced by skin effect.[7]

**Table I**

| Data From | $n^+$ | | $n^-$ |
|---|---|---|---|
| Predicted from 60-cycle corona | 2.4 | 3* | 3.6 |
| Brune and Eaton (figure 8) | 2¼ | | .4 |
| Conwell and Fortescue (figure 9) | 2½ | | — |
| Dykes (figure 3) | 2½ | | 4 |
| Dykes (figure 6) | 4 | | 6 |
| Skilling (figure 7) | | | 5† |

* Average of polarities.
† Polarity unknown.

## Other Theories

So far as is known to the author, there has been no previous attempt to account *in detail* for the change in shape of traveling waves due to corona loss. Boehne[11] in 1931 suggested that the change in shape is due to a change of the capacitance of a line during corona (in this connection, see also a paper by Gardner[12]). Bewley[6] in 1933 discussed the change of shape of waves due to ground resistance, and offered a theory of traveling waves which involved 2 or more velocities of wave components. He proposed the extension of this discussion, which appears to give beautiful results at voltages below the corona-forming voltage, to explain distortion due to corona on the basis of a change of capacitance of that part of the line on which there is corona. There would be no sharp distinction between such a theory and the one that is used in this paper if it were possible to express the postulated change in capacitance as a function of the voltage and to include the loss of energy involved. But when loss of energy is omitted, and only distortionless wave components of different velocities are considered, the extremely large attenuation which is actually produced by corona does not appear.

The following comment should be made in this connection. Distortion due to corona becomes less as the voltage of a surge is diminished, and the wave tends to flatten out, with the voltage of its flattish top equal, generally speaking to the corona-forming voltage. This is illustrated by both waves of figure 8, at the 14-mile position. But many factors which are of negligible importance when the surge voltage is high make themselves felt when the surge voltage is low. Energy lost due to line resistance and ground resistance, and energy transferred inductively to nearby conductors, are overshadowed at high voltage by the great loss of energy due to corona. At lower voltage they have much to do with determining the shape of the wave. It can be seen, for instance, by reference to the original oscillograms of the paper by Brune and Eaton,[7] that the waves of figure 8 at the 14-mile position do not have a simple flat top, but appear, in detail, to have 2 rather distinct humps. It is interesting to consider this shape in the light of the theory of multivelocity components. But it will also be seen from Brune and Eaton's curves that this is a minor effect which does not appear while rapid attenuation by corona is taking place. In other words, the reduction of lightning voltage from a dangerous value to a safe value is the result of energy loss in corona.

Any of the various empirical formulas which have been proposed can only hope to be true for an imposed wave of some standard form. This is clearly true when one considers that the corona loss at any particular voltage depends not only on the value of that voltage but also on the rate of change of voltage at that point; and consequently the rate of decrease of the crest voltage of a traveling wave depends on the shape of the entire wave. It is perfectly certain that any successful formula for the distortion and attenuation of waves that are affected by corona must take into account the whole wave, and not just the maximum voltage at the wave's crest.

## Conclusions

This paper is a derivation and discussion of a formula for the change of shape of a traveling wave that is distorted and attenuated by corona. The formula, equation 14 of the paper, is

$$t = F_0(e) + \frac{k}{ncv}\frac{(e - e_0)}{e}s + \frac{s}{v}$$

The first term of the right-hand member is the initial shape of the wave, and the second term is the change of shape due to corona. (The third term merely accounts for the lapse of time while the wave travels.)

All quantities in this formula, except $n$, can easily be predetermined. The factor $k$ is found from the measured or computed corona loss of the line at normal frequency. Approximate values of $n$ are 2.5 for positive waves and 4 for negative waves, but more data are needed to substantiate these values and to determine their range of application.

The derivation of the proposed law involves several approximations, but its agreement with experimental results over a wide variety of conditions is reassuring.

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## Relaxation of Copper

With the present tendency to employ higher temperatures in various industries, more extensive investigation of the behavior of metals at elevated temperatures has become important. Under a grant received from the Engineering Foundation during the years 1935–36, work on this subject was done by John Boyd with the facilities offered by the research laboratories of the Westinghouse Electric & Manufacturing Company in co-operation with the University of Pittsburgh, and reported in the paper "Relaxation of Copper at Normal and at Elevated Temperatures," which was presented at the annual meeting of the American Society for Testing Materials at New York, N. Y., June 28–July 2, 1937. The problem was suggested by Doctor A. Nadai of the Westinghouse laboratories.

The phenomenon of the decrease of stress at constant length, such as occurs in bolts, has been called relaxation. Some investigation of this phenomenon has been made, but few of the methods used have attempted to produce pure relaxation conditions. The tests described in this paper were made with an apparatus designed to eliminate the principal difficulties of former methods. Special attention was directed toward fulfilling the conditions of pure relaxation, that is, measuring the decrease in stress while the length of the test piece is carefully kept constant. Copper was chosen as a test material because of its importance in electrical machinery as well as its relative simplicity, and was used in the form of wire 0.204 inch in diameter.

A complete correlation has not as yet been made between data for relaxation and creep, which is the increase in length with time for material at constant stress. All experimental evidence seems to show that the creep rates found in relaxation tests are greater than those obtained from creep tests under what were assumed to be similar conditions. As a result, the magnitude of the decrease in stress in relaxation is larger than at first would be expected from considerations based upon creep rates observed in tests made with constant stress. A brief summary of the results is as follows:

1. For practical purposes, the relaxation of copper at room temperature and probably up to 200 degrees centigrade may be represented by an expression of the form:

$$\sigma = \sigma_i [1 - A \log (1 + Bt)]$$

where $\sigma$ is the stress at any time $t$, $\sigma_i$ is the initial stress, and $A$ and $B$ are constants.

2. A marked increase in relaxation takes place when the temperature is raised above about 80 degrees centigrade. At 200 degrees centigrade the stress is estimated to fall to about 20–25 per cent of its initial value in a service time of 20 years.

3. Recovery effects tend to decrease the creep rate found in the early part of a relaxation test.

4. The dissimilarity between the speed laws for decreasing and for increasing stress gives rise to rather large amounts of relaxation.

Further creep and relaxation tests are at present under way and may be expected to add to knowledge of this subject.

# The Saturated Synchronous Machine

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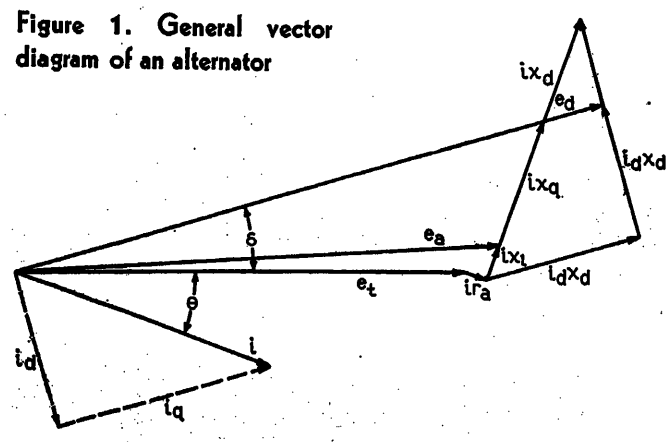
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WHILE the unsaturated synchronous machine is in general well understood, the effects of saturation upon its performance are still subject to discussion. Knowledge on the influence of saturation is important because of power-angle relations, steady-state stability limits, and excitation requirements. The problem of saturation may be approached in several ways. One method[1] is to determine empirical factors which modify characteristics of the unsaturated machine, the saturation factors being single average values for a group of machines. A second way[2] leads to the introduction of equivalent reactances which allow calculation of the effects of saturation on small load changes about an initial operating point. Third, there is the derivation[3] of saturated synchronous reactances to be used in the investigation of power-angle curves and maximum power.

It is the purpose of this paper to present the physical concepts underlying the highly saturated synchronous machine operating under steady load, and to show how the theory developed for such a machine is in agreement with test results. With terminal voltage, current, and power factor known, the torque-angle and excitation may be determined accurately.

**Figure 1. General vector diagram of an alternator**




The analysis here proposed is general in that it applies to both salient-pole and cylindrical-rotor machines. It is based on Blondel's[4] 2-reaction theory of synchronous machines, and is a modification of the vector diagram given by Doherty and Nickle[5] in their extension of Blondel's work. The diagram for the unsaturated machine assumes constant values for armature resistance and the several reactances, and linear relations existing throughout the machine. Assuming no saturation in the armature or cross-field paths, figure 27 of the paper by Doherty and Nickle shows an additional field excitation along the pole axis to take into account saturation in the pole body. Under these assumptions, the torque-angle is not affected by saturation. Under conditions of saturation, and certainly for high saturation, all of the machine reactances are decreased in magnitude. The cross-field path, by way of the pole tips, and the armature teeth, will saturate as well as the pole body. Torque-angle therefore is appreciably affected as well as is the excitation requirement.

## Machine Constants

The machine constants which must be considered in any steady-state analysis of the synchronous machine are armature resistance, armature leakage reactance, and the direct and quadrature synchronous reactances. The effective armature resistance may be determined by methods previously described.[6] Tests on armature leakage reactance[7] have shown that it varies somewhat with saturation, being a function of the density in the armature teeth which in turn depends upon the air-gap flux. The variation, however, is relatively small, and without introducing appreciable error this quantity may be taken as a function of terminal voltage.

The synchronous reactances are a measure of the flux which the armature magnetomotive force produces in its magnetic circuit. In the case of the direct synchronous reactance the magnetic circuit consists of the armature iron, the air-gaps, and the rotor poles and spider. For the quadrature synchronous reactance the magnetic circuit consists of the armature iron, the air-gaps, the pole tips, and the interpolar region. With increasing flux through these circuits, the synchronous reactances decrease. While $x_q$ is a function of the voltage behind leakage reactance, or the total air-gap flux, $x_d$ depends also upon the field leakage to the extent that this flux increases saturation in the pole body.

The synchronous reactances are defined in terms of armature quantities, i.e., $x_d$, the direct synchronous reactance, is the ratio of the fundamental component of the reactive armature voltage, due to the fundamental direct-axis component of armature current, to this component of current under steady state conditions and at rated frequency. The quadrature synchronous reactance, $x_q$, is defined similarly. Slip tests,[9] which are used to obtain both $x_d$ and $x_q$, also may be used to determine the saturated values of these quantities. Subtracting vectorially the armature resistance and leakage reactance voltages from the terminal voltage, the synchronous reactances may be

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1. For all numbered references, see list at end of paper.

plotted as functions of the air-gap voltage. The air-gap voltage, $e_a$, may be expressed[8] as

$$e_a = e_t[\sqrt{1 - (r_a/x)^2} - x_l/x]$$

where $x = x_d$ or $x_q$, as desired. $e_t$ is the terminal voltage and $r_a$ the armature resistance. The treatment presented in this paper makes use of the unsaturated direct and quadrature synchronous reactances, and the saturated quadrature synchronous reactance.

## The Vector Diagram

The steady-state performance of the unsaturated synchronous machine may be represented by a vector diagram. Figure 1 shows such a diagram for an alternator operating at a lagging power factor. The purpose of the diagram is ultimately to give the torque-angle and excitation requirement of the machine under load. This paper follows the per-unit notation, and the nomenclature is given in the following tabulation:

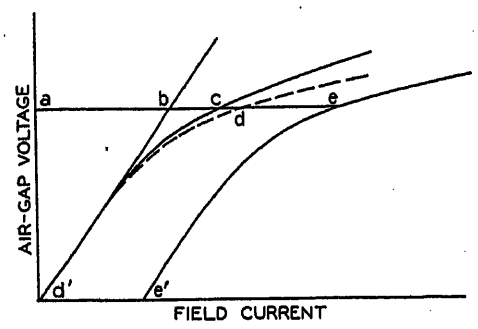



**Figure 3. Relation between zero-power-factor curve and field current required for pole leakage under saturation**

$e_t$ = machine terminal voltage
$i$ = armature current
$\theta$ = power factor angle
$r_a$ = effective armature resistance
$x_l$ = armature leakage reactance
$e_a$ = air-gap voltage (voltage behind leakage reactance)
$x_d$ = direct-axis synchronous reactance
$x_q$ = quadrature-axis synchronous reactance
$x_{ad}$ = direct-axis reactance of armature reaction
$\delta$ = torque-angle
$i_d$ = direct-axis component of armature current
$i_q$ = quadrature-axis component of armature current
$e_d$ = excitation voltage giving field current for no saturation
$I_f$ = field current

**Table I. Comparison Between Calculated and Test Values of Torque-Angle and Excitation for the Saturated Salient-Pole Synchronous Machine**

Three phase, 6 pole, 40 horsepower, 1,200 rpm, 440 volts, 44.5 amperes

| $e_t$ (Volts) | $i_{avg}$ (Amperes) | $W_1$ (Kilowatts) | $W_2$ (Kilowatts) | Angle (Degrees) Calculated | Angle (Degrees) Test | $I_f$ (Amperes) Calculated | $I_f$ (Amperes) Test |
|---|---|---|---|---|---|---|---|
| **Motor, 0.8 power factor leading** | | | | | | | |
| 535 | 0 | 0 | 0 | 0 | 0 | 7.05 | 7.05 |
| 535 | 6.7 | 3.56 | 1.42 | 2.7 | 2.8 | 7.61 | 7.51 |
| 535 | 11.45 | 6.08 | 2.40 | 4.6 | 4.8 | 8.05 | 7.97 |
| 535 | 15.15 | 8.05 | 3.19 | 6.0 | 6.0 | 8.37 | 8.30 |
| 535 | 21.0 | 11.17 | 4.47 | 8.1 | 8.0 | 8.98 | 8.88 |
| 535 | 25.8 | 13.72 | 5.52 | 9.8 | 10.0 | 9.48 | 9.40 |
| 535 | 30.0 | 15.96 | 6.39 | 11.0 | 11.0 | 9.99 | 9.92 |
| 535 | 37.3 | 19.82 | 7.76 | 13.3 | 13.2 | 10.90 | 10.70 |
| **Motor, unity power factor** | | | | | | | |
| 535 | 0 | 0 | 0 | 0 | 0 | 7.05 | 7.05 |
| 535 | 8.25 | 3.82 | 3.82 | 4.3 | 4.2 | 6.97 | 7.00 |
| 535 | 15.95 | 7.40 | 7.40 | 8.1 | 8.1 | 7.01 | 7.04 |
| 535 | 24.5 | 11.36 | 11.36 | 12.5 | 12.3 | 7.11 | 7.20 |
| 535 | 31.9 | 14.80 | 14.80 | 16.1 | 16.0 | 7.29 | 7.39 |
| 535 | 39.6 | 18.35 | 18.35 | 19.8 | 19.8 | 7.58 | 7.70 |
| 535 | 46.8 | 21.70 | 21.70 | 23.1 | 23.1 | 7.84 | 8.05 |
| **Motor, 0.8 power factor lagging** | | | | | | | |
| 535 | 0 | 0 | 0 | 0 | 0 | 7.05 | 7.05 |
| 535 | 7.75 | 1.61 | 4.11 | 3.0 | 3.0 | 6.34 | 6.38 |
| 535 | 15.5 | 3.21 | 8.22 | 6.4 | 6.3 | 5.71 | 5.76 |
| 535 | 22.85 | 4.83 | 12.15 | 10.0 | 10.2 | 5.18 | 5.20 |
| 535 | 28.05 | 5.95 | 14.90 | 12.7 | 12.8 | 4.86 | 4.93 |
| 535 | 33.95 | 7.14 | 18.04 | 16.0 | 16.0 | 4.55 | 4.62 |
| 535 | 39.1 | 8.06 | 20.74 | 18.8 | 18.7 | 4.29 | 4.40 |
| 535 | 44.5 | 9.54 | 23.66 | 22.1 | 22.0 | 4.23 | 4.36 |

The vector diagram of figure 1 is general, and is essentially that shown by Doherty and Nickle in "Synchronous Machines–I."[5] From it, for the unsaturated machine, may be obtained directly the displacement

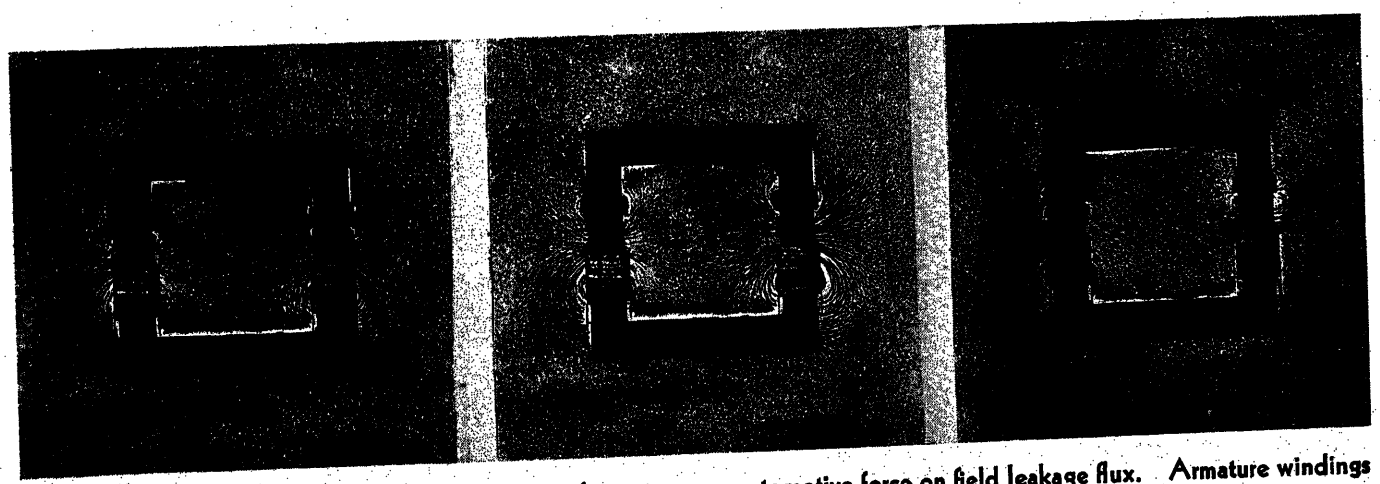


**Figure 2. Iron-filing pictures to illustrate effects of armature magnetomotive force on field leakage flux. Armature windings above, field windings below**

Left—No-load representation. Armature $NI = 0$, field $NI = 150$. Center—Demagnetization. Armature $NI = 150$, field $NI = 300$. Right—Magnetization. Armature $NI = 75$, field $NI = 75$

angle, $\delta$, and the field current, $I_f$, corresponding to the excitation voltage, $e_d$. It is assumed that the reader is familiar with the method.

With saturation, however, the torque angle is decreased, and the required field current is increased. These statements hold regardless of motor or generator action, or of power factor. The angle obtained by way of the unsaturated machine constants must be corrected, and the proposal made in this paper is to determine that angle directly by using the saturated value of $x_q$ to locate the true direct axis. The angle is thus given immediately without subtracting a correction angle. The closeness with which test results agree with this method of determining torque angle is shown in tables I–IV.

In appendix *D* of "Synchronous Machines–I and II," Doherty and Nickle outline a manner of obtaining the increase in excitation to care for saturation. Figure 27 of that paper contains the fundamental ideas involved. The projection on the direct axis of the voltage behind leakage reactance is carried to the saturation curve, the field current to be added being that measured by the horizontal separation between the air-gap line and the no-load saturation curve. This added field current, however, is not sufficient for the saturated machine with demagnetizing armature current. Depending upon the degree of saturation and the armature current, it may be far less than is required. On the other hand, the machine with magnetizing armature reaction is overcompensated in field current.

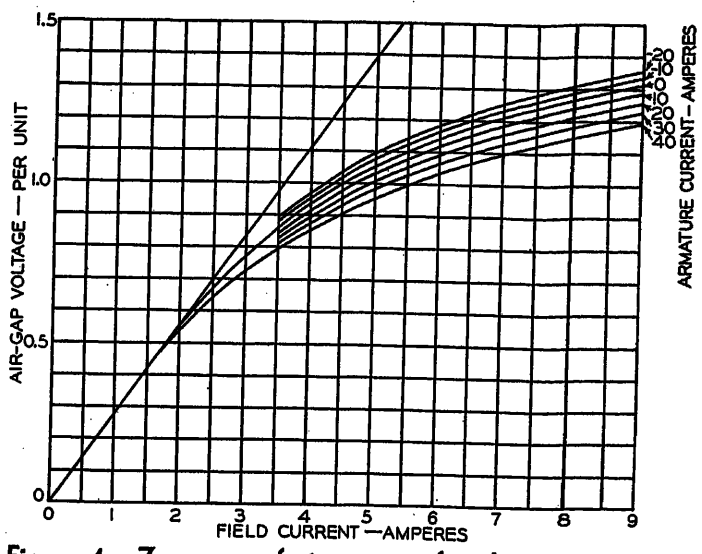



**Figure 4. Zero-power-factor curves for determination of field current required for saturation**

Part of the field magnetomotive force which must be added to care for saturation is that required to force the flux through the entire saturated circuit, and is represented by the distance between the air-gap line and the no-load saturation curve. This component takes care of normal field leakage at this flux density. In addition a second component of magnetomotive force is required to force an increased leakage flux through the saturated path at the base of the pole due to the demagnetizing effect of the $i_d$ component of armature current. The second portion of magnetomotive force may be represented by an additional number of ampere turns indicated on the saturation curve by the distance between the no-load curve and what may be called the field leakage curves.

**Table II. Comparison Between Calculated and Test Values of Torque-Angle and Excitation for the Saturated Salient-Pole Synchronous Machine**

Three phase, 6 pole, 7.5 kva, 1,200 rpm, 220 volts, 19.7 amperes

| $e_t$ (Volts) | $i_{avg}$ (Amperes) | $W_1$ (Kilowatts) | $W_2$ (Kilowatts) | Angle (Degrees) Calculated | Angle (Degrees) Test | $I_f$ (Amperes) Calculated | $I_f$ (Amperes) Test |
|---|---|---|---|---|---|---|---|
| **Motor, unity power factor** | | | | | | | |
| 540 | 0 | 0 | 0 | 0 | 0 | 10.60 | 10.60 |
| 540 | 5.3 | 2.42 | 2.42 | 2.8 | 2.7 | 10.35 | 10.32 |
| 540 | 10.5 | 4.92 | 4.92 | 5.4 | 5.4 | 10.20 | 10.22 |
| 540 | 15.6 | 7.37 | 7.37 | 8.1 | 7.8 | 10.17 | 10.20 |
| 540 | 20.3 | 9.55 | 9.55 | 10.3 | 10.2 | 10.20 | 10.20 |
| **Motor, 0.8 power factor lagging** | | | | | | | |
| 540 | 0 | 0 | 0 | 0 | 0 | 10.60 | 10.60 |
| 540 | 6.2 | 1.37 | 3.19 | 2.3 | 2.5 | 9.70 | 9.74 |
| 540 | 11.3 | 2.47 | 5.93 | 4.4 | 4.8 | 9.00 | 9.03 |
| 540 | 16.35 | 3.46 | 8.63 | 6.5 | 6.7 | 8.37 | 8.42 |
| 540 | 21.6 | 4.65 | 11.42 | 8.9 | 8.9 | 7.71 | 7.72 |

**Table III. Comparison Between Calculated and Test Values of Torque-Angle and Excitation for the Saturated Cylindrical-Rotor Synchronous Machine**

Three phase, 6 pole, 7.5 kva, 1,200 rpm, 220 volts, 19.7 amperes

| $e_t$ (Volts) | $i_{avg}$ (Amperes) | $W_1$ (Kilowatts) | $W_2$ (Kilowatts) | Angle (Degrees) Calculated | Angle (Degrees) Test | $I_f$ (Amperes) Calculated | $I_f$ (Amperes) test |
|---|---|---|---|---|---|---|---|
| **Motor, unity power factor** | | | | | | | |
| 450 | 0 | 0 | 0 | 0 | 0 | 67.0 | 67.0 |
| 450 | 5.5 | 2.04 | 2.04 | 17.5 | 17 | 67.1 | 67.2 |
| 450 | 9.95 | 3.78 | 3.78 | 30.9 | 30.5 | 69.8 | 71.5 |
| 450 | 14.9 | 5.76 | 5.76 | 43.0 | 43 | 80.2 | 82.0 |
| 450 | 20.5 | 7.92 | 7.92 | 53.2 | 53 | 95.8 | 97.0 |

## Field Leakage

The magnetomotive forces of the field and armature windings act on the main magnetic circuit of the machine to produce the resultant flux. These magnetomotive forces may wholly oppose each other, as in the case of the zero-power-factor-lagging generator (zero-power-factor-leading motor), or they may wholly assist each other. Between these 2 extremes the armature current will have one component which is directly magnetizing or demagnetizing, and a second component which acts on the cross-field magnetic circuit. The first of these supplies the direct component of armature magnetomotive force, and the second is synonomous with the quadrature component of armature magnetomotive force. The strength and relative direction of the components depend, of course, upon both load current and power factor.

Under no load, and below saturation, equal increments of field current produce equal increments of total flux through the field coils. By far the greater part of the flux follows the main magnetic circuit and is mutual to both field and armature windings. The other part encloses

the field winding alone and is known as field leakage flux, most of it being located near the base of the pole. Both parts increase in the same proportion up to the point of saturation. With saturation, successive equal increments of field current produce diminishing increments of total flux, the increments of the mutal or air-gap flux being less in proportion to the increments of field leakage flux up to a certain point of saturation which usually is beyond the working range of any machine. The reason for this phenomenon is that the main flux follows a path consisting mostly of iron, while the path of the leakage flux has a far greater ratio of air to iron. At extremely high saturation, when the reluctance of the iron in the main path is very great, the increments of air-gap and leakage fluxes approach a constant ratio again, although not the same ratio as for no saturation.

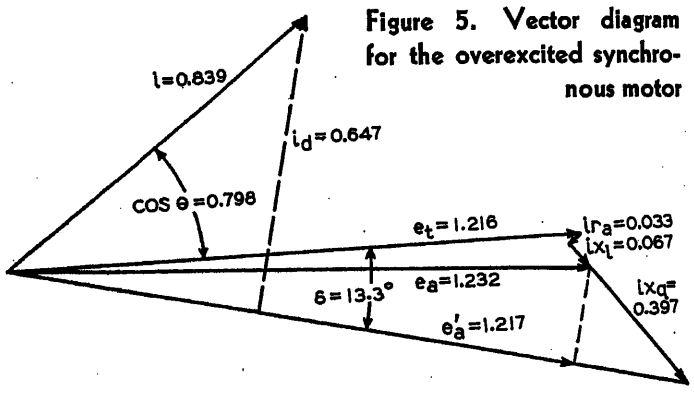



**Figure 5. Vector diagram for the overexcited synchronous motor**

With no saturation, and for a given air-gap flux, any demagnetizing ampere turns of the armature must be met by an equal rise in field ampere turns. The field leakage obviously increases. Similarly, magnetizing armature current requires an equal decrease in field magnetomotive force with a corresponding reduction in field leakage flux. Although this leakage flux varies, it maintains the same linear relation with respect to total field magnetomotive force as exists at no load, no saturation.

Under saturation, and at no load, there exists a given field current to provide a desired air-gap flux. If with the application of demagnetizing armature ampere turns the field ampere turns are increased by an equal amount, there will be an increase in pole saturation due to the increase in field leakage flux. This increased saturation decreases the air-gap flux, and to maintain the desired air-gap flux the field ampere turns must be increased by an additional amount to overcome the effects of the greater pole saturation. Conversely, magnetizing armature ampere turns will require a decrease in field ampere turns greater than the corresponding change in armature magnetomotive force.

The iron-filing pictures of figure 2 are given as an aid in visualizing field leakage, the circuit representing the elements of the sychronous machine. Figure 2*a* indicates conditions of no load. Figures 2*b* and 2*c* show the effects of armature magnetomotive force on field leakage for the 2 cases of demagnetizing and magnetizing armature ampere turns. The same air-gap ampere turns exist in all cases.

## Field Leakage Curves

The full lines *d'c* and *e'e* of figure 3 show, respectively, the no-load and the full-load zero-power-factor overexcited saturation curves of a synchronous machine. Whereas the horizontal separation at the zero ordinate in the usual manner of treatment is that value of field current which would produce a voltage on the air-gap line equal to $ix_d$, in figure 3 the separation corresponds to $ix_{ad}$. Similar curves may be obtained for any value of magnetizing or demagnetizing armature current.

The dotted curve *d'd* of figure 3 is the zero-power-factor curve moved to the left by that amount of field current corresponding to the voltage of armature reaction for unsaturated conditions. The distance *ae* represents the total field current required to produce, with full-load demagnetizing ampere turns on the armature, the air-gap voltage indicated. This total field current may be thought to consist of several components. The first is that which produces the magnetomotive force to overcome the demagnetizing effect of armature reaction, and is given by *de*. The second component, *ab*, is the field current required to send the main flux across the air gap. The third component, *bc*, is that necessary to force the mutual flux through the iron of the magnetic circuit under conditions of no-load saturation. Lastly, there is the added field current, *cd*, to care for the increased saturation caused by the increased field-leakage flux which in turn is caused by the demagnetizing armature current. This fourth component of field current is a function not only of air-gap voltage but also of armature demagnetizing magnetomotive force.

Figure 4 shows a family of field leakage curves plotted in the manner described, where the initial curves have been moved over by the amount of the respective field currents corresponding to the armature reactance voltages. The data for the curves were obtained by test on the 40-horsepower synchronous motor (described later under "Test Results") employing a single-turn full-pitch test coil so placed on the armature surface that it enclosed the main air-gap flux. Because the vector diagram for the

**Table IV. Comparison Between Calculated and Test Values of Torque-Angle and Excitation for the Saturated Salient-Pole Synchronous Machine**

Three phase, 6 pole, 15 kva, 1,200 rpm, 220 volts, 39.4 amperes

| $e_t$ (Volts) | $I_{avg}$ (Amperes) | $W_1$ (Kilowatts) | $W_2$ (Kilowatts) | Angle (Degrees) Calculated | Angle (Degrees) Test | $I_f$ (Amperes) Calculated | $I_f$ (Amperes) Test |
|---|---|---|---|---|---|---|---|
| Motor, unity power factor | | | | | | | |
| 277 | 0 | 0 | 0 | 0 | 0 | 11.88 | 12.10 |
| 277 | 10.2 | 2.45 | 2.45 | 4.4 | 4.5 | 11.83 | 12.02 |
| 277 | 19.8 | 4.75 | 4.75 | 8.8 | 8.8 | 12.02 | 12.04 |
| 277 | 29.4 | 7.06 | 7.06 | 13.2 | 13.1 | 12.64 | 12.60 |
| 277 | 39.06 | 9.37 | 9.37 | 17.7 | 17.9 | 13.42 | 13.45 |
| 277 | 48.4 | 11.62 | 11.62 | 21.9 | 22.0 | 14.37 | 14.30 |

synchronous machine is based on fundamental voltages, harmonics in the air-gap voltage were eliminated by using a wave analyzer, thus giving the values of fundamental voltage directly.

For an overexcited machine at zero power factor, the armature current is wholly demagnetizing and is represented in the vector diagram by a positive $i_d$. Conversely, for an underexcited machine at zero power factor the armature current is magnetizing and is designated by a negative $i_d$. The field leakage curves indicate these relations, the parameter being amperes armature current. The curves are entered with the direct axis component of the air-gap voltage. The horizontal distance between the no-load saturation curve and the interpolated curve for the direct axis component of armature current, also found from the vector diagram, is the field current required to supply the increased field leakage flux caused by that component of armature current.

## Application

The application of the foregoing theory is illustrated by 2 examples. The first is that for the 40-horsepower overexcited synchronous motor operating at 535 volts with a line current of 37.3 amperes at 0.789 power factor. Figure 5 is the vector diagram for this case with all corresponding quantities given in per-unit terms. The torque-angle of the machine is found immediately upon location of the direct axis and is 13.3 electrical degrees, agreeing with the angle of 13.2 degrees obtained by test.

The field current is calculated on the assumption of no saturation, the method following that discussed in conjunction with figure 1. To this value of field current there is added a correction for saturation. Following the method of Doherty and Nickle, the direct-axis component of the voltage behind leakage reactance is carried to the field leakage curves, figure 4. The field current correction is given by the distance between the air-gap line and the interpolated field leakage curve corresponding to the value of $i_d$ in amperes.

The second example, shown by figure 6 is that of the underexcited synchronous motor operating at 535 volts with a line current of 44.5 amperes at a power factor of 0.805. The procedure in determining the torque-angle and excitation is the same as for the first example with the exception that $i_d$ is now negative, indicating magnetizing action of the armature current. It is to be observed that

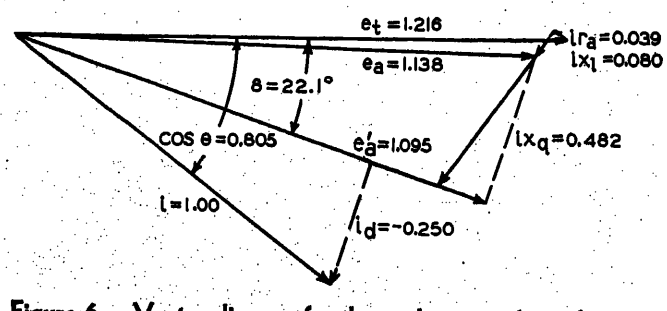



**Figure 6. Vector diagram for the underexcited synchronous motor**

the diagrams of figures 5 and 6 are for purposes of correction, and do not completely represent the unsaturated machine.

## Test Results

Tables I–IV show the comparison between calculation and test of torque-angle and excitation for synchronous machines operating at high voltages under steady load. The data of table I were taken on a salient-pole general-purpose synchronous motor rated 3 phase, 6 pole, 40 horsepower, 1,200 rpm, 440 volts, 44.5 amperes. Tests were taken on the machine, both as a motor and as a generator, over a range of voltages extending from below saturation to 535 volts. All calculations gave the same close agreement with test as shown in the table, but for purposes of comparison only the results of 3 general conditions of load are presented. The curves of machine constants used in these calculations are given by figures 7–9. Motor operation at 535 volts was chosen for presentation because of the high degree of saturation introduced, coupled with the fact that the motor still could carry approximately rated current before reaching the limit on instruments or commutation of the d-c machine connected to it.

Tables II and III show data on a 3-phase 6-pole 7.5-kva 1,200-rpm 220-volt 19.7-ampere alternator designed for operation as a salient-pole generator or as a wound-rotor induction motor by interchanging rotors. Table II gives results for operation of the machine as a salient-pole

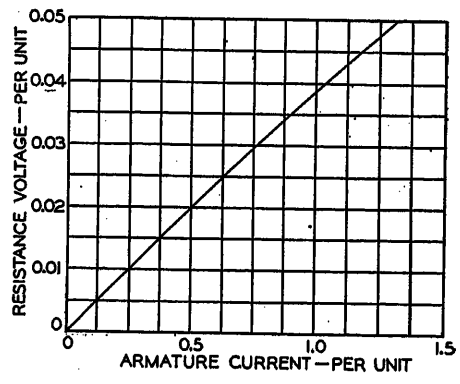



**Figure 7. Effective armature resistance of a 40-horsepower 1,200-rpm 440-volt synchronous motor**

motor. Table III shows data for operation of the machine as a cylindrical-rotor synchronous motor, direct current having been supplied the wound rotor. Due to the fact that saturation was extremely small at rated voltage, tests were carried out at the relatively very high voltage shown.

Table IV gives similar results on a 3-phase 6-pole 15-kva 1,200-rpm 220-volt 39.4-ampere generator. Due to inherent voltage unbalance within this machine, the field current did not check the saturation curve when the machine was connected to an infinite bus with no power exchange. This also accounts for the small discrepancies between calculated and tested field currents at the lower loads.

Zero readings were obtained by adjusting the field currents on both machines so as to give no deflection on the

wattmeters. All constant losses therefore were supplied by the d-c machine. Measurements were taken at those times when the power supply gave balanced voltages because it was found that an unbalance, although very small, introduced errors. Adjustments of the wattmeter readings for desired power factors were occasionally a trifle difficult to make under pump-back operation of the set. Limits on instruments, field heating, and commutation of the d-c machine prevented loading the synchronous motor as highly as was desired.

## Summary

The theoretical discussion given in the paper offers a general method of treating the highly saturated synchronous machine operating under steady load. To as great an extent as possible the mode of attack employs the accepted form of the vector diagram based on Blondel's 2-reaction theory. Torque-angle is obtained by using the saturated quadrature synchronous reactance rather than the unsaturated reactance. Saturation in the interpolar axis affects the displacement angle of the machine, the angle decreasing with saturation, thus leading to a stiffer machine. For accuracy, the effective armature resistance may not be neglected, at least for smaller machines.

While direct axis saturation requires less field current to overcome direct armature reaction, this decrease is more than offset by the required increase in field current to care for increased field leakage flux caused by this direct armature magnetomotive force. The total field current may be thought to consist of several components; one to force the mutual flux across the gap, a second to overcome armature reaction, a third to care for no-load saturation, and a fourth to account for an increase or decrease in saturation due to a change in pole leakage when current is present in the armature. In a manner, the first 2 components are included in the calculation from the vector diagram for the unsaturated machine. The last 2 are obtained from field leakage curves.

The paper is offered as a theoretical analysis on the effects of saturation, and as such should lead to a better understanding on the performance of the synchronous machine. In addition, it should aid in the proper evaluation of empirical methods, and in furthering studies on the saturated machine operating under transient conditions. It is felt that the good agreement between calculation and test results, as shown in the tables, greatly substantiates the theory given in the paper.

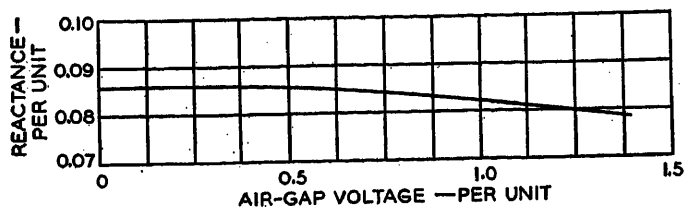



**Figure 8. Armature leakage reactance of a 40-horsepower 1,200-rpm 440-volt synchronous motor**

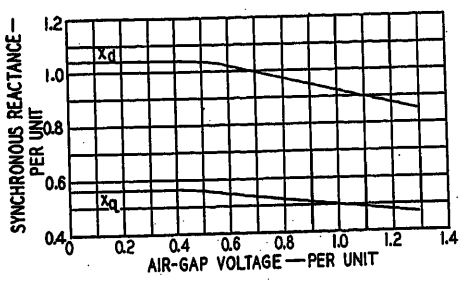



**Figure 9. Variation of synchronous reactances with saturation for a 40-horsepower 1,200-rpm 440-volt synchronous motor**

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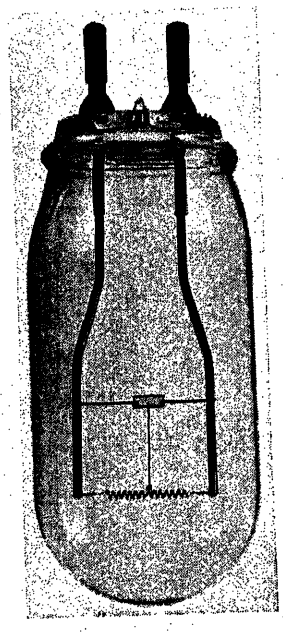
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## New Bipost-Base Street-Series Lamp

A new type of street-series lamp has been designed especially for use in "high visibility" lighting equipment. The 4,000-lumen lamp, which is 6½ inches in length and which is designed to burn base up, is equipped with a medium bipost base, a relatively small tubular-shaped bulb of clear hard glass, and a horizontal bar filament about one inch long. Application of the bipost method of construction results in the following advantages: reduction of inaccuracies in filament positioning, permanency of lamp and reflector adjustment, a major reduction in size, a rugged straight-sided bulb which is immune to bulb breakage from sudden temperature changes and which is less likely to collect dirt than pear-shaped lamps, and a simplified filament assembly which eliminates several old steps formerly required in lamp making, with economy for both user and maker.



# Discussions

## Of AIEE Papers—as Recommended for Publication by Technical Committees

ON THIS and the following 45 pages appear discussions submitted for publication, and approved by the technical committees, on papers presented at the sessions on communication, electric welding, electronics, instruments and measurements, power distribution, selected subjects, and synchronous machinery at the 1937 AIEE winter convention, New York, N. Y., January 25–29. Authors' closures, where they have been submitted, will be found at the end of the discussion on their respective papers. Other discussion of winter convention papers will be published as it is made available.

Members anywhere are encouraged to submit written discussion of any paper published in ELECTRICAL ENGINEERING, which discussion will be reviewed by the proper technical committee and considered for possible publication in a subsequent issue. Discussions of papers scheduled for presentation at any AIEE meeting or convention will be closed 2 weeks after presentation. Discussions should be (1) concise; (2) restricted to the subject of the paper or papers under consideration; and (3) typewritten and submitted in triplicate to C. S. Rich, secretary, technical program committee, AIEE headquarters 33 West 39th Street, New York, N. Y.

## The Resistance Welding Circuit

**Discussion and author's closure of a paper by C. L. Pfeiffer published in the August 1936 issue, pages 868–73, and presented for oral discussion at the electric welding session of the winter convention, New York, N. Y., January 28, 1937.**

**H. C. Cogan** (nonmember; National Electric Welding Machines Company, Bay City, Mich.): Mr. Pfeiffer's paper "The Resistance Welding Circuit" is very timely. Since the advent of positive cycle control apparatus for resistance welding equipment, and further, since the welding machines themselves have been improved considerably, materials are now being welded by the resistance method that demand close calculation as to their power-demand and welding-circuit conditions.

The welding-machine manufacturers can, through accepted and now standard calculations determine the total impedance of a welding machine circuit (electrodes to transformer) and thereby design a transformer and circuit to deliver a specified current at the weld.

It has not been very easy, however, to calculate the desired current at the weld and thereby specify the fundamental requisite as a starting point for machine and transformer design.

Mr. Pfeiffer's paper is very interesting inasmuch as it shows original methods and a very clear analysis of the possible determination of the voltage-drop and current characteristics at various points in the weld area proper. With the development of methods as outlined in this paper the capacity of resistance welding equipment may be known in time by the maximum current (secondary amperes) that can be delivered at the welding electrodes at a predetermined primary supply, all of which can be definitely put on the name plate of the welding machine, and this alone will be a great step forward in a mutual understanding among the user of the welding machine, the manufacturer of the welding machine, and the power company supplying the power, which supersedes the antiquated and useless kilovolt-ampere rating of resistance welders.

**C. E. Heitman** (Edward G. Budd Manufacturing Co., Philadelphia, Pa.): To those of us vitally concerned with resistance welding and its applications, it is gratifying to note an increasing amount of published information concerning this subject. Mr. Pfeiffer's present paper is noteworthy in that it emphasizes the effect which the electric circuit has upon the successful operation of any resistance welding application. This phase of the problem has been more or less neglected in the past, perhaps because the earlier types of machines did not require such a thorough analysis of the electric circuit as more elaborate machines of today.

The author's discussion of this subject is indeed interesting, although the examples cited apply to a type of welder with which I am not very familiar. All of the spot welding applications with which I have been concerned demand machines having much higher secondary or lead impedances than shown in the vector diagrams of figure 3, due to the physical characteristics of the product being welded. For this reason, I feel that the ratios obtained from these vector diagrams may be misleading if applied to the welding machines used in the average sheet-metal shop.

On various portable spot-welding jobs, wherein the welding electrodes are connected to the transformer by means of cables 5 or 6 feet in length, my experience has been that the voltage drop in these cables alone is approximately 85 per cent of the open-circuit secondary voltage of the transformer, and over 90 per cent of the secondary load voltage. In some cases these figures increase to 90 per cent and 95 per cent respectively. In such cases, little or no difference is made upon the amount of secondary current, whether there is ferrous metal between the electrodes or whether the electrodes are brought together with no metal between them. In the case of the upright stationary machine, the impedance of the leads may be a smaller percentage of the total secondary impedance, depending upon the length and spacings of these leads. In any event, I have found that this lead impedance is practically all reactance, so that this voltage drop must be added at right angles to the almost purely resistance voltage across the weld. For this reason, the impedance of the weld does not add materially to the total circuit impedance. In all such cases the voltage drop across the weld is considerably less than the voltage drop in the secondary leads, even when welding relatively thick sheets of ferrous materials. In cases where the coupling between electrodes and transformer is very close and where the spacing between these leads is small, the values given by the author would no doubt apply, but such machines have comparatively little utility in large sheet metal plants.

I mention these welding conditions as being typical of those with which I have dealt, and which I believe are typical of other manufacturing plants, in the hope that it may shed some additional light upon the problem, and perhaps stimulate further discussion. The field of resistance welding is very broad, and impossible to thoroughly cover in any one discussion.

I wish to express my thanks and appreciation to the author for a most interesting and enlightening discussion of this subject.

**J. W. Dawson** (Westinghouse Electric & Manufacturing Company, East Pittsburgh, Pa.): The author is most sincerely concurred with in his hope that this elementary paper will stimulate a more thorough investigation of the resistance welding circuit which is so well known and yet so imperfectly understood.

Phenomena occurring in the weld area are very much of transient nature. During the welding period, the electrical, thermal, and metallurgical conditions and even electrode pressure undergo very rapid changes, particularly in so-called "short time" welding. This fact adds to the other practical difficulties in thoroughly investigating this area.

An important part of future study of the resistance welding circuit will undoubtedly concern itself with the adjoining surface layers of the parts being welded, and the transmutation of their contact resistance into the resistance of highly heated metal layers during the weld. The author's discussion of surface film break-down is of interest in this connection.

The author presents data in tabular form showing the voltage drop in various parts of the resistance welding circuit. It is under-

stood that instrument measurements were necessarily made with relatively long welding periods. Mention is made, however, of oscillographic measurements of these quantities and it would be of interest to learn whether the oscillograph showed appreciable changes in weld area voltages during welding.

The author's use of work-body resistance as a criteria in roughly calculating conditions in the weld area, seems to the writer a rather inaccurate basis of approach to this problem. Although less convenient, the all important contact surface resistances are given too little attention. Likewise, Jean's formula $r/4a$ would not seem to apply here. The chief justification for considering the problem in the light of this formula should lie in the fact that resistance is assumed a function of the number of contacting surfaces. Even on the basis of metal-body resistance, this formula should not give correct results since the sheets are of small dimension in the direction of current flow although, as stated by the author, of very large cross section.

Referrring to the 2 vector diagrams, figure 3, it is not clear to the writer how the vector quantity $E_i$ denoting transformer voltage drop has been determined from the measurements given.

The writer cannot entirely agree with the author in that definite energy input to the weld is always the ideal basis for terminating the weld, although in "slow" welding, it would seem a step in the right direction. First of all, the rate of applying energy to the weld area is extremely important, particularly in "short time" welding, one factor being the flow of thermal energy away from the weld through body of the work. Considering the extreme case, a proper total quantity of energy might be applied to the weld but at such extremely low rate as to result in barely warming the weld surfaces. Secondly, and again particularly for the "short time" welding, it is very difficult to terminate the weld excepting at the end of $1/2$ cycle of current. For these reasons, accurate control of all factors would seem the best practice for "short time" welding, which is being much used at present.

**H. A. Woofter** (nonmember; The Federal Machine and Welder Company, Warren, Ohio): Mr. Pfeiffer's excellent paper on resistance welder circuits is one of the best that has been written to date. A few notations and elaborations might be helpful to the reader.

Referring to figures 4 and 5 the layman might take it for granted that because practically any number of projection welds can be made instantaneously from a single circuit as shown in figure 5, that it would immediately follow that practically any number of spot welds could be made instantaneously from a single circuit as shown in figure 4. It is an outstanding fact, however, that only one good spot weld can be made at one time from one circuit with one set of leads. The reason for this is as follows: A spot weld is virtually a short circuit of the secondary of the transformer. Now, when 2 or more points are used, or attempted to be used, the power will not break through all of the points at the same time. One spot will break through under one point first. This as stated above establishes a dead short circuit which knocks down the secondary voltage of the circuit to such an extent that the other points do not have sufficient voltage to make a good spot weld. This, however, can be corrected by bringing out a separate set of leads to each electrode point. It can also be further improved by having individual pressure applied to each individual point, such as a pressure spring, small hydraulic cylinder, air cylinder, or any of the well-known pressure devices.

Referring to figures 6 and 7, especially the latter, when attempting heavy work, requiring large amounts of power, the 3 transformers shown can sometimes be connected to the 3 phases of the power circuit, thus balancing the load on the power line. Under such conditions, however, it is necessary to insulate the 3 heads on one or both sides of the transformer to eliminate the leakage between phases, which on a 3-phase circuit is the square root of 3, which amounts to 1.73 times as much voltage between the phases as there is across the points of the welder.

While perhaps 99.99 per cent of resistance welding is done single phase there are some cases of projection welding, mash welding, wire-mat welding, etc., where the projections or intersections can be grouped into clusters of 3 or multiples thereof, and each cluster welded on a separate phase. This is sometimes done by connecting one side of the transformer to a single lower table with the 3 phases insulated above. At other times it is necessary to insulate the phases on both upper and lower tables.

**L. H. Frost** (nonmember; The Electric Controller & Mfg. Co., Cleveland, Ohio): Mr. Pfeiffer's paper indicates that the electrical circuit involved in a resistance-welding machine is not complicated and that the coordination of 3 principal factors; namely, current, electrode pressure, and time of current application, is essential to proper welding. This is true as a general statement, but it is not generally realized what effect changing values of these factors has upon the total result.

The current which will flow through the welding circuit depends upon conditions as outlined by Mr. Pfeiffer, but the current which is important from the angle of welding is the current which actually flows through the work pieces. Within reasonable limits, this current will be constant for given physical dimensions and electrical characteristics of the welding machine but may vary somewhat due to change of the effective resistance between the work pieces, and the work and the electrodes. In order to show clearly how these factors affect each other, and in general, the amount of heat required to make a weld, refer to figure 1, in which electrodes $E1$ and $E2$ are shown as being of conventional design. $S1$ and $S2$ are the 2 work pieces, in this case indicated as sheets. Between the work pieces and the electrodes are 2 contacting surfaces which have been designated as number 1 and number 3, respectively, and between the 2 pieces there are 2 other contacting surfaces which have been designated as number 2. The area involved in each of these conditions has been termed $A1$, $A3$, and $A2$, respectively.

It will be evident that the point of greatest resistance in this circuit is at the contacting surfaces themselves rather than through the various conducting portions of the circuit,

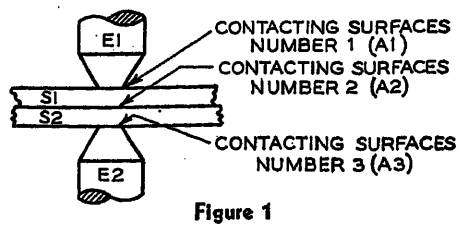



**Figure 1**

$$H_W = (H_D - H_L)t \tag{1}$$

but

$$H_D = I^2R \tag{2}$$

$$R = \frac{r_1}{P} + \frac{r_2}{P} + \frac{r_3}{P} \tag{3}$$

$$r_1 = \frac{C_1(\Omega_{E1} + \Omega_{S1})}{A_1P} \tag{4}$$

$$r_2 = \frac{C_2(\Omega_{S1} + \Omega_{S2})}{A_2P} \tag{5}$$

$$r_3 = \frac{C_3(\Omega_{S2} + \Omega_{E2})}{A_3P} \tag{6}$$

$$R = \frac{1}{P}\left(\frac{C_1}{A_1}(\Omega_{E1} + \Omega_{S1}) + \frac{C_2}{A_2}(\Omega_{S1} + \Omega_{S2}) + \frac{C_3}{A_3}(\Omega_{S2} + \Omega_{E2})\right) \tag{7}$$

$$H_L = K_{E1}V_1 + K_{S1}(V_2 + V_3) + K_{S2}(V_4 + V_5) + K_{E2}V_6 \tag{8}$$

$$H_w = t\left[\frac{I^2}{P}\left(\frac{C_1}{A_1}(\Omega_{E1} + \Omega_{S1}) + \frac{C_2}{A_2}(\Omega_{S1} + \Omega_{S2}) + \frac{C_3}{A_3}(\Omega_{S2} + \Omega_{E2})\right) + K_{E1}V_1 + K_{S1} \times (V_2 + V_3) + K_{S2}(V_4 + V_5) + K_{E2}V_6\right] \tag{9}$$

where

$H_w$ = heat required for weld
$H_D$ = heat developed by current
$H_L$ = heat lost by conduction
$t$ = time
$I$ = current
$R$ = resistance
$r_1, r_2, r_3$ = effective resistance at contacting surfaces 1, 2, and 3
$C_1, C_2, C_3$ = constants for resistivity of contacting surfaces, 1, 2, and 3
$\Omega_{E1}, \Omega_{S1}$ = resistivity
$\Omega_{S2}, \Omega_{E2}$ = resistivity
$P$ = pressure
$K_{E1}, K_{E2}$ = thermal conductivity of electrodes 1 and 2
$K_{S1}, K_{S2}$ = thermal conductivity of sheet 1 and 2
$V_1$ = volume and gradient of electrode 1
$V_6$ = volume and gradient of electrode 2
$V_2$ = volume and gradient of sheet 1 affected by area $A_1$ and electrode 1
$V_3$ = volume and gradient of sheet 1 affected by areas $A_1$ and $A_2$
$V_4$ = volume and gradient of sheet 2 affected by areas $A_1$ and $A_2$
$V_5$ = volume and gradient of sheet 2 affected by area $A_2$ and electrode 2

therefore, heat will be generated at contacting surfaces number 1, and number 3 and also at number 2. It is further evident that the resistance between contacting surfaces number 2 must be greater than between surfaces number 1 and number 2, if a weld is to occur between contacting surfaces number 2. This is a general statement, of course, for there may be a wide dissimiliarity between the fusion points of the electrode material and the work pieces. It is possible to allow the heat to be conducted through from the outside surfaces to the center, but in general, this does not provide a satisfactory welding condition.

Following through the discussion applying to figure 1, we find that the total heat required for welding is equal to the heat developed by the passage of the current minus the heat lost due to conduction into the work pieces and electrodes, times the time required for welding. The heat developed follows $I^2R$, as shown in equation 2. Since $R$ is the unknown and the variable in which we are interested in analyzing, this may be expanded as shown in equation 7. It will be noted that pressure has been introduced into the equation and that the resistance varies inversely with the pressure. This point has been shown in many tests relating to current carrying capacity of contacting surfaces and voltage drop across contacting surfaces and is familiar to everyone.

The heat lost is given in equation 8. The constant designated by $K$ is the thermal conductivity of the electrodes and work pieces expressed in standard units. The factors designated as $V_1$, $V_2$, etc., are a combination of the volume and gradients involved. It will be evident that the gradient will not be linear as in the case of a steady condition, but will be a curve. A mathematical expression of this gradient has not been used as this would unnecessarily complicate the final equation. It should be noted, however, that since heat is being absorbed into the work pieces and into the electrodes at the same time, if there is a high temperature at contacting surfaces number 1, number 2, and number 3, and a low temperature in the electrodes and work pieces, that this gradient cannot be a straight line. The mathematical expression is complicated because of this fact and also because the temperature is increasing throughout the initial portion of the timing period. Therefore, the terminal temperature at the contacting surfaces is variable and that combined with the heat absorbed into the conducting materials makes this a complicated expression.

The final expression for the heat required for a weld is given in equation 9. It will be evident from this equation that the most important single variable in this equation is the time of current application. This is more important even than the amount of current applied since it affects not only the heat developed for welding, but also the heat lost by conduction. It is, therefore, important that the time of welding be controlled. The next most important variable is the current which, as indicated above, is influenced by the resistance of the welding circuit for given physical and electrical characteristics of the welding machine. The third most important variable is the pressure which affects the current inversely. From the equation 9 it will be evident that the relationship between the 3 principle factors of current, electrode pressure, and time of current application, is definite and it is possible to place the proper value in general upon each of these variables. From this equation it is also evident that if the resistivity of the electrodes and the work pieces are the same that the 3 expressions for resistance will be equal and that the heat will be divided in 3 points in equal amounts which will prevent satisfactory welding. This indicates one limit to which electrodes and materials may be changed.

To express this in concrete terms, it would be impossible to obtain satisfactory welds when using steel electrodes for welding steel sheets or by using copper electrodes for welding pure-copper sheets. This, of course, is for electrodes of conventional design as shown. It is sometimes possible, by using a special design, to change the constants $C_1$, $C_2$, and $C_3$.

The constants $C_1$, $C_2$, and $C_3$ must be determined by actual test. Also the effect of the factors $V_1$, $V_2$, etc., may be determined by actual test although in this case a mathematical expression can be obtained. It will be obvious that for various oxides and coatings on the work pieces, different values of $C_1$, $C_2$, and $C_3$ will be required. This will affect the electrical characteristics required in the welding machine to some extent as shown by Mr. Pfeiffer on page 871, but in general the adjustments on the machine permit a reasonably wide range of control for these conditions.

One interesting fact shown by equation 9 is that due to the relationship of current, electrode pressure, and time of current application, it is often possible by increasing the pressure to cause a decrease in resistance which for the given current requires an increased time to make the proper weld. This means that in the case of certain materials where practice has indicated that welds can be obtained only in the shortest possible time, that it may often be possible to increase the pressure and for the same current obtain satisfactory welds in a somewhat longer time.

Mr. Pfeiffer's article is certainly of importance in stimulating activity in the art of resistance welding. In the last few years there has been considerable done to improve means of timing the welds, but there is still much research work to be done in determining what factors influence the welding operation in detail. This work can best be done by educational institutions and engineering foundations, and if Mr. Pfeiffer's article or this discussion can stimulate any such activity, the effort expended in preparing the paper and this discussion will be amply repaid.

**J. H. Zimmerman** (nonmember; The Linde Air Products Company, Newark, N. J.): This simple treatment of the resistance-welding circuit should be of much help to the nonelectrical engineer and to the practical man who does resistance welding. It is hoped that the paper will also serve to stimulate more publications on the same subject, particularly papers dealing more specifically with phenomenal changes in the immediate vicinity of the weld as has been suggested by the author.

For example, little is known of the fluctuations, in electrode pressures during the short time interval of welding. It has been estimated that as much as 60 per cent of the original pressure may be relieved by the surge of current through the secondary. The elastic recoil of the machine following this surge may frequently serve to reverse this effect when the weld metal is in poor condition to withstand sudden overloading. These same pressure fluctuations will naturally produce corresponding electrical disturbances, and a paper embracing this phase of the subject would be valuable.

The title of the paper might better have been "The Spot-Welding Circuit" for much of the subject matter may not strictly apply in the case of flash welding which is also a resistance welding process. Regardless of the title, however, the author is to be complimented for a fundamental addition to the scarce literature on the subject.

**R. H. Hobrock** (nonmember; Bundy Tubing Company, Detroit, Mich.): It is gratifying to see that Mr. Pfeiffer has taken it upon himself to again call our attention to the fact that the resistance-welding circuit as well as the control equipment used in conjunction with resistance welders is in need of further study. Very little has been published on this subject in this country and, although I believe that considerable work is being done in Europe, particularly Germany, not a great deal of the results have as yet found their way into the literature.

The author has mentioned that "the great problem for improvement in resistance welding processes is absolute control of power input to the weld area." This should be emphasized. I have, on several occasions, heard welding engineers describe the ideal control as one which would parcel out exactly a predetermined amount of energy. This is obviously false since the requirement for producing a spot weld is that the temperature of a certain volume of the metal be raised to some value within the welding range of the metal. Whether or not this temperature will be reached is dependent upon the specific heat and specific resistance of the metal, the mass of the metal in the weld area, in some cases on the value of the heat of fusion, and on the temperature gradient between the weld volume and the surrounding metal. The temperature gradient is again dependent upon the heat conductivity of the metal and the shape, size, distribution, and temperature of the electrodes and upon time. Obviously then a given amount of energy, if supplied at low power, may never achieve the fundamental requirement of raising the weld volume of the metal to the temperature required for welding.

The ideal weld control would be some device which permits the current to flow until a predetermined temperature is reached in the weld volume. Two methods have been tried to accomplish this. One method attempts to measure the temperature of the weld volume by measuring the resistance between the electrodes—actually a system of relays opens the primary circuit of the welding transformer when the potential drop across the electrodes reaches a set value. The variable contact resistances between electrodes and sheet as well as between sheets and the variable volume of the material which acts as the electrical conductor are great hindrances to the success of this scheme.

Another method employs the photoelec-

tric cell for measurement of the temperature of the weld spot and through a system of relays controls the flow of current in the welding circuit so as not to exceed a certain predetermined temperature range (see H. Zetzmann, *Archiv f. d. technische Messen*, volume 214, 3, September 1934 and G. Mueller, *Elektroschweiszung*, volume 6, number 1, 1934).

I should like to ask the author why he assumes the volume of the metal carrying the current to be 3 times the volume of the cylinder with bases equal to the diameter of the electrodes and with an altitude equal to the thickness of the 2 sheets, when, from the example of data given, a factor of 2 would be more nearly indicated. Observations made by F. Goldmann (*Elektroschweiszung*, volume 2, page 8, 1931) seem to indicate that the path of the electrical current through one sheet is in the shape of the frustrum of a cone with the smaller diameter equal to the diameter of the electrode. If a cross section of a spot weld is examined and the diameter of the weld spot at the former interface of the 2 sheets measured and if this is assumed as the larger diameter of the frustrum of a cone, the volume of the path traversed by the major portion of the welding current can be calculated. In a few such measurements and calculations made by the author, the factor 2 seemed to be indicated for calculations based on the cylindrical path.

**R. A. Gilbert** (nonmember; General Electric Company, Pittsfield, Mass.): When the article "The Resistance Welding Circuit," by C. L. Pfeiffer, was published in the August 1936 issue of ELECTRICAL ENGINEERING it was recognized as being of considerable fundamental value; in fact, so much so, that photostat copies were made for our files.

The fundamentals of the welding circuit have been thoroughly analyzed by Mr. Pfeiffer and while it could hardly be expected that such a paper would cover all of the ramifications of resistance welding, we feel that he has provided the ground work for more data in a field where little or nothing is available in the current literature.

There is great need for a handbook or textbook on resistance welding, covering not only the fundamental circuit but also other phases of the art such as welding technique, welding machine design, modern tube control devices, electrode materials, etc.

We trust that such a work will soon be available.

**I. T. Hook** (nonmember; American Brass Company, Ansonia, Conn.): Mr. Pfeiffer has brought to our attention some important features of the resistance-welding operation. For instance, he places *electrode pressure* on par with current value and time of heat-on period. For a long time, the importance of maintaining the pressure uniform was under estimated. As a matter of fact, in welding low-carbon plain steels, the pressure may vary greatly without seriously impairing the strength of the connection. Steel is weldable over a long range of temperature and pressure. Since common steel was, for the most part, the material seam and spot welded, little attention was given to the maintenance of a constant pressure.

However, with the fabrication of the stainless steels and copper alloys by resistance welding, more precise control over the 3 fundamental variables became necessary. In the case of the copper alloys, a weld was obtainable only by melting the metal. A slight variation one way or the other in the pressure would cause nonfusion, and consequently no weld, or weaken the connection by squirting the molten metal out of the spot forming troublesome cold slivers between the sheets.

With metals which are inclined to be hot short as is the case of some of the newer copper alloys, it is important that the pressure be controlled to a nicety in order that hot short cracks may be avoided in the welds.

The modern machines with air-weighted electrodes seem to fulfil the requirement of exact pressure control.

Mr. Pfeiffer has made it quite clear that exact timing is also important in spot and seam welding. Short time intervals down to that required for a single wave of a 60-cycle current may be an advantage in the case of the copper alloys for 2 reasons (*a*) it avoids heat losses by conduction into the surrounding areas and (*b*) it minimizes the danger of hot short cracks adjacent to the spot besides restricting heat effects to the spot itself.

Mr. Pfeiffer points out that "the best weapons to combat such variables as surface oxides, heat losses to surrounding areas, etc., are relatively high voltages, high current intensities and short time intervals." We believe that the importance of these electrical and timing desiderata has not been sufficiently emphasized.

What we desire above all things is a definite quantity of energy (electrical at the outset converted to a definite quantity of heat energy at the spot) delivered in a short period of time, say $^1/_{120}$ second. By controlling primary voltage, electrode pressure and time, we are attempting to do this. However, this set-up calls for a source of primary energy capable of overcoming high momentary loads which means a relatively high kilowatt-hour rate.

Studies such as Mr. Pfeiffer has given us help greatly in elucidating the problem. Perhaps we shall see, in the not distant future, some more convenient means of delivering definite quantities of energy in a small fraction of a second of time.

**G. G. Somerville** (nonmember; General Electric Company, Pittsfield, Mass.): This paper presents a very clear and complete theoretical picture of the conditions found in ideal spot and projection welding. The discussion is systematic and straightforward showing a clear understanding of the subject by the author and the writer should be congratulated on his contribution to the art. His attack of the problem and his method of obtaining reliable readings are unique and well worth study by welding engineers.

The practical application of the material presented in the paper by the welding application engineer or welding foreman would present difficulty, however. In practice every welding job is a problem in itself and unless the job is very carefully analyzed the actual voltage, current, and pressure best suited to the problem can be only a guess based on the experience of the supervisor. Many variables enter into the picture such as amount and shape of the material being welded; for example, a steel cylinder extending over one of the welding arms may increase the reactance of the welding circuit to a point where calculated values are useless. Again in practice the ideal spot weld is the exception rather than the rule—generally a great percentage of the welding current is by-passed by previous welds or by the inherent shape of the work. In simple cases the increase in current to compensate for these conditions may be estimated, but in general the proper values of current and time can be determined only by trial.

In a paper such as Mr. Pfeiffer has prepared, it is readily understood that any detailed discussion of problems encountered in practice could not be covered—but it is believed that his paper would be enriched if he included in his summary, a brief paragraph showing where a theoretical attack of some practical welding problems would lead to complications.

**D. I. Bohn** (Aluminum Company of America, Pittsburgh, Pa.): Mr. Pfeiffer is to be commended for presenting his analysis of the resistance-welding circuit.

The rapid changes in resistance-welding technique, as well as the development of suitable equipment for welding nonferrous materials, has required a more intimate knowledge of the electrical conditions actually existing in this type of equipment than has been known in the past.

I am in hopes that this paper will inspire others of a similar nature in the future.

Mr. Pfeiffer mentions that "it is this condition that makes difficult the welding of materials of high electrical conductivity such as copper, brass, or aluminum, because surface conditions often force the use of currents higher than otherwise necessary with the result that the joint is badly burned when the surface resistance between parts or between electrodes and parts approaches zero." I cannot agree with this general statement regarding aluminum, as, with suitable equipment, aluminum is being spot and seam welded commercially with results comparable to those obtained with other materials.

This welding is done without any burning or pitting of the surfaces, and, where desired, one of the surfaces may be welded so that the weld is practically invisible.

**Bela Gati** (Katona Rail Welding Concern, Mount Vernon, N. Y.): The author's comment that "the lack of available literature on this subject inspired the preparation of this paper" is very significant to me since this scarcity is especially evident in European and other countries. I have, in the past, been able to get copies of such papers for a quarter and have found it advisable to send such copies to my boss. It is not considered good practice in the Orient to send an article torn out of ELECTRICAL ENGINEERING, but when I send the whole issue, it gets passed on to a subordinate due to the boss's lack of time and the need to have a subordinate study the other articles contained therein.

The present article is already being studied by the Katona Concern. This concern has arc welded 25,000 rail joints in Hungary and some hundred test joints in other countries. I realize that about 10,000 welded rail

joints have been made in the United States in tunnels and on bridges and that most of these are made by the thermit process and were not made during traffic. I would like to inquire whether the author has had any experience with the resistance welding of rail joints. I would like to make a general inquiry as to whether the Sperry Company could furnish such information and also if any information is available on the mystic infrared X-ray welding of Doctor Longoria.

One hundred million rail joints need to be welded, and this should give work to 100,000 welders for a year. At the present time the battering of steel rail ends in the United States so affects their life as to cause them to last only 5 years and this would be much shorter in case of war. North America might lose such a war because of the failure of her unwelded rails; thus good maintenance of her railroads may be even more important than the acquiring of very costly battleships.

**C. L. Pfeiffer:** I am pleased by the general comments given in all the discussions which emphasize the need for investigating the weld area more thoroughly.

I agree with Mr. Heitman that in most cases the impedance of the leads and transformer is the determining factor in determining the current through the weld and that this is mostly reactance. I also feel that it is usually desirable to have high impedance in the leads and transformer as this acts as a stabilizer and sometimes brings definite rewards in weld quality. The question of electrical efficiency in the weld circuit is often quite secondary to quality in manufacturing operations especially on lower kilovolt-ampere welders. The little data that was given was in connection with relatively low kilovolt-ampere welders having short leads.

Mr. Zimmerman's reference to fluctuations in electrode pressure during the welding interval is an interesting problem for investigation and no doubt would require an ingenious set-up for accurate measurements in short intervals of time.

Mr. Cogan's remarks indicate that he appreciates even an approximate rule-of-thumb method which allows a sufficient factor of safety in determining voltage drop in the weld area and which may be used as a starting point in the design of a welding machine to be used on a specific job. The factor of 3 given in the paper includes a factor of safety for design requirements and should answer Mr. Hobrock's question as to why 3 is used when 2 appears to be more nearly correct.

In connection with Mr. Dawson's comments on oscillographic measurements, not enough data is at hand to say what voltage variations there are in the weld area, although on copper-rod butt welding I can say that no appreciable change was noted on any of hundreds of oscillograms. The references to Jean's formula and related matter are simply suggestions because the whole problem is one of groping around for a possible line of attack. The vector diagrams represent actual vector values for all quantities except $E_T$ which is obtained by subtraction as mentioned and because of the angular relationships can only fit in one way. I agree with Mr. Dawson that definite energy input into the weld area cannot be generally used and only works out in a practical way by the use of ignitron or thyratron control. Because of variable contact or material conditions it is important to know when occasionally a weld or poorer quality is made and this might be accomplished by measurement of voltage drop and current values by an instrument which indicates or reports an off-normal condition. This weld can then be put aside as being questionable. Mr. Hobrock's discussion of energy control into the weld area is correspondingly interesting.

To supplement Mr. Woofter's remarks I wish to point out that figure 4 was made and an example given to show primarily what should not be done, and that the other circuits, figures 5, 6, and 7, are far superior.

In my references to difficulties in welding "materials of high electrical conductivity such as copper, brass, or aluminum" I did not wish to give the impression that there is much trouble in welding aluminum as questioned by Mr. Bohn, but instead that one must be more alert in making machine adjustments and have better welding equipment than in welding low-carbon steels.

Mr. Frost's discussion presents a very clear picture of the input energy and loss factors involved in spot welding and I wish to compliment him in presenting an equation which is a good starting point for nearly any further investigation of the weld area.

I am not in a position to discuss resistance welding of rails or Dr. Longoria's secret process as mentioned by Mr. Bela Gati. Offhand it seems to me that the flash welding of rail ends in the field is a problem of having portable equipment of sufficient capacity available in remote places. Certainly a power supply of perhaps between 1,000 and 2,000 kva to be made available just anywhere along a railroad is a problem by itself.

Further comments on remarks by Messrs. Gilbert, Hook, and Somerville are hardly necessary. Of course I agree with Mr. Somerville that an entirely "theoretical attack of some practical welding problems would lead to complications." At a given voltage the welding machine will duplicate its work time after time providing the parts fed to it are uniform in every respect. One hundred per cent uniformity in fractions of a thousandth of an inch, in surface condition, or contact area is practically impossible. These small variables are not usually of major importance on most jobs but the welding engineer must recognize them, and on critical jobs the design of parts, materials, the type of machine, tools, and control, must be such to reduce possible variations to a minimum.

In conclusion I wish to thank the various discussers for the time spent in examining my paper and preparing their discussions.

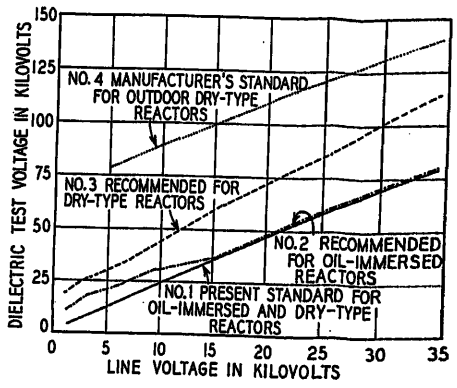



**Figure 1. Standard dielectric test specification for current-limiting reactors**

## Proposed Transformer Standards

**Discussion of a paper by J. E. Clem published in the January 1937 issue, pages 32–36, and presented for oral discussion at the selected subjects session of the winter convention, New York, N. Y., January 25, 1937.**

**S. I. Oesterreicher** (Metropolitan Device Corporation, Brooklyn, N. Y.): I would like to discuss Mr. Clem's paper on the proposed transformer standards and in particular that section which deals with current limiting reactors.

The paper recommends certain insulation requirements for oil immersed and dry type reactors. I believe the values given in table IV are conservative and there should be no difficulty in complying with the suggested requirements.

Up to the rated voltage limits given in table IV, dry-type reactors are used for both indoor and outdoor service. Therefore, it should be made clear whether or not the given values apply to both kinds of service. I believe that for outdoor service we can afford to increase the low-frequency applied voltage tests to higher values so as to be better than the transmission line. To summarize the past and proposed test potentials, I have prepared a diagram which shows the practices followed for the various kinds of reactor services.

However, it is misleading to believe, that due to the new and higher test voltage requirements the reactor will automatically become a superior product. The recommended low frequency dielectric strength requirements are easily met by providing the proper supporting insulators. But this leaves the reactor winding in the same dielectric test muddle as it has been in the past and as stated in the Institute Standards, section # 13, namely: "although it is generally recognized that a test between turns is desirable, no rules have as yet been established." It is not to be thought that because no rules have been set as yet, the designer has an easy task—on the contrary his job is the more difficult. One purchaser specifies a 40-kv high-frequency test for a 13.2-kv line. Another is satisfied with 56 kv on a 24-kv system. One wants a 100-kv impact test with a steep wave front. Not so long ago a 1/4-cycle front on a 60-cycle system was considered steep. Nowadays we speak of wave front in fractions of microseconds, etc. To correct these inconsistencies, I would suggest Mr. Clem and his associates on the transformer subcommittee tackle also this phase of the standardization rules and recommend certain minimum requirements and some uniform procedures which will give us a guide for testing reactors on a more equal basis.

I noticed in the report that the committee changed the classification of the reactors to that of oil-insulated and air-insulated reactors. I would suggest that the present classification namely, oil-immersed and dry-type reactors be retained.

**K. B. McEachron** (General Electric Company, Pittsfield, Mass.): The use of the rod gap as a means of determining the potential to be applied to transformers when undergoing impulse test is not a very satisfactory means of determining test conditions.

The volt-time spark-over curve of the rod gap is very different in shape from the volt-time breakdown curve of transformer insulation. Furthermore, since the transformer insulation strength is not affected by external atmospheric conditions, and the rod gap is so affected, it would appear that the use of kilovolt crest for a given wave shape would be more satisfactory. Thus, the crest value and wave shape without respect to polarity would be specified for each rating of transformer. If it is desired to spark over a parallel rod gap as in test (*a*) of the paper, its spacing would be adjusted to correspond to the existing conditions of humidity, air density, and polarity.

The change from inches of gap to kilovolt values should not now be difficult, since data agreed upon by the various American laboratories are available for both polarities, and corrections for atmospheric conditions are pretty well agreed upon. It seems to me that there is no very good reason for continuing the use of inches of rod gap as a standard, when kilovolt crest values are much more fundamental and can be regarded as a true standard.

For other wave shapes than the standard $1^1/_2$x40, sufficient data concerning the volt-time breakdown curve of transformer insulation are becoming available, so that the proper kilovolt value can be readily chosen. I would like to recommend to the transformer subcommittee that serious consideration be given to the use of kilovolt values rather than inches of rod gap.

In making the impulse tests which have been called for, upon transformers, one rather serious difficulty has arisen, which has increased both the time and cost of making the required tests. I refer particularly to transformers having more than 2 windings, in which case one winding will be utilized for excitation at normal frequency and potential. The winding under test will have one terminal grounded, the impulse being applied to the other end of the same winding while any other windings (and there may be several, particularly if the transformer is 3-phase) will have an air gap connected across each terminal to ground. Quite often these gaps spark-over, and the sudden change of constants affect the wave shape of the impulse applied to the winding under test in an unpredictable degree, and at the same time power follow may take place across the gaps. To prevent such power following, lightning arresters are frequently connected to ground from the terminal of each winding not under test. This is not a complete answer, however, partly because of the multiplicity of arrester ratings required, and partly because the arrester's resistance is nonlinear, being infinite until the gaps spark over, dropping to a low value which increases as the current decreases.

A considerable improvement in testing technique would result if a resistance of proper ohmic value could be connected between each terminal of windings not being tested and ground. This, however, is impractical as long as the power-frequency excitation is a required part of the test, since the energy loss in the resistors is very high. This situation is somewhat improved by the use of a high voltage fuse in series with the resistance and having a series gap just great enough to prevent the normal-frequency excitation potential from putting the fuse into the circuit until the arrival of the test impulse.

A solution of this problem, it seems to me, would be to make the 3 tests as now outlined in Mr. Clem's paper, without the use of power excitation, and follow with a fourth test with normal excitation with the applied impulse reduced to a level just below the spark-over values of the gaps in parallel with the terminals of the winding or windings not being tested. For this last test, the resistor which had been bridged across the bushings for the 3 previous tests would have been removed. Such a procedure would greatly facilitate the test, since the proper impulse-generator constants can be set up in advance using the transient analyzer (The Oscillograph Electric Transient Analyzer, N. Rohats, *G. E. Rev.* volume 39, 1936, page 146), since the transformer constants would not change due to the flashover of gaps connected to windings not being tested.

**I. W. Gross** (American Gas and Electric Company, New York, N. Y.): I am sure we very much appreciate the efforts of Mr. Clem in studying in detail the proposed transformer standards and pointing out those features which are outstanding, so far as suggested changes or revisions are concerned, before they are written into the standards with which we may be tied up for some period of time in the future.

There are several comments I would like to make on this paper: first, in regard to the rated circuit voltages listed in the first columns of tables I and VI, I think the setup of both tables would be much simplified by omitting voltage classifications where no data is given, such, for example, as voltage ratings of 120, 240, 480, 2,400, 4,160, and 4,330. It is not clear why these have been included in the table and it would seem to be a very simple matter to footnote this column to indicate that transformers to be used at rated circuit voltages which were not listed would fall in the class of the next higher voltage class.

In table VI, also, the voltage rating of 2.5 kv is given but data are not given for bushings in this voltage class. Either this voltage rating should be omitted or proper data should be inserted in the table.

Another point which has continually come up for consideration is the designation of impulse strength of transformers. I note that specifying impulse strength in terms of inches of gap is still retained to the exclusion of any other method. In table I, the value of the impulse characteristics of transformer insulation would be very much enhanced if the so-called "basic insulation level" were given in kilovolts. This does not mean that the tabulation of gap spacing need be omitted, but I feel very strongly that the kilovolt values should appear. At the present time, there is no tie between the inches of gap spacing given in table I and the impulse strength of the transformer without searching the literature for the corresponding impulse strength of the gap levels indicated. Such an omission in "Standards" is going to be decidedly burdensome to those who have frequent occasion to design a protective system in conjunction with either lightning arresters or gaps in their various forms.

It cannot be too strongly emphasized that the gap is only a test device for applying voltage under specified conditions and has impulse characteristics quite different from fibrous transformer insulation. For example, the gap spacings given in table I are suitable only for positive waves; for negative waves the spacing must be changed. For fast rising waves, the gap permits higher voltages on the transformer, even to the point of exceeding the transformer ultimate strength. To adopt such a test device as a basic insulation level for transformers seems fundamentally unsound.

Commercial impulse tests on transformers have now been made for a period of several years, and in our own company such tests are usually made on all large high-voltage transformers. In this connection, I wish to point out that the procedure indicated on page 33 under "Impulse Test on Transformers" is, at present, rather confusing. Apparently, the intent is to apply 3 impulse waves; one, a full wave; one chopped on the tail (by gap flashover); and one chopped near the crest (by bushing flashover). If these waves were definitely specified as to the crest kilovolts, with tolerances for time at the instant of flashover, I believe the situation would be fully covered. It seems the logical way to define a test voltage is by magnitude and duration, leaving to the test code such problems as type of equipment to use for the test and the conditions under which they are to be made. Another point in connection with items (a), (b), and (c) referring to the application of the test wave, shows that 2 voltages are applied under the existing conditions of humidity, and air density, and another test under standard conditions. Under these conditions, therefore, the transformer winding will receive a voltage test depending, to some extent, upon weather conditions, and there seems to be no justification for this. I would suggest that all impulse tests be made under definite standard conditions. This again would be accomplished if the test voltages were specified in terms of volts and time rather than in terms of the device used to make the test.

I believe this section on the impulse test data on transformers could be, and should be, very much clarified before being written into the permanent standards.

## A New Electrostatic Precipitator

**Discussion and author's closure of a paper by G. W. Penney published in the January 1937 issue, pages 159–63, and presented for oral discussion at the selected subjects session of the winter convention, New York, N. Y., January 25, 1937.**

**R. E. Hellmund** (Westinghouse Electric & Manufacturing Company, East Pittsburgh, Pa.): The rather brief reference in the paper to the beneficial effects of the electro-

static precipitator upon those suffering from allergic conditions conveys very little idea of the very important part which this device may play in the relief of such suffering. An allergic condition as referred to in the paper simply means a supersensitiveness which some persons have to certain substances which they eat or with which they come in contact in other ways. If these persons breathe air containing substances to which they are supersensitive and which in the majority of cases seem to be of an organic nature, it results in the irritation of the nose, throat, or eyes so familiar to victims of hay fever. If the bronchial tubes are sensitive, the result will be astlima, either of the hay-fever type caused by pollen in the air, or of a type caused by other substances. It is claimed that even certain skin irritations, such as eczema, are caused by similar conditions. Asthma, in particular, seems to be caused to a great extent, although by no means exclusively, by something emanating from moulds or fungi growing in damp places. One method of cure consists in innoculating the patient by hypodermic injections of the particular substance to which he is supersensitive. However, the number of cures claimed by this method is small because so few of the substances likely to cause these allergic conditions are known at this time. In view of this, it is at once evident that this electrostatic precipitator offers relief to a great many people. It is claimed that about 15 per cent of the population (about 20,000,000 in the United States) are suffering from some allergic condition or other, and it seems that only a small percentage of these are affected by substances other than those conveyed by the air.

In view of the prevalency of asthma in Holland, a chair for the study of it was created in the University of Leyden several years. Dr. W. S. van Leeuwen, following some original work done in America, obtained some very excellent results. He was the first one to experiment with means for cleaning the air to bring about relief. He arranged for air intakes a considerable distance above the ground and used large amounts of cotton as filtering material. In some cases this yielded very good results to those who spent their nights in these rooms and went about their regular duties in the daytime. However, in other cases he failed to get results, though his analyses had shown that they were also due to substances conveyed by the air. It is well known that air even at considerable height contains particles of organic materials, and from Mr. Penney's investigation it is evident that the cotton was effective in removing only some of the larger particles; as a consequence, those sufferers affected by the smaller particles naturally did not obtain relief. It is in this connection that the electrostatic precipitator is likely to be of great value. As indicated in the paper, some astounding results have been obtained with it and comparative experiments on patients have definitely proved its superiority over the mechanical filter; in fact, it seems to give almost 100 per cent results in cleaning the air.

There are some persons, however, who are affected by dust or other irritating substances located in wearing apparel, bedding, etc. Dr. van Leeuwen has, for instance, established as a cause certain moulds growing on the feathers in pillows in damp localities. Such substances can, of course, reach the breathing organs through air which immediately surrounds the sleeper and which has not been passed through the precipitator. Again, such substances as face powder, dandruff, and the like have been suspected as possible causes, and here it is again impossible to accomplish complete filtering before the particles enter the patient's breathing organs. However, with the many substances eliminated which can be filtered out by the electrostatic precipitator, the remaining possible causes are narrowed down to a very few, thus making it relatively easy to determine what they are and to eliminate them from the living quarters of the sufferer. Dust particles, in addition to causing allergic conditions, are quite generally assumed to carry certain bacteria, and therefore their elimination may also lessen the danger of contagious diseases caused by germ-laden air.

**Myron Zucker** (The Detroit Edison Company, Detroit, Mich.): Mr. Penney calls it a precipitator, but its real meaning would be brought home better if he called it a filter.

Mr. Penney's development is of great interest because of the fields it opens. The 2 major contributions seem to be the practical elimination of ozone (which is now considered an active poison), thus permitting the use of the cleaner for air conditioning; and increased economy. Since no costs are given, however, it is difficult to imagine just how widespread the precipitator's use might become. Would the author give some orders-of-magnitude for initial cost, power demand, and power consumption for sizes ranging from his window air filter up through 500,000 cubic feet per minute in plants?

Also, similar figures for physical size of the units, and the corresponding gas velocities to be used for satisfactory filtration would help orient the field for this precipitator.

Have any tests been made for ionization remaining in the cleaned air? It might be a favorable by-product in case researches now being conducted show that ionized air is healthful.

**E. M. Strong** (Cornell University, Ithaca, N. Y.): The author has produced a very commendable improvement in the technique of electrostatic filtering. A really effective dust remover has enormous possibilities in many fields and in large quantities. I am interested especially in the field of hay-fever treatment which the author mentions. While this is an allergic affliction and therefore concerned with food and other factors in addition to dust and pollen, it is true that removal of these particles is a major preventive. The author may very well initiate a humane service in this field which involves a large share of our population.

There are 2 major objectives indicated by the author in the development of his precipitator:

1. Reduction of power and space required
2. Reduction of generation of unhealthful products

It is regrettable that more definite quantitative data are not given in the paper to show just how well these objectives were realized. I would inquire what power is used by the models now built and how it is proportioned between ionizer and precipitator.

The generation of unhealthful products seems to me a matter of major concern and one which demands thorough investigation before the apparatus is made available to the general public. So far as I am aware, our knowledge of the effects on the health of humans, exposed for long periods to the products of corona in confined air, is very meager.

One very logical application of the apparatus illustrated by the author is in the air circulating system of the modern air conditioning unit for home or other use. With customary high percentage recirculation it is conceivable that the "very low generation" of unhealthful products may well accumulate to sizeable and definitely dangerous proportions.

If the author has as yet any data on this aspect of the application of the precipitator, surely they are of major importance; if not, I would urge that a careful study be made into the consequences of long-time living with the apparatus before it is put on the market.

**G. W. Penney:** Mr. Strong and Mr. Zucker asked for definite figures on the size of the unit and the reduction in size as compared to the previous precipitation practice. This is frequently given in terms of precipitation time. The precipitation time which we have used varies from 0.12 seconds to 0.6 seconds, depending on the application. In other words, a precipitator to handle 3,000 cubic feet per minute would occupy a volume of 6 to 30 cubic feet. From published figures I believe that the precipitation time in older practice has been of the order of 5 seconds, which would correspond to a precipitator volume of 250 cubic feet to handle 3,000 cubic feet per minute. These volumes refer to the actual volume occupied by the precipitator proper and does not include any space occupied by ducts.

The high-voltage power consumption is approximately one watt per 100 cubic feet per minute. For the 3,000-cubic-foot-per-minute unit referred to above, the transformer and tube losses amount to about 30 watts so that the total power consumption is about 60 watts.

There is apparently no disagreement as to the harmful effects of the amount of ozone present in the air from the older precipitators. However, I believe that the danger from minute quantities of ozone is frequently exaggerated. There are many things which are essential to life in certain concentrations but which are very harmful in excessive concentrations. In discussing this question with a number of doctors, they have all agreed that ozone is probably beneficial and certainly not objectionable as long as it is present only in a concentration not exceeding that found in outdoor air.

The generation of ozone is controllable over a considerable range, although a unit for very low ozone generation is somewhat more expensive. The ozone generation which we have regarded as the allowable limit is based on the same premise as that suggested by Mr. Strong, which is that when used in a house with full recirculation,

the natural infiltration and the decomposition of ozone must keep the ozone below any objectionable limit. We assume that the ozone is not objectionable provided that its concentration does not exceed that present in outdoor air in bright sunshine. Our measurements give the ozone generated as less than one part in 300,000,000 parts of air. However, methods for measuring such minute quantities of ozone may not be entirely reliable in giving the absolute concentration, but at least the comparison between outdoor air and the air from the precipitator should be reliable.

Mr. Zucker asked for cost figures. This device has been produced in relatively small quantities to date so that manufacturing costs are not stabilized, so that for the present we can only quote prices on specific applications. However, when manufacturing methods are developed for quantity production it is expected that the cost of equipment for cleaning the air in a house should be comparable with the cost of the household refrigerator.

In reply to Mr. Zucker's question as to the ionization remaining in the cleaned air, there is some residual ionization and this can be varied over a wide range but our present viewpoint is that this ionization probably does not have any noticeable effect.

## Studies of Stability of Cable Insulation

**Discussion and authors' closure of a paper by Herman Halperin and C. E. Betzer published in the October 1936 issue, pages 1074–82, and presented for oral discussion at the selected subjects session of the winter convention, New York, N. Y., January 25, 1937.**

T. B. Jones (The Johns Hopkins University, Baltimore, Md.): At The Johns Hopkins University studies are in progress dealing with the nature of the radial variations of power factor as affected by oxidation of the compound and by the type of metals used as electrodes. By varying the amount of oxygen in the compound it is possible to obtain rising power factor-time curves with very high values of power factor at elevated temperatures in the vicinity of 80 degrees centigrade. However, when the specimen has cooled down and radial power factor measurements are made it is found that the average of the radial curves does not differ greatly between good specimens and deteriorated specimens. This is in agreement with the authors' table I. Since the radial measurements indicate the degree of "solid" loss then the difference between the average value of the radial tests and the final over-all value of power factor of the sample before dissembling should give an indication of the interlayer or ionization losses. I would like to know if the authors have made any determinations of this nature and if such results correlate with the ionization factors of the complete samples.

The ionization factors in table I are taken at room temperature. Is there any change in ionization factor with increase in temperature? Our results indicate ionization factors as high as 0.006 at 80 degrees centigrade whereas when the temperature is reduced to 25 degrees centigrade the ionization factor is zero. Moreover the final over-all values of power factor at room temperature do not differ greatly among good and poor samples, this would seem to indicate that the high losses occurring in samples with oxidized compound can in all cases be associated with elevated temperature.

W. A. Del Mar (Habirshaw Cable and Wire Corporation, Yonkers, N. Y.): Load cycle life tests are the penultimate tests of cables, the ultimate tests being, of course, actual service under proper supervision.

The company with which I am associated has used and continues to use such tests for comparing different cable oils, papers, and designs. Formerly the criterion of these tests was the number of cycles until failure occurred. Tests on this basis often lasted for several months and as the capacity of the equipment was necessarily limited, the number of tests that could be made per annum was not very great. Thanks to Messrs. Halperin's and Betzer's work, this condition has been changed and a great many more tests can be made in a given time. This is accomplished by establishing a number of arbitrary test limits and stopping the test when any one of these has been reached. These test limits include power factor, temperature, and ionization, as well as life. The limits are chosen by experience to distinguish a cable that is practically stable from one that is unstable.

Messrs. Halperin and Betzer choose a test voltage of $2^1/_2$ times the working voltage. I think that it would be more revealing if they said that they use a maximum stress of 234 volts per mil (calculated by the simple logarithmic formula). Using this stress it is possible to practically parallel Mr. Halperin's results using cable of different design, for instance, thinner walls at lower voltages and indeed, this is what we do in our standard tests, using 220 mils of insulation.

Mr. Halperin's tests were made on horizontal cable, whereas some tests by Detroit Edison Company were made on vertical loops. We have made tests both on vertical U's and horizontal lengths and find that quite different results are obtained. There is some question as to which type of test gives the more reliable results, i.e., results most consistent with operating conditions. However the test is made, it seems important to have the ends horizontal, so that the oil in the end paper (where there is no lead sheath) will not drip into the remainder of the cable.

There is difficulty in obtaining consistent results on a number of apparently identical cables and until this has been removed, some suspicion attaches to the validity of all these tests. We have made series of 4 cables of apparently identical materials, given identical and simultaneous treatment under the most carefully controlled laboratory conditions and yet the cables, on test, will show different results. Dr. Whitehead's voltage-time tests on laboratory prepared cables showed similar divergencies. In those tests only 15 layers of paper were used, so that differences in paper density might not have been averaged out, but in our tests, there are normally at least 36 layers of paper, so that the probability of many low-density spots being superimposed is rather remote. Nevertheless, we find that the variance is much less with high than with low-density paper.

Mr. Halperin has spoken of the better results given by cables impregnated with rosin-blended oils. We have found that such cables exhibit better adhesion of compound to the paper and are less subject to excessive drainage. The use of rosin, however, is advantageous only with certain types of oil, instability resulting from its use with certain naphthene base oils now advocated for cables.

G. M. L. Sommerman (American Steel & Wire Company, Worcester, Mass.): The results presented by Halperin and Betzer show that cables made under identical conditions of fabrication, but with different saturating materials, possess widely differing values of stability and life. This leads to the general conclusion that the problem of finding stable impregnating compounds is fully as important as the problem of reducing deteriorating influences by the use of improved methods in the manufacture of cables.

Load cycle life tests indicate whether one cable is better than another, but, in themselves, give little information as to why it is better. Various methods of diagnosis, such as the dyeing of tapes and the radial power factor test, indicate reasons for superiority more clearly. The authors are to be commended for their discovery of a correlation between life and the quantity: inch-hours of vacuum maintained by the cable. In order to determine the ultimate basis of superiority, however, the materials used in cables must be subjected to various simplified tests, each determining some isolated characteristic. The results of these simplified tests must then be correlated with the observations covering load cycle life tests. As an illustration of this, it has been found by simplified tests made in our laboratory that there are at least 3 advantages accruing from the use of rosin in impregnating compounds, in addition to the obvious effects arising from the increased viscosity of such compounds.

It is now being more generally recognized that the stability of insulation and the properties after some service are more important than the initial properties. This should have an effect on the choice of cable saturants. The use of rosin in the saturating compound is a case in point. Many cables made 5 to 10 years ago contained from 5 to 15 per cent rosin in the saturant. Because the rosin then in use was relatively crude in form, these cables had maximum power factors of the order of 2 per cent (at 85 degrees centigrade), while cables containing no rosin had lower power factors. Although it was realized in a general way that rosin stabilized the insulation, there has been a general trend away from its use during the last 6 years—mainly because of the lower initial power factors obtainable by the use of straight oils. The load cycle life tests made prior to several years ago were so accelerated (employing voltages from 3 to 10 times the rated values) that differences in dielectric loss were greatly magnified. Because of these exaggerated conditions, the probability of thermal instability in test was high for the rosin-containing

cables, and these cables consequently showed up rather poorly. The load cycle life test has, from its inception, enjoyed such prestige that the results were allowed to subordinate the results of electrochemical stability tests and cable operating records.

In the last few years, 2 things have occurred. One has been the development of improved rosins and the use of these rosins in cable saturants, with the result that the cables so made have power factors little if any higher than those of cables made with straight oils. Another has been the improvement of load cycle life testing procedures which are less accelerated in character, and which yield cable failures approximating those occurring in service. The work of Halperin, Betzer, and their associates is an important contribution to this latter field. As a result of these developments, both of which have made thermal instability improbable in the life tests, the more stable characteristics of rosin-containing cables have become manifest. In view of this, it would not be surprising to see a trend back to the greater use of rosin or similar addition agents in the saturants of paper-insulated cables.

**M. G. Malti** (Cornell University, Ithaca, N. Y.): Various writers,[1,2,3,4] on dielectrics have ascribed the breakdown of dielectrics to heat, asserting that electric breakdown is essentially a heat phenomenon. Over 9 years ago, in a paper,[5] I asserted that the absence of valuable data on the nature of dielectric breakdown with alternating potentials renders the formulation of a theory, or even a definition thereof, a matter of wild conjecture. I further disagreed with the propounders of the so-called pyroelectric theory of breakdown on the following grounds:

(*a*). The energy dissipated in the period from the time of voltage application to the time of breakdown, does not raise the temperature sufficiently to account for a breakdown due to heat

(*b*). Actual temperature measurements[6] show that no temperature rise exceeding 10 degrees centigrade does occur in glass before rupture.

The results of the present paper[7] furnish excellent evidence against the pyroelectric theory. Indeed that the breakdown of a solid dielectric cannot be a heat phenomenon is shown by the following facts brought out by the paper:

1. The fact that power factor is sometimes lower at high temperatures than at room temperature (see reference 7, figure 1).

2. The fact that breakdown is always accompanied with a change in the physical condition and chemical composition, and that no breakdown occurs except where such a change shows up (see reference 7, figure 5).

3. The fact that breakdown sometimes takes long paths (over 5 feet as shown by reference 7, figure 7). Indeed if breakdown were simply a heat phenomenon, it would occur where heat would be concentrated, that is, over short paths.

4. The fact that breakdown sometimes starts at the sheath (reference 7, figure 7) where presumably the cable is coolest.

5. The fact that it takes "ageing" to reveal weakness and that different samples presumably subjected to the same heat show no failure unless chemical and physical changes occur (see figures 1 and 5 and conclusion 13 of reference 7).

6. The fact that the authors have observed (see conclusion 6, reference 7) that *ionization* not heat is the cause of deterioration which ultimately results in failure.

7. The fact that stability of the impregnating compound (not heat) is a primary factor in insulation deterioration (see conclusions 5 and 10).

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**R. J. Wiseman** (The Okonite Company, Passaic, N. J.): In stability tests on cables we are largely concerned with small movements or migrations of the free oil, that is, the oil between the paper tapes, in the gaps between the paper edges, and the oil between the strands of the conductor. For this reason, the amount of oil which flows longitudinally into or out of the joints is of importance in determining the life of the cable. However, because this is such a variable factor, and because the section of a long cable farthest from the ends is the most isolated, and usually the most liable to breakdown on stability test, it appears to be preferable to seal the ends of the cable as completely as possible. The authors' cable joints were designed to prevent longitudinal flow and this was "closely approached," but not "completely achieved." What tests were made to check the amount of longitudinal flow?

If this lengthwise flow is eliminated, then stability tests on 50 foot lengths of cable, or even somewhat less, are practical. The cable should be long enough to include in a representative way those slight irregularities which are the reason for breakdown initiation at one point rather than another, and so that the effect of the inevitable loss of a few drops of oil at a splice or insulating joint is insignificant.

If the length of cable under test has the ends perfectly sealed, the only oil movement when the cable is heated is a radial movement, which expands the sheath. If the sheath expansion is measured at different points around the circumference, and at intervals along the length, very considerable differences will be found in sheath expansion. Even with pressures of 40 or 50 pounds per square inch inside the sheath, there may be a decrease in diameter along one axis. The differences in sheath expansion probably account for the unequal stability of samples 60 and 61, which were identical except for being sheathed separately and with different kinds of lead.

The difficulty of predicting failure by making periodic power factor tests is well illustrated by the radial power factor tests made on a few inches of cable involved in incipient failures. Take the case of curve *H*, figure 3, where the carbon extended about 30 per cent of the distance from the conductor to the sheath. The radial power factor curve shows the remainder of the wall to be in good condition. It is easy to estimate approximately the effect of the high power factor of this short section on the average power factor which would be measured on a reel length of cable. Suppose 50 per cent of the insulation was broken down completely, then this whole section would be at conductor potential and except for the increased stress on the good 50 per cent remaining, its power factor would remain unaltered. So that if 50 per cent of the insulation was completely broken down, there would be no appreciable change in the average power factor of the cable.

If this 50 per cent, instead of being completely short-circuited, had its power factor increased 40 times, the power factor of the short section under consideration would be about 10 times what it was before. If this section was about 6 inches long, this effect would be lost in a 500-foot length, for it carries only 1/1,000th of the total capacity current, and the power factor would only be increased by 10/1,000th or 1 per cent of its previous value. Such a small increase is completely masked by temperature changes and other effects.

On this account, the authors have made their power factor measurements on 25-foot sections, but the introduction of insulating joints is open to objection, chiefly because it disturbs the cable. A better method for locating incipient failures and testing longitudinal uniformity is to measure the temperature rise along the sheath with thermocouples at points located 2 or 3 feet apart. If the power factor of a few inches of cable increases 10%, the heat generated in that section will increase 10 per cent and the sheath temperature would increase 10 per cent were it not for heat conduction along the cable. If a 66-kv cable is held at say 115-kv with a similar dead cable alongside for use as a temperature zero level, then the heat of dielectric loss will give a temperature rise of something like 3 degrees centigrade for a 66-kv cable with a 0.0035 power factor. A one-degree-centigrade rise above normal at a point on the sheath represents a "hot" spot, and by making careful measurements the point of failure of a cable has been predicted a month before breakdown occurred. This would have been impossible with power factor measurements.

It is important to decide whether the quality of a cable is to be judged by the interval between the start of test and the time when instability sets in, or if the time to failure is to be used to make comparisons. Figure 4 shows that class *A* and class *B* cables could easily be distinguished from the other classes by the small increase in power factor at elevated temperature. The actual time to failure, once failure has set in, does not seem so important, for conditions might be very local at the fault. Probably the best way to compare cables on stability tests is to make sheath tempera-

ture or "hot spot" measurements at 2-foot or 3-foot intervals along the sheath, and to use the curves of sheath temperature rise versus length, obtained after a standard interval of say 2 or 3 weeks to grade the cables. Whereas figure 4 shows that grade *B* cables had similar average power factors to grade *A* cables, the local deterioration which was found in grade *B* cables, and which is evident from figure 5, would become apparent from sheath temperature measurements.

It is quite possible that simultaneous voltages and load cycles are not necessary. The power factor of the cable could be tested with no more end preparation than is used for routine tests at the factory. Load cycles could be applied, followed by a final high-voltage test for making sheath temperature measurements. The oil movement caused by the load cycles is responsible for the formation of the ionizable voids and consequent increase in power factor, and the authors have shown in figure 3 that the carbonized areas created by the high voltage, contribute very little to the power factor in the earlier stages of the test.

The difficulty of correlating power factor tests with cable condition is increased by the difficulty of controlling the ambient temperature. A change of a few degrees in the room temperature may change the oil pressure in some cables from a good vacuum to a few pounds above atmospheric and this will have an important effect on the measured ionization. It is also tied in very closely with the effect of previous heat cycles on sheath stretching and it may be that a hot spot or local deterioration originates at a point where the sheath expansion is abnormal. The sheath stretches most where, measured around the circumference, there are the longest sections of thin lead.

The improved stability resulting from the use of paper and oil which are gas free, is well illustrated in the authors' paper. The reason for this is not as obvious as it might seem, but it is probable that in a highly degassed cable, the oil returns radially inward on cooling in a continuous unbroken column, and the voids are created near the sheath, where the stress is lower. If this is the case, we should expect that in class-*A* and *B* cables, failure would initiate at the sheath, whereas it would commence at the conductor in the poorer classes. An examination of figure 7 shows samples 24 and 64 (in class *B*) apparently do belong to the sheath failure class, whereas in samples 97 and 114 (in class *D*) the breakdown evidently initiated at the conductor.

It is said that the primary cause of failure is the bombardment of the compound by ionization in gaseous spaces. Is not the primary cause rather the production of ionizable spaces? The most effective method of improving high voltage cables is not in finding a compound which will withstand bombardment, or evolve a minimum of gas, but to prevent or minimize the formation of these ionizable voids in the first place, or else to restrict their formation to a part of the cable which is not under stress.

When a sheath failure occurs which is not accompanied by insulation breakdown, repairs are made in the manhole or shop. The cable insulation is removed until all traces of moisture is eliminated. It is difficult to decide whether a tape is moist or not by its appearance, and power factor tests are not practicable under such conditions. However, high-voltage d-c tests on paper tapes are said to be a good indication of the presence of moisture and are easily carried out on portable apparatus.

The article proves the value of stability tests to determine the ability of the cable to operate satisfactorily in service. Some manufacturers have been making these tests for a long time, and have found them invaluable in arriving at the operating characteristics of new types of cable.

**Herman Halperin and C. E. Betzer:** In reply to T. B. Jones' question, the results of power-factor measurements of individual tapes when properly averaged give the power factor of the cable as a whole at sufficiently low voltage to avoid ionization providing that conducting paths have not formed in the insulation. Such paths do not necessarily have the same effect in the test of individual tapes as in the test of the complete cable.

We have noted in a previous series of aging tests of 66-kv cable that in most cases ionization factors increased with increasing temperature but in a few cables the reverse was true. We have no explanation for this phenomenon. In the tests covered by this paper ionization measurements were made at room temperature only.

Although the point is not emphasized in the paper, we are pleased to have W. A. Del Mar point out again the fact that aging tests need not be continued to failure.

His suggestion that the test voltage be expressed in terms of maximum stress is in general agreement with our statement that for cables to operate at less than 66 kv the ratio of test voltage to operating voltage might be more than $2^1/_2$ on account of the relatively low operating stresses. Voltage tests in general are based on average stresses instead of maximum stresses in the insulation and probably the same should apply to aging tests.

In connection with the differences in test results for apparently identical cables it should be noted that such cables often differ widely in service. Sometimes a few lengths fail in service in a few weeks or months while other lengths have normal lives.

We agree with Sommerman that service performance is the all-important consideration. The aging test is the only known method of determining the performance in a shortened time. We have endeavored also to obtain all available information from auxiliary tests and service.

As emphasized by Malti, deterioration and failure in these tests resulted primarily from ionization, and this has been the weakness in insulation that has caused service failures in our 66-kv cables made in 1927 and later. We do not consider the test results proof, however, that breakdown by thermal instability is impossible. In one series of aging tests at $1^1/_2$ times normal voltage, 66-kv cables were immersed in oil. One 1926 cable deteriorated until its power factor at 70 degrees centigrade was 0.23 and then it remained stable for over 2 weeks. When the cables were removed from the oil, this cable soon failed in test. Apparently the failure was due to a pyroelectric effect which could not develop while the oil was conducting the heat away from the cable. It appears that failure can develop by ionization or by thermal instability and that increasing the voltage to accelerate the aging, hastens mainly the ionization action.

In reply to Wiseman's question, some of the joints had small standpipes in which loss of compound, if any, during the tests could be observed. When the joints were dissected, examinations were made for compound movement.

That differences in sheath expansion may have caused the differences in stabilities of samples 60 and 61 appears to be supported by the results of measurements of the gaps between insulation and sheath measured after the aging tests. These gaps were about 0.003 inch in sample 60 and 0.012 to 0.021 inch in sample 61. In general, however, no consistent relation was found between the sheath expansion and stability.

In these tests sheath temperatures were observed by means of thermocouples and by means of 2 stripes of heat-sensitive paint applied over the entire lengths of all samples. Information of this kind has been found to be helpful, but in all cases approaching failures were predicted by increases in power factor of the cable samples.

Concerning the suggestion that voltage and load cycles need not necessarily be applied simultaneously, failures have in some cases developed during the cooling period of our aging tests. Ionization effects are most pronounced during cooling when the greatest internal vacuum exists. In time after cooling, improvement in ionization factor and decrease in vacuum takes place. It appears important, therefore, that the voltage be on during the load cycles which simulates service conditions.

The theory that failure in class-*B* cable should start at the sheath does not agree with the test results. In 2 cables of class *B* failure started at the sheath while in three cables of this class failure started at the conductor.

We agree that the ionizable voids in cable insulation should be at a minimum. In cable of the ordinary type, however, some voids appear to be inevitable and therefore it is important that the compound be able to withstand bombardment at least to some extent.

## Electronic Transient Visualizers

**Discussion and author's closure of a paper by Herbert J. Reich published in the December 1936 issue, pages 1314–18, and presented for oral discussion at the selected subjects session of the winter convention, New York, N. Y., January 25, 1937.**

**N. Rohats** (General Electric Company, Schenectady, N. Y.): This paper presents some very interesting work on circuits for use with the cathode-ray oscillograph. The idea of repeating a transient in exact co-ordination with the oscillograph time axis so that a standing wave on the fluorescent screen is available for visual observation or permanent photographic records has already been used in a number of prac-

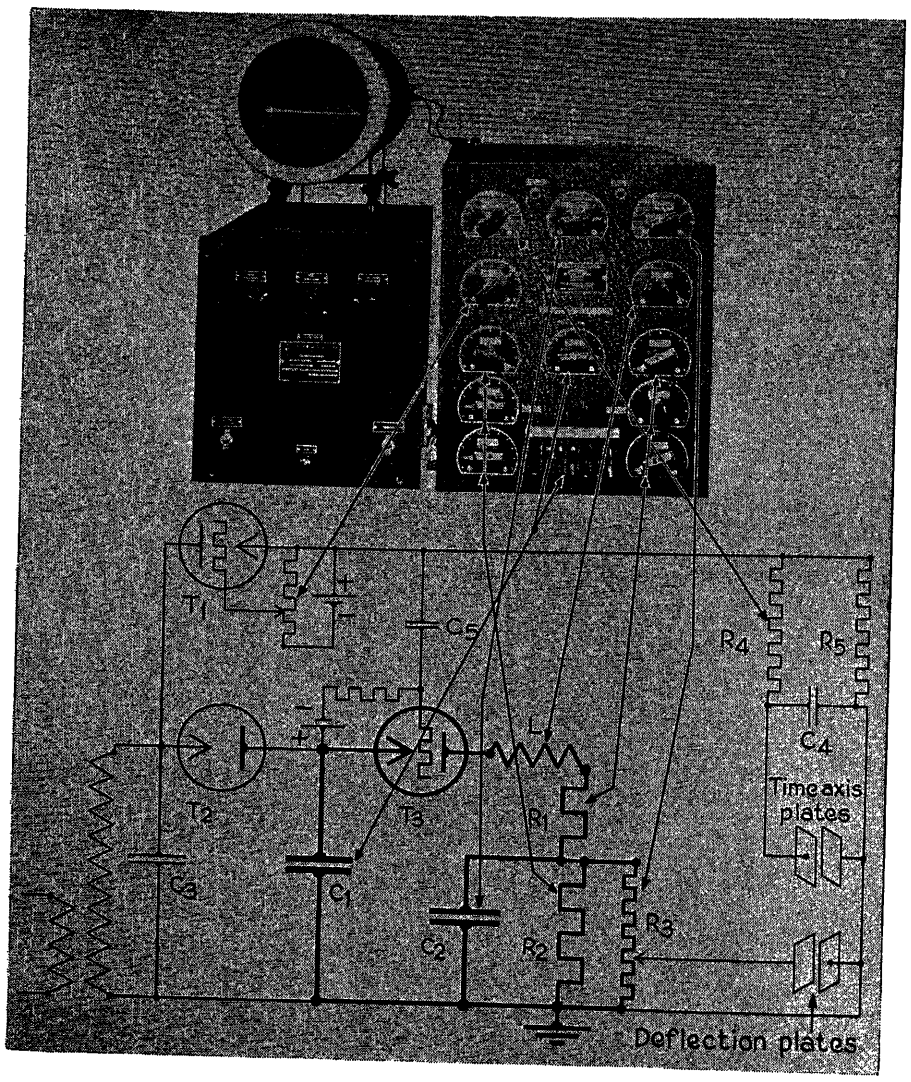



Figure 1

tical commercial applications. As the author points out, an arrangement which accomplishes this by mechanical switches has serious limitations for all but slow transients. Considerable objection may be found to the author's statement (quotation) "The device should not possess inductance, capacitance, or resistance—and this requirement prohibits the use of devices in which a capacitor or inductor charge or discharge is inherently associated with the action of that part of the switching device through which the transient flows" (quotation closed). The circuit arrangement which has been found most useful in general engineering work is one wherein the transient energy is originally stored in a capacitor and then released through a mercury-vapor tube to flow into an inductance and resistance discharge circuit. Presumably, this does not meet the author's requirements that the visualizer should be an ideal switching device. This requirement considered in the light of every day testing problems in transient work seems to have very little practical significance.

A more realistic general requirement is that such a device be capable of generating and imposing on circuits and machines, definite waves of a wide range of shapes. This requirement is met by the oscillograph electric-transient analyzer. The circuit arrangement is shown in figure 1. The complete analyzer consists of a set of variable capacitors, inductors, and resistors, a sweep circuit for a cathode-ray oscillograph time axis and the required means for properly co-ordinating these 2 so that a standing wave is visible on the oscillograph screen. Such a device from a testing standpoint is definitely related, as to type and use, to surge or impulse generators. When connections are arranged to give one output surge for each cycle of a power frequency supply voltage, it becomes a repeating type surge generator. It differs from the usual surge generator only in that it is low in voltage (1,000 volts), has a tube in place of the usual sphere gap, and is portable.

The miniature impulse generator is shown in figure 1 in heavy lines. Operation proceeds as follows: On the negative half cycle of the supply transformer $C_1$ receives a negative charge through rectifier $T_2$. On the positive half-cycle $T_1$ begins to conduct at the crest voltage, thereby sweeping the beam of the oscillograph at a speed determined by $R_4$ and $C_4$. The grid of tube $T_3$ receives an impulse through $C_5$ at the start of the sweep and becomes conducting thereby initiating the discharge of $C_1$ through $L$, $R_1$, $R_2$, $R_3$, and $C_2$ and producing the required wave shape across $C_2$.

The practical usefulness of such a device in the field of impulse testing is apparent. Many of the tests previously made with the single-discharge surge generator are now performed with a great saving in time over the old method.

For instance, in the adjustment of circuit constants of high-voltage surge generators to give standard waves such as the 1x5 or $1^1/_2$x40 for commerical impulse tests, such as for transformers, the analyzer is connected directly to the transformer and the circuit elements adjusted until the required wave is obtained on the oscillograph screen. The numerical values of circuit constants required are read from the dials of the analyzer and the high-voltage surge generator circuit constants set to correspond. This saves many hours of work.

The distribution of voltage across windings of transformers and generators is readily determined by applying output surges of the analyzer to one end of the winding and recording wave shapes at several tap points. This is a very important application because maximum surge-voltage strength is obtained only when the design is such as to cause uniform surge voltage distribution from one end of the winding to the other.

By connecting the output surges to a circuit or to machine windings and studying voltage and current reflection conditions for a range of values of resistance at the terminal end the surge impedance can be readily obtained.

These are all practical applications which have been made in many instances and through which valuable design and test information has been obtained.

Other uses such as demonstration of transient phenomena, study of induced voltages, and location of faults in circuits and windings are also of importance.

Returning to consideration of the visualizer and keeping in mind its conception as purely a switching device, it seems to be limited to special applications, particularly demonstrations of transients associated with switching phenomenon. Would the author comment on the limitation of current by the gas discharge tube itself? Also, does not the tube current controlled by the grid potential affect the shape of the transient? Also, does not tube voltage vary with current sufficiently to depart from a true switching device and to affect voltage distribution in the circuit?

The author is to be commended on the progress made in the design of visualizer circuits. It is hoped that his work will continue as the field is considerably unexplored and new factors of usefulness are quite certain to be obtained.

**H. J. Reich:** In discussing the limitation of my circuits to special applications Mr. Rohats seems to confine himself to the types of visualizer shown in figures 4 and 7 of my paper. This criticism also applies, however, to my circuits of figures 11 and 12 and to his own. Is it not generally true that the best instruments must be designed for specific fields of application?

I believe that the questions regarding the limitation of current by the tube and the effect of grid voltage upon the transient have been answered in my paper (paragraph 3, page 1314; paragraph 2, page 1317). So far as I have been able to determine, these factors do not affect the form of the transient.

In the type of visualizer shown in figure 7 the variation of anode voltage of an 885 gas-discharge tube affects the form of a starting transient to a certain extent when the supply voltage is low. The anode-voltage *vs.* anode-current curves of individual 885 tubes differ and are likely to change somewhat with tube age. The voltage of a typical tube falls from 17½ volts to 17 volts in the range from 40 to 6 milliamperes; at 1½ milliamperes it is 16 volts, and below 1½ milliamperes it falls to zero nearly linearly with current. A discontinuity of a volt or a volt and a half, accompanied by a change in the form of the discharge may occur at about 25 or 30 milliamperes, but its effect has not been observed in the transients, probably because of the rapidity with which the current changes during the transient. Distortion decreases with increase of supply voltage and with increase of average current. With a 45-volt supply and an average current of 40 milliamperes, the distortion is small. The distortion which results from the rapid fall of voltage below 1½ milliamperes can be prevented in most studies by shunting the transient circuit with a resistance of such size that the current does not fall below 5 or 6 milliamperes during the life of the transient. In the work referred to in reference 4 of my paper, Mr. Bennett showed that circuit parameters could be determined with considerable accuracy from oscillograms obtained with a transient visualizer of the type shown in figure 4 of my paper, using thyratrons. When transients are initiated by the interruption of current the tube does not conduct during the life of the transient and so cannot affect the form except as the result of its small inter-electrode capacitance. If the life of the transient is extremely short, some distortion may result from the finite deionization time of the tube, but this may be safely neglected in the study of transients whose life exceeds 1,000 microseconds.

Mr. Rohats' circuit is beautiful in its simplicity. It should prove to be valuable in many applications.

## An Electronic Regulator for D-C Generators

**Discussion and author's closure of a paper by F. H. Gulliksen published in the August 1936 issue, pages 873–5, and presented for oral discussion at the electronics session of the winter convention, New York, N. Y., January 27, 1937.**

**B. G. Ballard** (National Research Council, Ottawa, Ont., Canada): Those of us who have requested prices from manufacturers for electronic regulators will appreciate the development of a unit which sells at a price comparable to that of electromagnetic regulators.

The regulator described in Mr. Gulliksen's paper appears to possess particularly desirable features. It has dispensed with the amplifier usually employed and it apparently does not require a specially wound field. If a constant a-c input is assumed a sensitivity of 0.1 per cent is claimed which is equal to that of any precision regulator of which I am aware. In view of these desirable features I have been wondering if it would not be possible to adapt this regulator to a-c generators. It would seem feasible to heat the cathode of the diode with alternating current and feed the resistance in series with the cathode from a small filtered rectifier with a relatively short time constant. Since the alternating current supplied to the thyratrons should now be constant the over-all sensitivity of the unit should approach 0.1 per cent. I should appreciate the author's comments on this point and also I would like to know if the diode was specially developed for this application. Is it provided with a tungsten filament or a coated filament?

**Russell Ranson** (Duke University, Durham, N. C.): It is understood from Mr. Gulliksen's paper that the compensating or compounding rheostat in the filament circuit of the diode must be adjusted to suit the needs of the particular generator with which the regulator is used. This adjustment is similar to the adjustment of a diverter which is used in parallel with the series field of a compound generator to give flat compounding. It follows that a different adjustment of this rheostat is necessary for every voltage for which the regulator is set by the voltage-adjusting rheostat. This means that in order to change the regulated voltage from one value to another 2 adjustments must be made.

According to Mr. Gulliksen's curves the generator voltage varies in a straight line from no load to full load, either with or without the regulator. If this be true, why not pass the generator load current through a very low resistance similar to an ammeter shunt and impress the voltage drop across this resistor on the grid circuit to obtain the necessary phase shift? This will eliminate one electron tube, the diode. It is generally believed that a reduction in the number of electron tubes is desirable. Again referring to the curves given, the voltage change as given by the diode might be equaled by a voltage drop across a very low resistance as suggested with a loss of power that will be negligible.

Even if this plan were followed, it would still be necessary to provide adjustable resistors to match the generator characteristics and to provide for generator voltage adjustment.

**F. H. Gulliksen:** Mr. Ranson raises the question whether it is necessary to change the compensating adjustment if the regulated voltage is varied. Theoretically this assumption is correct, i.e., if the regulated voltage is varied the regulator will not have a flat characteristic from no load to full load, but the variation in regulated voltage will be so small (approximately $\pm 1/10$ of one per cent or less) that it will not be necessary to change the compensating adjustment. This is apparent from the curves *B* in figure 6 and 7 which show the regulator characteristic without compensation giving a drooping characteristic of 3 per cent and one per cent, respectively. If the characteristic in figure 6 is used it is apparent that the compensating adjustment may be varied 10 per cent without giving more than 0.3 volt error in regulated voltage from no load to full load. This is well within the guaranteed sensitivity of the regulator which is ±0.5 volts.

Mr. Ranson's suggestion to eliminate the diode may not be practicable because in that case voltage $E_2$ must be reduced considerably in order to obtain sufficient regulator sensitivity. If this be done the regulated voltage will vary with the changing grid-voltage characteristics of the arc discharge tubes caused primarily by varying tube temperatures.

In reply to Mr. Ballard's question, the author wishes to state that regulators for a-c generators operating on a somewhat similar principle are commercially available. In a-c generator applications a d-c exciter is usually needed and for this reason anti-hunting means must be added to the regulator circuits to obtain stable operation. The diode was specially developed for this application, and is equipped with a tungsten filament.

## Sealed-Off Ignitrons for Welding Control

**Discussion and authors' closures of a paper by David Packard and J. H. Hutchings published in the January 1937 issue, pages 37–40, and presented for oral discussion at the electronics session of the winter convention, New York, N. Y., January 27, 1937.**

**Bela Gati** (Katona Rail Welding Concern, Mount Vernon, N. Y.): Three little questions: Have you tried to weld nickel with aluminum? If so, did you preheat the nickel? Aluminum melts at 659 centigrades (Celsius), nickel at 1,452. Did you use your ignitron in rail-welding process?

**J. H. Cox** (Westinghouse Electric & Manufacturing Company, East Pittsburgh, Pa.): The authors have done a creditable piece of work in working out to a satisfactory conclusion, the numerous problems involved in manufacturing a sealed-off metal tube for use with a mercury arc. The paper could have been made more valuable by a discussion of the degassing processes essential in this type of device.

Limiting temperatures of 50 to 125 degrees centigrade are given. Our work indicates that the minimum temperature for satisfactory operation is a great deal less than 50 degrees centigrade, and a maximum of 125 degrees centigrade sounds impracticably high for a water-cooled device. Possibly Fahrenheit degrees were intended.

Unless more water is used than is usually necessary, a water jacket design results in a low water velocity, deposit of sediment and inefficient cooling. Cooling coils permit more flexibility in design and, for the above reasons, may supersede the jacket.

This paper provides additional confirmation of the contention made by Dällenbach several years ago, that it is impossible to build a sealed-off metal tube with a corrosive cooling system, since corrosion of iron in water produces hydrogen ions which diffuse through steel walls.

The authors mention peak currents of 7,000 amperes and 250-ampere average currents at lower peaks. I would like to ask

what average currents they are able to carry with 7,000 ampere peaks, and how large the tubes are that carry these currents.

I think that the list of advantages given is misleading, since most of them are characteristics of ignitrons in general and not limited to sealed-off designs. In general, there is an economic division between the field for sealed off tubes and continuously pumped tubes. At the lower ratings, the tube cost is low and the assembly does not justify the expense of a vacuum pumping equipment. At the higher ratings, the replacement cost of tubes would be prohibitive and the cost of a pumping set a small percentage of the total. The dividing point will be influenced by what proves to be the average life of the sealed-off tubes in service. It is quite likely that it will be greater than we are used to in the case of thermionic cathode tubes.

**W. C. White** (General Electric Company, Schenectady, N. Y.): In connection with the life of this form of ignitron, it is important to differentiate clearly between elapsed time and actual operating time. Unlike a tube with a thermionic cathode, it is absolutely as "dead" as an insulating bushing when not actually passing current. This is particularly true of these sealed-off tubes incorporating only one anode, as there is no holding arc or pump in operation. In normal industrial welding operating schedules, the tubes are actually "alive" only a relatively small part of the elapsed time. It is believed, therefore, that in this service tube failures will be from accidental causes traceable to use or manufacture rather than any normal deterioration factor in the ignitor or other parts of the tube.

As regards choice between sealed-off and pumped ignitrons, there is an additional factor. This is the number of years assumed for the write-off period of the investment in the welding equipment as a whole. In the resistance welding field, it is relatively short compared with, for instance, the central-station field. A short write-off period, in combination with the aforementioned intermittent operation, is favorable to the sealed-off tube. Another favorable factor is the inherent feature of this type of tube to be ready to operate the instant power is applied regardless of the time it may have been shut down.

**R. E. Hellmund** (Westinghouse Electric & Manufacturing Company, East Pittsburgh, Pa.): In addition to the previously mentioned advantages of the ignitron over other types of tubes for welding purposes, it has the further advantage that it can be built either "sealed off" or for operation in connection with pumps; this, of course, would not be practicable with gas-filled tubes. The question as to which way the ignitron should be built is then purely an economical one. The sealed-off tube has a somewhat limited life, which means either complete replacement from time to time or retreatment of the tubes. This maintenance cost has to be weighed against the carrying charges resulting from the higher initial cost of tubes designed for operating with pumps. It is at once evident that the smallest tubes mentioned in the paper will prove more economical as sealed-off tubes. It is also quite certain that the very large and high-power tube arrangements will be more economical under present-day conditions if equipped with pumps. Somewhere between these 2 extremes there is a dividing line, above which the one arrangement will prove more economical and below which the other will work out best. It will probably be some time before the dividing line can be definitely determined, and furthermore, as the design, manufacturing practice and treatment of the sealed-off tubes are improved, the dividing line may shift to a higher level. However, in order to establish even a preliminary dividing line, it will be necessary to know something about the life to be expected from the sealed-off tubes in their present state of perfection. While I appreciate that it is rather early to raise this question, it would be of assistance if the authors could give an approximate idea of the life of the larger sealed-off tubes having stainless steel walls, as described in the papers.

It is very gratifying to note that in the papers presented and the discussions relating to them, the same nomenclature was used for the various tubes mentioned. After the igniter principle had been discovered in the Westinghouse Research Laboratories and practical tubes had been designed, it was of course necessary to find a fitting designation for these tubes. The name "ignitron," signifying an igniting device, was chosen, and in accordance with the established practice, trademark rights were secured. While this is a perfectly legitimate commercial practice, it became more and more evident as time went on that such practice was resulting in great confusion in the establishment and application of a proper nomenclature for electronic devices. Therefore, at the suggestion of the General Electric Company, the interested manufacturers relinquished their trademark rights, thus permitting anybody to refer, for instance, to the gas- or vapor-filled, hot-cathode, grid-controlled tube as the "thyratron" or to call the pool-type tube with an igniter an "ignitron."

In talking about the life of tubes, from an engineering point of view it is of course logical to express this in the number of operations or load cycles performed by the tube. On the other hand, the purchaser of welding equipment in choosing between the pumped and sealed-off arrangement, is accustomed to calculate his carrying, maintenance, and replacement charges on an annual basis for his particular application. It may, therefore, be necessary for manufacturers eventually to determine the life of tubes for a number of selected and typical types of service on an annual basis. While in the previous part of my discussion reference was made to a dividing line between different ratings, it is quite possible that over a certain range of ratings the sealed-off tube may prove more economical for relatively light and infrequent service, and pumped tubes of the same rating may be preferable for continuous and heavy service.

**David Packard:** The question of where to draw the dividing line between the application of sealed-off tubes and continuously pumped tanks is one which cannot be answered definitely at this early stage of ignitron use. As was brought out in the discussion, there is no question but that the smaller tubes have the field to themselves, and as we pointed out in the paper we have not yet encountered an application which required higher welding currents or greater duty cycle than can be handled by the largest sealed-off tubes now developed. If it appears undesirable to make sealed-off tubes for higher currents, there is, of course, the possibility of going to higher voltages in which case tubes of essentially the same size might be extended to higher power.

The life which will be obtained from tubes now in the field will also be an important consideration in determining how much further sealed-off tubes may be extended. In the development of the sealed-off tubes we have had every indication that they will give very long service. Our experience with tubes in the field has substantiated this belief although they have not been in use long enough to determine just what the life will actually be. There have been failures, of course, but in general the failures have been traceable to either misuse or to manufacturing defects which have showed up when the tubes were first put into service or shortly thereafter. To state a typical case; one user of the water-cooled ignitrons with 50 tubes in service under severe conditions has been operating about 7 months with no failures other than manufacturing defects which became apparent due to transportation or when the tubes were first installed. Some of the smaller tubes have been installed for approximately 2 years. Although the life of the sealed-off tubes has been entirely satisfactory thus far, the users of the tubes are protected against excessive cost in 2 ways. In the first place, the tubes are supplied on a policy which assures the user that the tube cost per month will not exceed a certain maximum amount when the tubes are used within the specified ratings. In the second place, losses which might result from a shut-down in a production line because of tube failure are kept at a minimum with sealed-off ignitrons because they can be replaced quickly and are ready for service instantly.

In closing, it might be of interest to know how many sealed-off tubes are in the field. The total number of tubes now in service is about 500. Of these about 150 are water-cooled metal ignitrons, some of which have been in service nearly a year. The remainder are the air-cooled tubes, and some of these have been in service about 2 years.

**J. H. Hutchings:** In regard to the temperature range in which ignitrons will operate, work done by the authors and their associates has netted results in agreement with those expressed by Mr. J. H. Cox. As Mr. Cox points out, ignitrons are able to operate at quite low temperatures (far below 50 degrees centigrade). Reasonably reliable operation has been obtained, in fact, with tubes so thoroughly chilled as to solidify the mercury. The absence (for all practical purposes) of any minimum operating temperature limit for ignitrons is attributed to the fact that evaporation of mercury from the cathode spot supplies the vapor pressure necessary for conduction of the arc current.

The limiting temperature range of 50 to 125 degrees centigrade mentioned in the paper is a range of maximum temperatures for the 6 tubes under consideration, the variation being due mainly to circuit con-

ons. Fifty degrees centigrade applies as a imum where high voltage and peak cur- are encountered and the period of current duction is of long duration. Some air- ed tubes will operate reliably at 125 rees centigrade when voltage and cur- are low and the conduction period short. Mr. Cox asks how large a sealed-off igni- is required to pass peak currents of 7,000 peres and what average current can be ducted at this peak. Size: 5½ inches liameter. Average current rating: 110 peres at 550 volts, 160 amperes at 220 ts.

n answer to Mr. Bela Gati's 3 questions, have never attempted to weld nickel aluminum. Stainless steel and alumi- n, however, have been welded satis- torily, in which case it was not necessary preheat the stainless steel. We are not iliar with any attempt to use ignitrons ail-welding processes.

The matter of tube life has been discussed others. However, Mr. Hellmund in- res into life of tubes "having stainless el walls" and so brings the thought that miting factor in tube life may be gas ac- nulation through the process of hydrogen fusion. Preliminary tests recently com- ted indicate that many years would be uired for vacuum to be impaired through s mechanism.

## Watt-Hour Meter Bearings

**scussion of a paper by I. F. Kinnard and H. Goss published in the January 1937 ue, pages 129–37, and presented for oral scussion at the instruments and measure- nts session of the winter convention, New rk, N. Y., January 28, 1937.**

**. B. Brooks:** See discussion, page 880.

anley Green (Duncan Electric Manu- cturing Co., Lafayette, Ind.): In this per a great deal of work has been sum- arized leading toward a better watt-hour- eter bearing. The demand for such a aring which will last up to 20 years with- it replacement under the recently imposed nditions of outdoor operation with attend- nt variations in humidity and temperature as been insistent. The bearing problem rtainly is one of the most acute of any in e watt-hour-meter art today. During the ast few years I have followed with interest nd some concern the work outlined in much the bibliography appended to this paper nd also want to commend the authors on heir industry and thoroughness with respect the material in the paper.

Personally, however, I feel that we shall ot attain the object of our search until il is totally eliminated in bearings. Alloys must be obtained which will run on a jewel ry without being harmed. With the de- elopment in the field of alloys progressing s it is, I feel that there is more possibility long this line than that a perfect oil will ever e developed. Even if a perfect oil were vailable, there are still operating incon- eniences and uncertainties attached to its se.

**A. R. Rutter** (Westinghouse Electric & Manufacturing Company, Newark, N. J.): The authors have prepared an excellent paper which will be used by meter engineers as a reference on the subject of meter bearings. While most of the data deals with the pivot type of bearing, the ball type is mentioned a number of times in the paper. Some additional information on the ball bearing might be of interest to anyone studying the problem.

The ball type of meter bearing has been manufactured in America for over 35 years, during which time a large percentage of the meters manufactured have been equipped with this type of bearing. The functioning of the ball bearing is described in Mr. Lenehan's article in the November 1929 *Electric Journal*.

The performance of the ball bearing has been recognized by the utility companies because of 3 important fundamentals. These are:

1. Sustained meter accuracy
2. Long life without lubrication trouble and wear
3. Low maintenance cost

The ball bearing satisfies these outstanding characteristics because the ball turns between 2 jewels and acts as an infinite number of pivots, with the result that the wear of the parts is distributed over the entire surface of the ball and over a large portion of the jewel area. Since a double jewel is used and the ball rolls in the jewels, the jewel surface used is much greater than in the pivot bearing. For all practical purposes the ball has a rolling action and does not require lubrication. The action of the ball bearing is such that dirt does not interfere seriously with the bearing.

The radius of the ball used in American meters is 0.031 of an inch. The data in the paper, particularly figures 3, 4, and 12, confirm the reason for the very good results in service that have been obtained with the ball type of bearing.

A large amount of study has been given to the question of material for the ball, but, to date, no commercial materials have been accepted and approved as being superior to carbon steel.

**A. J. Allen** (Consolidated Edison Company of New York, Inc., New York, N. Y.): The paper "Watt-Hour Meter Bearings," by I. F. Kinnard and J. H. Goss is very commendable as it indicates an endeavor toward an end that is very much desired by meter engineers.

For a long period of years watt-hour meter lower bearings have consisted of natural or synthetic sapphire jewels with glass-hard steel pivots or balls. The use of steel in meter bearings has proved undesirable because if the steel rusts rapid failure of the bearing follows: Rust or ferrous oxide is most abrasive and forms readily unless some protective coating is maintained: for this purpose oil has been used. The oil also provided lubrication which is necessary for steel pivots but not for steel balls; in fact its presence in a ball bearing is undesirable from a lubrication standpoint.

The need to find or develop a substitute for high-carbon steel that would not form an abrasive oxide has been foremost in the minds of meter engineers and at their urgent request several meter manufacturers have given the development serious attention. The increasing practice to install watt-hour meters on the outside of buildings further intensifies the need, and it injects into the problem temperature range requirements for bearing lubricants not necessary for meters installed indoors. There is a well substantiated belief that oil is not necessary or desirable in a meter bearing. The authors state "the provision of a good lubricant is not a simple matter," this has been true ever since the first oil was placed in a meter bearing. The sad experience which followed the use of fish, vegetable and mineral oils and various oil compounds has well established the hope to eliminate the need for oil in meter bearings. As to this, the authors hold out a ray of hope when they state "While all tests definitely show that proper lubrication increased the life of bearings, it has also been shown that cobalt-tungsten performs exceptionally well even without oil."

Table I—"Properties of Pivot Materials" indicates in the second column whether the materials were corrosive or not. Cobalt-tungsten is shown as not being corrosive yet it oxidizes when exposed to air. If the oxide is nonabrasive that fact is naturally the most important. Beryllium alloys, as indicated in the table, may have some possibilities. I have experimented with a beryllium-nickel-copper alloy that has proved superior to beryllium alloyed with nickel or copper alone in respect to non-abrasive oxide.

The matter of shock resistance of pivot materials is most important. It appears that reducing the contact area to an area as small as possible has been responsible for considerable damage to jewels. The advantage of a larger area is apparent from the tests made in comparison with steel and cobalt-tungsten pivots. It appears that a cobalt-tungsten pivot should have a contact area equal to that created by the shock of the short-circuit test on the assumption that a short-circuit shock would not cause deformation of a pivot having this area.

Accelerated life tests, while necessary, do not prove entirely the serviceability of a material, they do, however, indicate a trend that can be expected. A meter bearing that has a life of 20 years and does not require oil is not far away.

## Amplification Loci of Resistance-Capacitance Coupled Amplifiers

**Discussion and author's closure of a paper by Anatoli C. Seletzky published in the December 1936 issue, pages 1364–71, and presented for oral discussion at the electronics session of the winter convention, New York, N. Y., January 27, 1937.**

**Dale Pollack** (nonmember; RCA Manufacturing Company, Inc., Camden, N. J.): In the form in which the author writes the vector amplification of a resistance-coupled amplifier, (2) of his paper, it appears that the locus is not a single circle, but is the vector sum of 2 different circles. However, the equation is easily manipulated to show

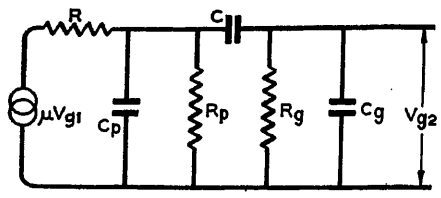



Figure 1

that it may, in fact, be represented by the locus of a single circle, and that the author's 2-circle representation is unnecessarily complicated. Consider the author's (2),

$$A = \frac{-jK\omega}{\omega^2 - jb\omega - c} \qquad (2)$$

dividing through by the numerator gives

$$A = \frac{1}{\frac{1}{k}\left[b + j\left(\omega - \frac{c}{\omega}\right)\right]}$$

Making the substitution

$$m = \omega - \frac{c}{\omega}$$

yields

$$A = \frac{1}{\frac{1}{k}(b + jm)} \qquad (2a)$$

where $m$ is now the parameter instead of $\omega$. (2a) is the locus of a single circle, which is evident by comparison with the author's (4), or from the following:

$$\frac{1}{A} = \frac{1}{k}(b + jm) = \frac{1}{|A|}e^{j\theta} \qquad (2b)$$

then

$$\frac{1}{|A|} = \frac{1}{k}\sqrt{b^2 + m^2} \qquad (2c)$$

and

$$\frac{m}{b} = \tan\theta \qquad (2d)$$

Substituting (2d) into (2c)

$$\frac{1}{|A|} = \frac{b}{k}\sqrt{1 + \tan^2\theta} = \frac{b}{k}\sec\theta$$

and, inverting,

$$|A| = \frac{k}{b}\cos\theta \qquad (2e)$$

(2e) is the polar equation of a circle passing through the origin with its center on the horizontal axis.

This same conclusion is reached by Luck in his paper "A Simplified General Method for Resistance-Capacity Coupled Amplifier Design," IRE *Proceedings*, volume 20, page 1401, 1932, when he states, on page 1403, "... there is a simple fixed relation between gain magnitude per stage and phase displacement per stage, the former being proportional to the cosine of the latter."

The author's ingenious algebraic solution is correct, except that the resulting locus is erroneously called a bicircular quartic instead of simply a circle. By starting with this single circle, instead of taking the sum of 2 circles as the author does, the computation is simplified. The writer has been using a graphical design method based upon the simple circular locus, and it may be of interest to present it. Using Luck's notation and analysis (see figure 1) which differ slightly from the author's,
let

$$\frac{1}{R_s} = \frac{1}{R} + \frac{1}{R_p} + \frac{1}{R_g}$$

$$\frac{1}{R_1} = \frac{1}{R} + \frac{1}{R_p}$$

$$w = \left(1 + \frac{C_g}{C}\right)\sqrt{\frac{R_g R_1 C}{R_s^2\left(C_p + C_g + \frac{C_p C_g}{C}\right)}}$$

then

$$A_0 = \frac{S_m/R_s}{1 + C_g/C}$$

is the maximum gain occurring at a frequency $f_0$

$$f_0 = \frac{1}{2\pi\sqrt{R_1/R_g(C_p C + C_g C + C_p C_g)}}$$

$S_m$ is the mutual conductance of the tube. Also let

$$y = \frac{f}{f_0} - \frac{f_0}{f}$$

be the frequency parameter. Then

$$|A| = A_0 \cos\left[\tan^{-1}\frac{y}{w}\right]$$

where

$$\phi = \tan^{-1}\frac{y}{w}$$

is the phase angle of the vector amplification. The only assumption made, aside from those from linearity and freedom from feed-back, is that

$$\frac{C_p - C_g}{C} << 1$$

This assumption does not affect the shape of the amplification locus but it does simplify some of the equations.

The general locus for any resistance-capacitance amplifier may now be sketched by drawing the circle on polar-co-ordinate paper, as in figure 2. By plotting the frequency determining parameter $y/w$ linearly along the vertical line, as shown, and projecting from the origin through the vertical line to the circle the frequency determining points on the circle are found. Knowing the constants of the amplifier, its gain and phase shift can be found very rapidly with the aid of the circle diagram. It is only necessary to calculate $w$ and $y$ for the desired frequencies from which the value of the vector gain may be read from the diagram. The converse process, for obtaining the circuit constants from a known frequency and phase characteristic, may also be carried out. The process is very similar to the one suggested by Luck, except that the circular locus on polar paper replaces Luck's generalized gain and phase curves. This reduces the labor involved and improves the accuracy of the method.

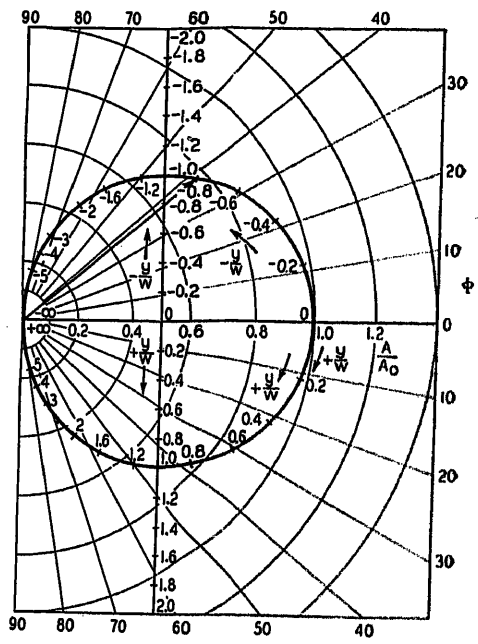



Figure 2

I. Rotkin (United Transformer Corporation, New York, N. Y.): This paper presents an interesting and convenient solution of the problem of calculating the complex response of a resistance-coupled amplifier from its circuit constants.

To the extent that grid-to-plate capacity in the vacuum tube is neglected the final result is, however, only an approximation. This is the case even in what Mr. Seletzky calls the exact equivalent circuit. The amount of error introduced by omitting consideration of the grid-to-plate capacity depends on the circuit constants, and it increases with frequency. There are 3 discrepancies introduced by this approximation.

When the grid-to-plate capacity is taken into account, the exact equivalent circuit of a resistance-capacitance stage of amplification becomes like the circuit of figure 3, where $C_{gp}$ is the grid-to-plate capacity of the amplifier tube, and $R_g'$ and $C_g'$ are, respectively, the effective input resistance and input capacity of the following tube. The other symbols are the same as those in the paper.

Except for very high frequencies $R_p\omega C_{gp}$ is much smaller than $\mu$. Hence the error introduced by neglecting the imaginary term, as the author has done, is negligible.

Very small, though not in general negligible, is the error introduced in the paper by neglecting the $C_{gp}$ term in the output capacity.

The third error is the most serious. It may be so large as to limit the author's method to the low audio frequencies for certain types of tubes. Mr. Seletzky assumes the input impedance of the following tube to be constant and to consist of the grid resistor and grid-to-cathode capacity of the following tube. Under actual condi-

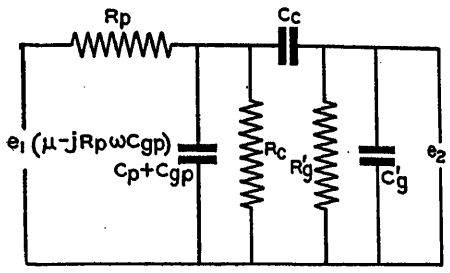


Figure 3

tions, however, the plate circuit of this tube is reflected back into its grid circuit through its grid-to-plate capacity. As a result the values of $R_g'$ and $C_g'$ vary with frequency.

I have calculated this effect for 2 types of tubes, the 6*F5* high-mu triode and the 6*J7* pentode, both of which are very commonly used in resistance-capacitance coupled amplifiers. A 6*F5*, with a one-megohm grid resistor, a 250,000-ohm plate-loading resistor, and total grid-to-cathode and plate-to-cathode capacities of 20 micromicrofarads including socket terminals and wiring, when used at 8,000 cycles, will have an effective input resistance of only 155,000 ohms and an effective input capacity of 162 micromicrofarads. In short, the effective input resistance is only 15.5 per cent of the one-megohm grid resistor, while the effective input capacity is 800 per cent of the grid-to-cathode capacity. At higher frequencies the error is even larger.

Even the 6*J7*, which has an extremely small grid-to-plate capacity (only 0.005 micromicrofarads), gives effective values of $R_g'$ and $C_g'$, respectively, of 0.99 megohm and 21.2 micromicrofarads. This represents an error of one per cent in resistance and 6 per cent in capacity. Here, too, the error would be greater for higher frequencies.

Mr. Seletzky's method is, nevertheless, a very valuable one. If care is used in its application, it should yield results of sufficient accuracy for most purposes with a minimum of effort. It will be especially useful in problems which involve phase shift.

**A. C. Seletzky:** Mr. Pollack in his discussion brings out several valuable comments on the design of resistance-capacitance coupled amplifiers. It should be noted, however, that throughout the entire paper, the angular velocity $\omega_1$ is treated as the scalar variable. *With respect to the scalar variable* $\omega$ the general equation for amplification as given by (2) remains a bicircular quartic, because it consists of the sum of 2 circles, which sum does not reduce to the canonical expression of the circle,

$$\frac{a + b\omega}{c + d\omega}$$

inasmuch as it involves higher powers of $\omega$, as may be seen from equation (2), namely

$$A = \frac{-jk\omega}{\omega^2 - jb\omega - c} \qquad (2)$$

In the author's opinion, the opening line of the paragraph in the paper following equation 6, "The variable scalar in the present case is the angular velocity . . . ." should make it reasonably clear that the variable scalar treated in the problem is the angular velocity.

Mr. Pollack throws the amplification equation into the form of a circle by changing the scalar variable from $\omega$ to

$$\omega - c/\omega$$

which is $(\omega^2 - c)/\omega$

and by this artifice considers the amplification to be circular in form. It is, but the scalar variable in the transformed equation is not the angular velocity $\omega$, but a new function of angular velocity, involving higher powers of $\omega$. Thus instead of using a linear scale line in units of $\omega$, Mr. Pollack is using a linear scale line in units of

$$(\omega^2 - c)/\omega$$

It should be evident, therefore, that Mr. Pollack, instead of contradicting any statements made in the paper, is merely introducing a new scalar variable of higher order. Thus the general equation of amplification may be considered to be either (a) a bicircular quartic, i.e., the sum of 2 circles, each component circle having a linear scale of $\omega$ or (b) a single circle with a linear scale in units of

$$(\omega^2 - c)/\omega$$

Mr. Pollack's modification of Mr. Luck's method applied to the single circle is very interesting and helpful. The author is gratified in observing the increasing use of the circle diagram to eliminate time-consuming computation. It is difficult to judge as to which particular method involves the minimum of time and effort. Generally speaking, however, it has been the experience of the author, that what is eliminated from the drawing board is merely transferred to the slide rule and tables of functions, and that best results are obtained from a judicious balance of the 2.

Mr. Rotkin's comments on the variation from linearity of the general circuit are greatly appreciated. This paper was written on the basis that the "exact" equivalent circuit as shown in figure 1, was sufficiently exact to be valid for the great majority of resistance-capacitance coupled amplifiers, and Mr. Rotkin concurs with this viewpoint in the closing paragraph of his discussion. Designers encountering the somewhat special conditions described by Mr. Rotkin should be guided by his observations. The author hopes that Mr. Rotkin will formulate the proper expressions of circuit coefficients, expressed as functions of the frequency, and incorporate them into a general method of determination of amplification loci.

## Development of a Modern Watt-Hour Meter

**Discussion and authors' closure of a paper by I. F. Kinnard and H. E. Trekell published in the January 1937 issue, pages 172–9, and presented for oral discussion at the instruments and measurements session of the winter convention, New York, N. Y., January 28, 1937.**

**Stanley Green** (Duncan Electric Manufacturing Co., Lafayette, Ind.): Performance of the new meter described in this paper is better than has been considered acceptable previously and the fact that it is now proposed indicates that there may be a demand for it by the utility users of meters. In general, such improved characteristics in a meter will cost more to manufacture—but not much more. The idea has been advanced by some utilities that by concentrating production in one size, this small cost increment can be overcome. Under these conditions, the low-capacity type would become rare and production would be concentrated in only 2 sizes, domestic and commercial, with the former greatly predominating. This view appears constructive and even if the future domestic meter were increased in cost slightly, the increased range could be worth it to the utilities, not only from simplification of operations but because it will give ample margin for the vitally important load building activities of the future.

The authors have accurately expressed the elementary design limitations in equations 1, 2, and 3 and the discussion relating thereto. On these, most designers should be in agreement. Unfortunately, space available has apparently not permitted a more detailed exposition of subsidiary design factors and their interrelationships, although some of these are mentioned by the authors. Relative gap lengths and proportions, pole configurations and proximity, relative flux density in interrelated parts and characteristic curves of the magnetic material entering into parts of the structure all so complicate the problem that many solutions instead of only one unique one are possible. This is where the skill and judgment of the designer are utilized and if it were not for this, there could be only one good meter design. Instead, there have always been many designs and generally each is a little better than its predecessors. A paper such as the present one is useful in a high degree as it supplies still another step in that stimulating chain of advances which is ever-lengthening because of changing requirements in the electrical industry.

The short mean length of potential-coil turn mentioned by the authors is a useful expedient. The recognition that load compensation is necessary to give linear performance at the heavy-load end of the registration curve is constructive. Better methods of controlling this form of compensation have been developing in the last few years and precision load compensation in any reasonable amount can now be obtained by several forms of compensators all working on the same "saturable bridge" principle. It has been recognized by designers for some time that the load compensator modifies the shape of the registration curve at light loads and I think we can look for continued beneficial effects from the compensator on this end of the curve in future designs.

In modifying the design of a given meter to meet the new long-range performance more than one path can be taken. It would be interesting to describe more than one avenue, but for brevity and clearness, I mention only one simple scheme:

In a paper in the October 1935, issue of ELECTRICAL ENGINEERING, I described a new watt-hour meter which has been manufactured in 5-, 15-, and 50-ampere nominal ratings. The 3 ratings in this meter could be modified easily to duplicate the new performance now proposed. In this modification the 15-ampere rating would become

the "domestic" meter. Its torque would be raised from 46 to 62.8 by increasing the potential-element ampere-turns. This would give the same torque at 12.5 amperes as the new watt-hour meter and would, of course, allow the same light-load performance as such performance is basically a function of torque available. The increased potential excitation would be accomplished at the expense of raising the potential watts loss from 0.9 watt to about 1.25 or the same as the meter of the paper under discussion. The increased ratio of potential to current flux makes it easy to compensate the modified meter so that the performance is straight line to 400 per cent load or 60 amperes since before modification the droop at this point was only 1.5 per cent. Increasing current-coil copper and providing a stronger damping magnet are details easily accomplished.

Since a stronger damping magnet would be used, the watt-hour constant would not be changed and for the 15-ampere 2-wire "domestic" meter would be one, which is also a desirable constant for use with all types of rotating standards now in use.

**H. B. Brooks** (National Bureau of Standards, Washington, D. C.): The papers by Kinnard, Goss, and Trekell are gratifying examples of the modern trend away from the old policy of secrecy. If the design of electrical measuring devices is to progress as it should, designers must be allowed a reasonable degree of freedom to publish the principles which guide them, the results of their experimental studies, and the particular structures which form the end result of their work. It is to be hoped that those who control the policies to which the designing engineer must conform will discern the advantages which will accrue to all concerned as a result of such co-operation in the advancement of the art.

Referring to the analysis chart, table I of Kinnard and Trekell's paper, I suggest that it would be interesting to have for comparison the corresponding figures for the meters now being produced by the other American manufacturers. Most of the data for one of these other meters was given in Mr. Green's paper in volume 54 of the TRANSACTIONS.

The suggestion of Kinnard and Trekell that modern watt-hour meters should be rated in terms of the nominal and the maximum current rating deserves consideration with a view to general adoption. The retention of the present nominal rating (i.e., 5 amperes for a meter with a maximum continuous rating of 15 or 20 amperes) is a necessity for calibration and comparison purposes for the present and for the immediate future. The straight-line accuracy characteristics over a large portion of the load curve raises an interesting question in regard to what shall be eventually taken as the nominal test point. If individual treatment of meters were practicable, the average load of the installation would be the logical one at which tests and adjustments would be made. Since this is not feasible, and since tests of modern meters at the maximum current would require that the testers should carry larger and heavier equipment, it seems logical to adopt the present values of calibrating current for the new meters.

Table II of Kinnard and Trekell's paper does not include a meter of 2.5 amperes nominal, 7.5 amperes maximum rating. This meter would differ from the authors' "low-capacity" meter only in having 20 turns on each current pole, and would be preferable to the nominal 5-ampere meter for use in connection with current transformers. I understand that meters of 2.5 amperes nominal rating are being used for this purpose. It seems advisable to recognize this formally as a fourth standard rating.

**F. C. Holtz** (Sangamo Electric Company, Springfield, Ill.): The authors are to be complimented on their very clear and concise presentation of a subject which, while fairly clear to the designer of watt-hour meters, may not have been fully appreciated by the user.

By a careful and systematic analysis it has been possible to greatly extend the useful range of a meter by the introduction of various types of compensating means. In this way the manufacturer has kept pace with the increased demand of the user until now it seems possible that we may be able to further limit the number of types or capacities required for a more diversified application.

From a manufacturing standpoint, I believe we agree with the choice of ampere-turns which will simplify our problems. In doing so, however, it should be on a basis which fully recognizes the requirements of the user as to convenience of testing and the use of testing equipment.

I doubt if the time is right for us to forget meter ratings in volts and amperes and merely refer to them as "domestic," "commercial" or other meters.

There is also some question as to the advisability of changing ampere rating from the series toward which the industry has been striving. This may be of no great importance or it may readily be modified by advancements which as in this case would definitely tend toward the elimination of one or more of the present types. The advantages in this case would lie in simplification of stocks which is a great benefit to producer and user alike.

In the present instance we may find ourselves in a dilemma. If the author's meter were to be rated at 15 amperes and given a watt-hour constant of 1.5, this would not agree as to constant with existing meters of similar manufacture. If it is given a rating of $12^1/_2$ amperes with the same constant, then the capacity is out of line with the present accepted standards. Of these 2 the choice should probably rest with the change in capacity in order that the constants may remain in line with present practice.

**E. D. Kane** (The Detroit Edison Company, Detroit, Mich): This paper is a worthy contribution to the art of metering, in that it presents a comprehensive discussion of the elements affecting watt-hour meter design. The watt-hour meter holds a unique position as an instrument for measuring a quantity from which revenue is derived because it is subjected to so many variable factors as a result of its operating location in the field. Also, the accuracy requirements must be more stringent than other forms of commercial measuring apparatus, with a minimum amount of attention.

Perhaps the nature of the problem and its importance has acted as an incentive for improvement in the art, so that now the most scientific methods of design and analysis are employed together with pure scientific research to determine the underlying theories of operation.

The contents of this paper graphically illustrates this fact and the treatment of analysis deserves special mention. Table I may well serve as a criterion for meter acceptance with perhaps some other constants added. Such a table allows uniform presentation of the data in a concise practical style. The determination of meter constants to establish performance characteristics might reduce the labor in making acceptance tests and reduce operating parameters to a more equal basis. Information concerning additional factors may prove desirable. Suggestions from designers as to the best parameter which could be used as a relative index of over-all performance would be interesting. No doubt such a value will be found in the future as the investigations are carried further into the problem to which this investigation has contributed so much.

It is to be hoped that the bibliography of meter research will continue to grow and the literature will be as productive of progress as that of other scientific and engineering fields.

The proposed rating discussed for new watt-hour meters appears to offer considerable advantage as is pointed out in the paper, namely;

(*a*). Reduced stock of meters and parts
(*b*). Meets field requirements to better advantage
(*c*). Offers improved standardization in test methods

The question of the test constant value of the "long range" domestic, namely; 1.5, may cause confusion but that condition can be easily overcome by proper run selection.

**I. F. Kinnard and H. E. Trekell:** Doctor Brooks has suggested that the 3 self-contained ratings be augmented by a meter of 2.5 ampere nominal current rating for use with instrument transformers. With a 5-ampere-secondary current transformer, the use of a 2.5-ampere meter provides greater insurance of accuracy of registration, especially at light loads, since the meter works at double torque. From a thermal standpoint, current transformers will not operate continuously at loads above 7.5 amperes in the secondary winding. A 2.5-ampere meter is the best choice for the actual operating range of the transformer. The burden of the current circuit of a watt-hour meter is sufficiently low that the increased burden of the 2.5-ampere meter is usually not objectionable.

Mr. Green has proposed an interesting modification of a present meter design. However, it has been found from experience that a small inherent error can be compensated much easier than a large error. Furthermore, due to variations in materials and manufacturing tolerances, attempts to compensate large, inherent errors usually result in considerable variations in the performance of the device.

As pointed out in the paper, any design

can be readily analyzed and its merit judged by a tabulation of data as shown in table I, page 178. It would be interesting, as suggested by Doctor Brooks, to give complete data of this nature for suggested alternate designs.

While it is true, as Mr. Holtz points out, that when rated in accordance with present established constants the "domestic" meter described is in reality a 12.5-ampere size, yet it might be called a 15-ampere meter. In this event, however, the relation between watt-hour constant and ampere rating is different from any established standard. If this is done in order to meet present rating classifications, the inherent, nominal full load of 12.5 amperes should also appear on the nameplate to prevent confusion.

Mr. Kane's discussion is very much to the point, and as he points out, meter design and operating constants can be rationalized and guided by scientific analysis.

# Impulse-Generator Voltage Charts for Selecting Circuit Constants

**Discussion and author's closure of a paper by J. L. Thomason published in the January 1937 issue, pages 183–9, and presented for oral discussion at the instruments and measurements session of the winter convention, New York, N. Y., January 28, 1937.**

**C. F. Harding** (Purdue University, Lafayette, Ind.): This paper provides a much-needed rapid method of adequately determining and standardizing surge test results as they are undertaken in the various laboratories wherein some difficulties have been experienced in the past in securing comparable data. Demands on the part of prospective customers for surge tests to be made in independent laboratories are becoming more numerous and therefore any developments, such as are outlined in this paper, looking toward the co-ordination of results obtained from surge generators of varying capacitance and discharge constants represent a distinct contribution to the pioneer work of our profession.

In the accompanying discussion, which I shall present with my endorsement, from Mr. C. S. Sprague, who is in charge of the surge testing of our high-voltage laboratory at Purdue University, a further simplification of the standard calculations of the paper which are applicable to the frequently used $1^1/_2$x40 wave will be evident.

**J. H. Hagenguth** (General Electric Company, Pittsfield, Mass.): Mr. Thomason has presented a paper which should prove very useful in laboratories where impulse work is being done. Especially in those laboratories, where cathode-ray oscillographs are not available the charts and curves presented should save considerable time as compared to the more laborious methods of actual calculations to obtain accurate information of the wave shape used for a particular impulse circuit.

Where accuracy required is within ±5 per cent of actual values some rather simple

**Table I**

| Constant | By Test | By Chart | By Equations |
|---|---|---|---|
| $K_1$ | 0.30 | 0.30 | 0.30 |
| $K_2$ | 0.057 | 0.057 | 0.057 |
| Front (microseconds) | 1.9 | 1.9 | 1.88 |
| Duration (microseconds) | 40 | 39 | 37.7 |
| Crest (per cent) | 72 | 71 | 73.2 |
| $K_1$ | 0.128 | 0.128 | 0.128 |
| $K_2$ | 0.073 | 0.073 | 0.073 |
| Front (microseconds) | 1.4 | 1.5 | 1.35 |
| Duration (microseconds) | 44 | 44 | 43.3 |
| Crest (per cent) | 81 | 80 | 82.5 |

equations are available as follows using the same notations as the paper:

$$\text{Wave front: } 3R_1C = 3R_1C_2\frac{1}{1 + C_2/C_1} \quad (1)$$

$$\text{Wave duration: } 0.697(R_1 + R_2) \times (C_1 + C_2) = 0.697R_2C_1(1 + R_1/R_2) \times (1 + C_2/C_1) \quad (2)$$

$$E/E_0 = \frac{1}{1 + R_1/R_2}\,\frac{1}{1 + C_2/C_1} \quad (3)$$

These equations yield remarkably good results if $R_1$ is equal to the critical resistance as explained in the paper.

Applying these equations to the 2 examples presented the values of table I are obtained.

It can be seen that the equations give numerical values which check closely the test results and the values obtained by means of the charts. Often it is desired to have a higher crest than that obtained with the circuit of figure 2 but maintaining the same wave duration. In such a case it is an advantage to insert another resistance $R_3$ from the junction of $C_1$ and $R_1$ to ground. In that case the equations 1 and 3 remain unchanged, while the equation 2 changes to

$$\text{Wave tail: } 0.697R(C_1 + C_2)$$

where

$$R = \frac{(R_1 + R_2)R_3}{R_1 + R_2 + R_3} \quad (4)$$

For transformer testing more complicated charts would have to be used to take care of the inductance to ground of the transformer. It is also relatively difficult to determine the impulse capacitance of the transformer winding, which with any additional load capacitance determines the wave front. Although these voltages, wave fronts, etc., can be calculated, it would be a rather time consuming task to do so, when a large number of transformers have to be tested. Fortunately the electrical transient analyzer is available, with which the circuit constants required for any particular transformer can be determined rapidly and accurately.

**C. S. Sprague** (Purdue University, Lafayette, Ind.): Although the use of charts and curves for quickly determining the impulse generator constants for producing a specified wave is not new, the author, by the use of *ratios* of circuit constants, and of wave front and duration times, presents a method whereby the circuit constants may be determined for producing practically *any* wave shape, or conversely the wave shape produced by a given set of constants may be determined.

For a wave, such as the $1^1/_2$x40, which is in sufficiently general use to warrant the procedure, the use of the curves can be considerably simplified by plotting, in figures 4*b* and 4*B*, $K_1$ *vs.* $K_2$ for the constant value of $t_1/t_2$ representing the $1^1/_2$x40 wave. Likewise in figures 4*a* and 4*A*, the value of $C_1R_2$ may be plotted against $K_2$ for the particular wave front time $t_1 = 1^1/_2$ microseconds. This procedure would reduce figures 4*a*, 4*A*, 4*b*, and 4*B* to a single curve each, and avoid interpolation between a family of logarithmically spaced curves on a logarithmic scale. In the more general nature of the data as presented by the author, these simplifications could not be obtained; however, it might be well to indicate the advantages to a particular laboratory of limiting the variables to those representing conditions in that laboratory.

The author indicates the growing need for specification not only of the time constants of the impulse but also of the circuit constants of the generator producing the impulse.

The above seem to be the principal contributions of this paper.

As is well known a particular wave shape can be obtained from a variety of circuit constants. However, the actual test results obtained, particularly in flashover tests of equipment having considerable time lag, will depend upon the series impedance or the rate at which energy can be supplied to the test piece. This is particularly true at short flashover times or flashover on the rising front and is a further argument for specifying, at least the permissible range, of the generator constants.

On page 185 under circuit II, the author calculates a necessary inductance of 58 microhenrys and states that if this value cannot be obtained, or if the actual $L_1$ = 40 microhenrys, that the values of $R_1$ and $R_2$ can be adjusted on a straight line basis. Will not this change the duration of the wave? Why not add 18 microhenrys to obtain the calculated value of 58 microhenrys? Theoretically the limitation on $L_1$ is the minimum value of the inherent self inductance of the generator circuit.

In chart II the author states (page 5) that

$$L_1 = \frac{R_1^2C}{4}$$

or in other words

$$R_1^2 = \frac{4L}{C}$$

so that oscillations of the generator inductance and the effective series capacitance cannot occur. Three values of $W$ are denoted by asterisks as indicating real roots, presumably meaning a unidirectional impulse, which the author designates (page 6) as a "smooth wave." Are all other waves oscillatory, and if so, cannot a damped oscillatory wave be smooth? From the conditions

$$L_1 = \frac{R_1^2 C}{4}$$

superimposed oscillations could not occur. Perhaps the author's definition of a "smooth wave" might clear up this point.

On page 188 a value of 1.4 microseconds is given for the wave front as determined from the oscillogram of figure 7. With the slow sweep used in figure 7 the accuracy of determination of the wave front time seems somewhat questionable.

**P. L. Bellaschi** (Westinghouse Electric & Manufacturing Company, Sharon, Pa.): The impulse generator came into engineering prominence about 5 years ago. At that time the basic circuits and generator characteristics when testing electrical apparatus were analyzed and carefully studied.[1] Since then the literature on the subject has grown both here and abroad.[2] Some of these contributions relate to the experience acquired, others pertain to further refinements in the analysis or method of calculation.

The present paper is of a character that should be helpful in reducing labor where charts similar to those in figure 4 may not be available. The calculation of these or similar charts is based on circuit analysis, on methods where terms are expressed as ratios between similar circuit constants and on plotting the results conveniently and effectively in terms of the time constants of the circuit—all of these having been developed and applied some 5 years ago. The usefulness of such methods is well demonstrated in the present paper.

Reference is made by Mr. Thomason that the circuit diagram of figure 2 has been recommended as basic by the International Electrotechnical Commission. This statement should not be misconstrued perhaps to the effect that this circuit represents all circuit conditions encountered in present-day testing. For example, this is not necessarily the basic circuit when testing transformers for such apparatus may introduce other elements into the circuit, such as low inductance to ground, substantial energy drain from the generator into the transformer circuit proper and also into the circuit from which the transformer may be excited at normal-frequency voltage. A consideration of the work by the IEC covered in the report in question will bring to light that this circuit representation is really intended, when such loads as insulators, gaps, bushings, and similar equipment are connected to the generator.

A good number of impulse generators have come into existence both in this country and in Europe since 1932. These generators have for the greater part been built to generate a smooth impulse voltage of a 1½x40-microsecond duration or thereabout. When we compare for example the half-a-dozen impulse generators built hereto for 3 million volts, particularly those for testing equipment of relatively large capacitance, we find that the generator capacitance, the self-inductance, the stray capacitance, the damping resistance, and the load resistance for each generator are respectively of the same order of magnitude as the corresponding constants of the other generators. Thus in practice for a given voltage rating of the generator the part of the circuit charts, such as in figure 4 of the paper, which would be used is rather localized. Considering the various voltage ratings of generators even then only certain "practical" regions in the charts would really be used.

REFERENCES

1. CHARACTERISTICS OF SURGE GENERATORS FOR TRANSFORMER TESTING, P. L. Bellaschi. AIEE TRANSACTIONS, volume 51, December 1932, pages 936–951.

2. In addition to the works by P. L. Bellaschi, J. L. Thomason, and C. S. Sprague presented to the AIEE, there have been contributions elsewhere in recent years by Roys (Purdue University), Lewis (Bureau of Standards), Angelini (Italy), Goodlet (England), Elsner (Germany), and others both in this country and abroad.

**J. L. Thomason:** In their discussions of this paper Dr. C. F. Harding, and Messrs. C. S. Sprague, J. H. Hagenguth, and P. L. Bellaschi have extended the art of impulse-voltage testing by adding new and qualifying information.

Mr. Sprague has asked for the author's definition of a smooth wave. It can be stated thus: "In impulse testing the voltage wave applied to the test piece will be considered smooth and when its mathematical expression for a circuit of five constants (figure 2 in paper) takes the form

$$e = Ae^{-at} + Be^{-bt} + Ce^{-ct}$$

and conversely the voltage wave will be considered oscillatory when its mathematical expression takes the form

$$e = Me^{-mt} + Ne^{-nt}(\cos \omega t + Q \sin \omega t),$$

where all the symbols are constants except $e$ and $t$. While the smooth-wave form of the equation could express a wave that would cross the zero-voltage axis, this does not usually occur in a circuit of 5 constants (figure 2 in paper) for ordinary values of the circuit constants." This definition of a smooth wave was used in the paper. For practical purposes the wave could be considered smooth even though the part

$$Ne^{-nt}(\cos \omega t + Q \sin \omega t)$$

in the oscillatory form amounts to one per cent or more of the voltage at its crest. This idea also was used in the paper to allow for the rigorous use of the relation

$$L_1 = R_1^2 C/4$$

because even when using this relation the oscillatory form of impulse-voltage test wave does generally result as indicated in the paper. This also falls in line with Mr. Sprague's thought of increasing the inductance to the value of $L_1$ demanded by this relation. In general this is a good idea but normally increasing $L_1$ increases the wave front, and depending upon the wave shape desired, it might be better to juggle the values of $R_1$ and $R_2$—this gives a minimum wave front with a maximum economical crest for a practically smooth wave.

There is one idea in this paper that I believe should be emphasized again and that is this: Considering the mathematical expression of the voltage wave applied to the test piece, as long as the ratios $K_1$ and $K_2$ are constant and

$$L_1 = R_1^2 C/4$$

all test waves will be identical throughout.

Mr. Hagenguth has presented some very useful approximate equations and has shown their accuracy with examples. Such equations should be very helpful in reducing the time required to select circuit constants. Mr. Hagenguth has also referred to the usefulness of the electrical transient analyzer[1] which is a valuable adjunct to any laboratory doing impulse work.

Mr. Bellaschi has brought out a point which may have been overlooked in the paper by some readers—that is, that figure 2 in the paper is for only a capacitance load. In his discussion Mr. Bellaschi apparently overlooked the fact that the original investigators, Steinmetz and Peek, had analyzed the behavior of the impulse generator considerably earlier than 5 years ago.

Dr. Harding has indicated the need of co-ordinating the data obtained in various impulse-voltage laboratories and to this I will add that there is the ever present need of reducing the time and cost of making tests.

REFERENCES

1. THE OSCILLOGRAPH ELECTRIC TRANSIENT ANALYZER, N. Rohats. *General Electric Review*, volume 39, March 1936, pages 146–0.

## Short-Time Spark-Over of Gaps

**Discussion and author's closure of a paper by J. H. Hagenguth published in the January 1937 issue, pages 67–76, and presented for oral discussion at the instruments and measurements session of the winter convention, New York, N. Y., January 28, 1937.**

**C. S. Sprague** (Purdue University, Lafayette, Ind.): The shielded resistance divider described by the author seems to be the first real attempt to make this type of divider suitable for fast fronts and very short times. With regard to this divider the writer wishes to ask what length of resistance wire is used to obtain the 7,000 ohms employed in the divider. The voltage applied to the entering end of the cable arises, in part, from the current flowing through the resistor, and in part from the induced charges due to the shielding and ground capacitances. With very steep waves the latter must form a reasonable percentage of the total, especially on the rising wave front; if not, then there would be no need for shielding. That portion of the voltage at the entering end of the cable, arising from the capacitance effects, is presumably applied simultaneously with the rising voltage at the top end of the divider, while that portion resulting from the surge current flowing

through the resistance is not applied until the wave has traveled over the length of resistance wire between the top end of the divider and the cable connection. There is also the fact that the induced charges are continually leaking to ground during the short interval before the current wave has traversed the entire length of the resistance wire. The argument becomes complicated and will be carried no farther, however, it seems remarkable that the resistance dividers when used for such fast fronts are as satisfactory as they are stated to be.

With reference to the author's figures 4*a* and *b* the writer agrees with the author as to the elimination of $L_g$ in so far as possible. However, where some $L_g$ must be tolerated, it appears that the impulse generator and oscillograph grounds could be made to the circuit at the lower end of $R_d$, providing the voltage drop across $L_g$ was not too high so as to damage charging equipment, etc.

For some time the writer has contended that short-time flashover and breakdown values are considerably affected by the amount of series resistance and inductance in the generator circuit. It is gratifying to have this confirmed in the author's figure 5 and thus lend further support to the suggestion that surge generator constants, or at least their range, should be specified as well as the wave shape.

**K. B. McEachron** (General Electric Company, Pittsfield, Mass.): There appears to be a real need for a high-voltage divider, to be used in laboratories where impulse testing is carried on, which will successfully reproduce steep-fronted waves and still be compact in design and uninfluenced by surrounding fields. Such a divider Mr. Hagenguth has described, and should prove to be very useful indeed. Additional tests are of course necessary in connection with this divider, so that all of its uses are completely understood, but the data presented by Mr. Hagenguth appeared to indicate quite clearly that it gives results which may be relied upon. It is, of course, unfortunate that no standards exist in this field of measurement when times shorter than a microsecond or so to breakdown are considered.

I hope that this paper will not be interpreted in any sense as being intended to propose steeper and still steeper waves for impulse testing of apparatus. From my experience relating to surges due to natural lightning, either at the point of inception or elsewhere, there seems as yet to be no indication that waves having an over-all steepness much in excess of 1,000 kv per microsecond need be considered.

It is true that much of our information along this line is deductive and based to a considerable degree upon the effects observed of direct strokes on apparatus and structures of one sort or another. These observations are, of course, coupled with results of tests made in the laboratory where wave shapes are known, and there does not seem at this time much justification for further increase in the rate of rise of test impulse waves.

From the point of view, however, of being certain of the accuracy of the results for the steepness of waves expected in practice, it is quite desirable that our measuring equipment be so designed and operated that measurements can be taken at rates of rise considerably in excess of those expected. These additional data points will lend support to the accuracy of those points within the expected lightning range, and help to appreciably increase our confidence in the results obtained. It would seem, therefore, in the absence of data to indicate these ultrasteep waves, that we would do well to confine our co-ordination studies to waves not exceeding 1,000 kv per microsecond at least, until such time as field data indicate that still steeper waves are to be encountered in practice.

There is one situation in which waves may appear whose steepness compares with that found in the laboratory, and this is the case of flashover between one conductor and another where the time to breakdown would be of the same order as observed in the laboratory for the same distances.

In Mr. Hagenguth's paper, mention is made of the difficulties involved in describing the front of the wave in those cases where sufficient prespark-over current is drawn to cause the applied voltage wave to depart from its normal expected rise. It seems to me that the best answer to this situation, from the point of view of the testing laboratory, is to so proportion impulse-generator capacitances, and load capacitances and series resistance that this turning over characteristic will be so small as to be negligible. If this result can be obtained, then the kilovolts at breakdown divided by the time to breakdown would give a correct rate of voltage rise, assuming of course that the zero of time was determined by the intersection of the line drawn through the 10 and 90 per cent point on the front of the wave and its intersection with the time axis. To get such a rate of rise with a sharp breakdown when testing on the front of the wave may require some modification in some of the impulse generators now in use, but it certainly would prevent considerable confusion with respect to the meaning of the data obtained.

**H. L. Rorden and P. M. Ross** (Ohio Brass Company, Barberton, Ohio): In surge-voltage testing, the accuracy of recorded waves and voltage calibration has been the object of much discussion and question. The voltage divider is a necessary part of surge testing and its accuracy might well be questioned, since with high voltages an accurate means of calibration or check is lacking. When the new laboratory of the Ohio Brass Company was put into operation in 1934, one of the major items of consideration in the design of the surge generator was to obtain an electrostatic field which, inherent to the design, would be substantially uniform throughout the height of the generator, illustrated in figure 1. The divider is placed in the field adjacent to the generator structure, which is built in the form of a helix. In each revolution of the helix a capacitor is close to the divider and maintains a voltage proportional to its physical height above ground. This results in a uniform voltage distribution throughout the length of the divider and is a desired condition for accurate reproduction at the oscillograph.

At the several available junctions of the divider the potential differs by less than 3 per cent from a uniform distribution. For further check, volt-time characteristics of

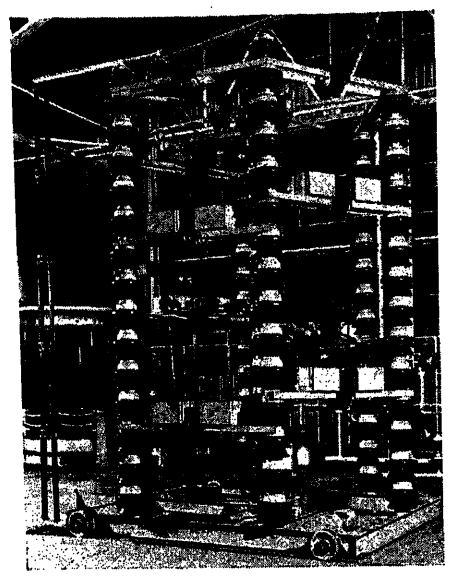


**Figure 1. The Ohio Brass Company surge generator**

spheres were obtained, the results of which are in close agreement in the $^1/_4$-microsecond region with Mr. Hagenguth's figure 15.

In many of its features this generator fits the description suggested by Mr. McEachron in his discussion as being desirable. Due to the helical design it is compact; it has a substantially uniform voltage distribution; the entire generator including the divider is portable. The divider and other circuit resistors are enclosed in porcelain, also the supporting insulation is porcelain. The generator may be used outdoors without damage in the event of inclement weather.

In his figure 5 showing the change of wave shape with a change in circuit constants, we believe Mr. Hagenguth has touched upon an item which should receive serious consideration in setting up standards of surge testing. Other investigators directly familiar with surge testing have undoubtedly observed this phenomenon. It seems very evident that considerable energy is required to charge corona and ionization streamers prior to complete breakdown. Insertion of damping resistors in surge generators is very necessary, since otherwise it seems impossible to obtain uniform waves. The damping resistance so limits the available energy at the test that prior to breakdown the voltage across a gap falls appreciably from that of its normal wave shape. This becomes increasingly greater with overvoltages and appears to be present in all cases where flashover is dependent upon the completion of corona streamers.

An outstanding example of the inability of surge generators to maintain their wave shape before spark-over is illustrated in figure 2. This illustration, with additions, is reproduced from the March 1936 *Journal* of the British IEE. The limitations mentioned are very evident. It may be observed that the final flashover of the overvoltages occurs below the wave of the minimum flashover. These authors have proposed to set up British standards of testing on the basis of their results, which would seem to be of questionable accuracy.

We have also noticed this phenomenon to be present, although to somewhat lesser degree, if the damping resistance is removed. Also it is greater with generators of low energy, such as were used by early investigators when the so-called 1x5 wave was proposed as a standard for testing. It is now generally recognized that with the

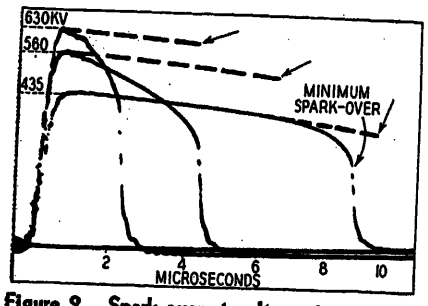



**Figure 2. Spark-over at voltages in excess of minimum impulse spark-over**

generators of higher energy in use, the 1x5 wave so limits the available energy and voltage for test, due to the necessary high damping resistance, that it is undesirable for test purposes. This wave was readily obtained in generators of low energy but imposes a serious handicap on present methods.

Surge testing is complicated by several such limitations and we wish to stress the importance of this point which Mr. Hagenguth has touched upon.

**P. L. Bellaschi** (Westinghouse Electric & Manufacturing Company, Sharon, Pa.): The paper by J. H. Hagenguth is a further contribution on the short-time spark-over of gaps and to the technique in obtaining such data. In attempting to compare his results to data published in the past few years, the first question which arises is one on method of scaling oscillograms and plotting data.

It has been and is the common practice in testing with impulse voltages chopped on the front to specify the steepness of the front in kilovolts per microsecond and the crest voltage. In table I the results from typical oscillograms are given. In the first column the steepness of the front is determined according to established definition, that is drawing the line of the slope through the 2 points on the oscillograms at 10 per cent and 90 per cent the crest value. Circuit conditions present in practical testing often result in some superimposed oscillations on and distortion of the main component of the rising front. Some judgment is necessary in applying the 10 per cent–90 per cent definition and this is best done scaling the steepness of the front along the major component. The second column of table I gives the values determined from the application of this practical method. It shows that the results in general are in substantial agreement with those applying the 10 per cent–90 per cent rule. In the third column the time-to-breakdown has been employed to calculate the rate of voltage rise (average). It is apparent that the results from this third method are not in general comparable to those from the first 2 methods.

The values in column 3 are 10 to 20 per cent lower than those in column 2. Considering the different methods, it will be seen that the data for the rod gaps in figure 9 (by the author) are in better agreement with the previously published data (ELECTRICAL ENGINEERING, June 1934, page 870 and ELECTRICAL ENGINEERING, September 1936, page 985) than it may appear from a superficial comparison. The data in the paper and those reported by the writer for bushings, insulators, and similar equipment

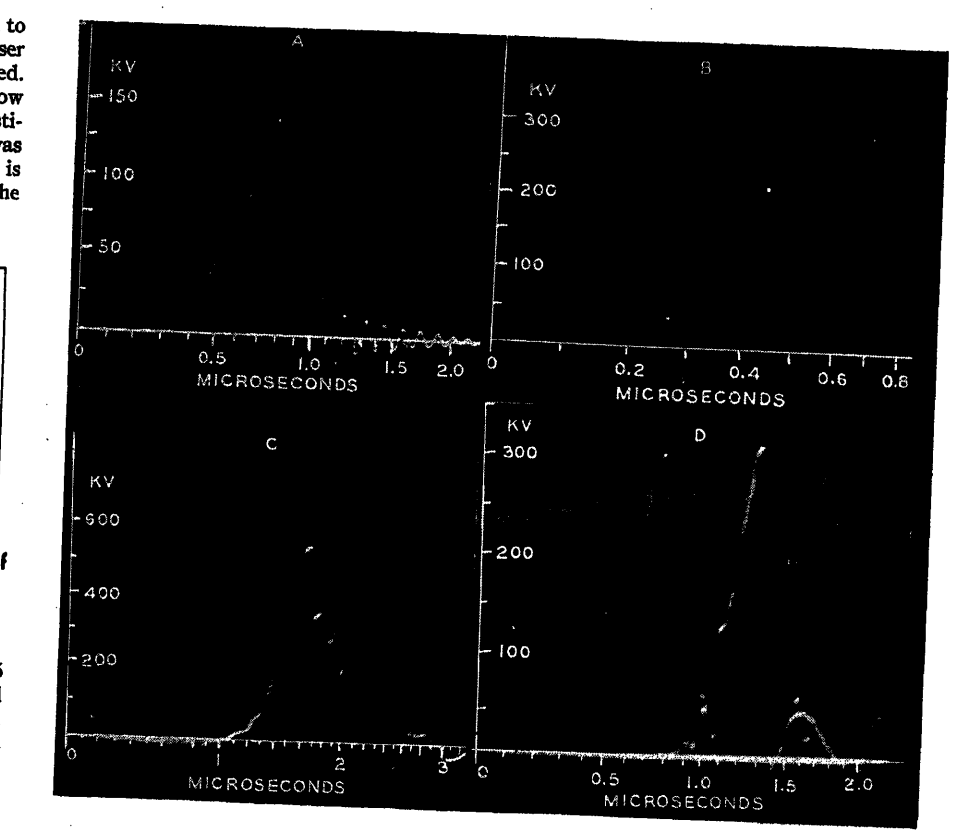



**Figure 4**

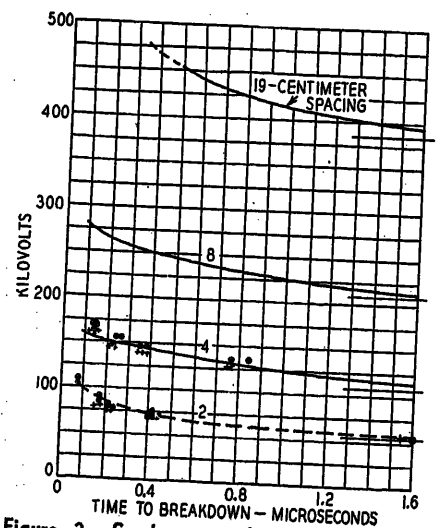



**Figure 3. Spark-over voltage of 25-centimeter sphere gap on positive impulse**

Crosses represent resistance-divider measurements (recent data)

Circled crosses represent capacitance-divider measurements (recent data)

Curves in solid lines are from figure 6 of "Sphere Gap Characteristics on Very Short Impulses," *Electric Journal*, volume 32, March 1935, page 120

(*Electric Journal*, June 1936, page 274) are substantially in the same order considering the character of the tests. It would have been well had the author called attention that his data for solid and for the combined solid and liquid insulation applies for single or a limited application of tests.

Table II gives data for rod gaps which were taken recently in the course of ordinary tests. These data have been scaled according to the established technique (method in column 2 of table I) from such oscillograms as *C* and *D* of figure 4. A comparison of these sample data with those first presented to the AIEE (ELECTRICAL ENGINEERING, June 1934, page 874, figure 6) shows adequate agreement from a practical standpoint. This shows that the methods and technique used can give practically good results. In this connection it is well to note that departures from the average of some ±10 per cent for the voltage and about ±20 per cent for the rate of rise are to be expected and such variations should be considered permissible at the present. That these and even greater variations are present and inherent in work of this kind will be evident also from a close study of the data in figure 8 of the paper. The smoothness of this curve at the short times is more apparent than real.

There are a number of points which come to the attention in studying this paper:

(*a*). According to the author, the method of measuring steepness in terms of time to breakdown comes into the picture because of the flattening effect on the crest of the wave when a high series resistance (2,000 ohms) is used in the generator. Judging from the experience in a good many laboratories the series resistance more commonly used is about 400 to 500 ohms. Besides, as the author suggests, this resistance could

be removed partially or altogether to get the steep fronts when the load is of high capacitance. Because of this the flattening effect would not be expected in any great amount in the more common test arrangements.

(*b*). While the steeper fronts are obtained by the removal of the series resistance there are disadvantages entailed from this practice. For example, it is often convenient or desirable to have an identical setup of the generator to test the same gap or apparatus with either the $1^1/_2$x40 microsecond wave or a steep-fronted impulse. Another disadvantage would be that the effects of leads are accentuated upon complete removal of the series resistance.

(*c*). The scheme in figure 4 (*b*) of the author in attempting to reduce the effect of voltage drops in the ground discharge circuit has been recognized. There are physical limitations to the degree this method can actually be applied. There are other possibilities and approaches possible to minimize the ground effects such as the following. Good results are obtained keeping the cable of the divider away from the discharge circuit or insulating it from ground. It should also be possible to ground at the test piece and connect this grounded end directly to the generator by means of cables so as to confine the discharge currents in a definite known path.

The data on the short-time spark-over of the 25-centimeter sphere gap in figure 15 of the paper are substantially in disagreement with the results obtained by the writer and W. L. Teague from tests on this size of sphere gap at exactly the same spacings (*Electric Journal*, March 1935, page 120). For example the data for 4-centimeter spacing at a time to breakdown of 0.2 microsecond is 40 per cent higher in figure 15 than in the corresponding data plotted essentially on the same basis which appears in figure 6 on page 122 of *Electric Journal*, March 1935.

Since taking the data in the *Electric Journal*, check tests have been made from time to time with substantially good agreement. Recently a series of check tests have been made in a different laboratory from the one where the original data were taken. Results of these tests for the 2- and 4-centimeter spacings are plotted in figure 3. Approximately half the measurements were recorded at the cathode-ray oscillograph with the resistance divider having a resistance of 3,300 ohms and with a short cable (surge impedance equals 44 ohms). The other half of the tests were recorded with a capacitance divider. Figure 5 shows the test and measuring setup. Oscillograms recorded are given in figure 4 (*A* and *B*). A study of these data leads to the conclusion that the 2 dividers are in good agreement. It further shows that the use of these 2 methods of measurement has the great advantages of confirming results and establishing confidence in measurement.

At the same time these check tests were made on the 25-centimeter sphere gaps data were taken also on the 12.5-centimeter sphere gap for spacings of one centimeter, 2 centimeters and 3 centimeters (plotted on figure 6). On this same figure are also plotted data obtained by A. K. Nutall (*Journal* Institution of Electrical Engineers, February 1936, page 229) on the 12.5-centimeter sphere gap for these same spacings by means of a cathode-ray oscillograph of such construction that the measurements are directly recorded at the oscillograph plates. The agreement between data obtained from the 3 methods of measurement (figure 6) is amply close for all practical purposes. Because of this good agreement there are good reasons to question the data of figure 15 in Hagenguth's paper.

In conclusion it is gratifying to note the progress that has been made possible through the application of the resistance divider. The resistance divider has come into wider use in the past few years and in greater favor. A good number of laboratories in the country are now also using the capacitance divider. Experience has shown that the judicious use of these 2 methods of measurement can fulfill most if not all practical requirements, in impulse voltage measurements.

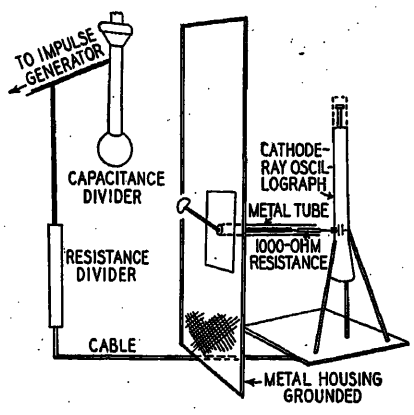



Figure 5

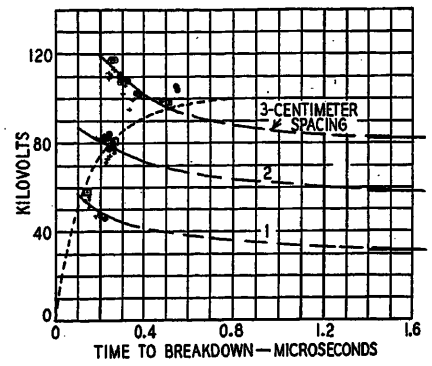



**Figure 6. Spark-over voltage of 12.5-centimeter sphere gap on positive impulse**

Crosses represent resistance-divider measurements
Circled crosses represent capacitance-divider measurements
The squares give the data for the one-centimeter, 2-centimeter, and 3-centimeter spacings reported by A. K. Nuttal (*Journal* of the Institution of Electrical Engineers, February 1936, page 229), and the dotted curve indicates the fully developed wave used in these tests

**Table I. Comparison of Methods of Scaling Oscillograms to Determine the Rate of Rise of Voltage**

| Method by 10 Per Cent to 90 Per Cent Definition Kv/Microseconds | Method Averaging Front on Main Component Kv/Microseconds | Method Using Time-to-Breakdown Kv/Microseconds | Oscillogram Crest Voltage Kv |
|---|---|---|---|
| 1,460 | 1,360 | 965 | 820 |
| 2,600 | 2,320 | 2,300 | 1,310 |
| 1,880 | 1,875 | 1,620 | 1,315 |
| 2,750 | 2,440 | 2,400 | 1,100 |
| 3,000 | 3,140 | 2,370 | 1,160 |
| 1,850 | 1,990 | 1,440 | 1,035 |
| 2,070 | 2,150 | 1,520 | 1,035 |
| 1,330 | 1,450 | 1,160 | 640 |
| 1,140 | 1,220 | 1,040 | 855 |
| 640 | 695 | 520 | 835 |
| 020 | 640 | 570 | 895 |

**Table II. Sample Data on Rod-Gap Breakdown on Front of Wave**

| Gap Spacing (Inches) | Polarity of Impulse | Crest Voltage* (Kv) | Rate of Rise Kv/-Microseconds |
|---|---|---|---|
| 5.75 | Positive | 261 | 500 |
| 5.75 | Positive | 300 | 620 |
| 5.75 | Positive | 313 | 800 |
| 5.75 | Positive | 320 | 840 |
| 10.0 | Negative | 500 | 1,245 |
| 10.0 | Negative | 520 | 1,475 |
| 10.0 | Negative | 515 | 1,460 |
| 20 | Negative | 770 | 1,110 |

*Rad = 1.0; Humidity = 2.0 to 3.4 grains per cubic foot.

**J. H. Hagenguth:** The discussions are principally related to the divider, effect of circuit constants, and the steepness of waves and will be taken up in that order.

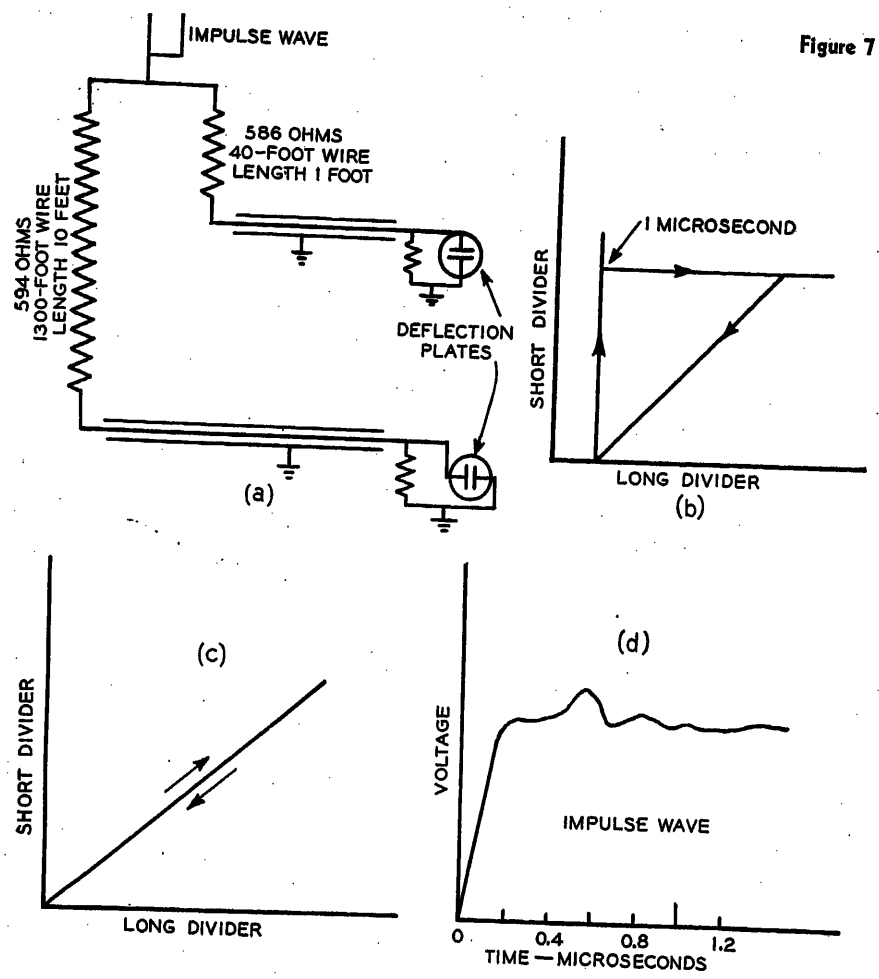
In answer to Mr. Sprague the length of wire used in the divider described is approximately 850 feet. However, the total physical length of the resistance elements is only 6 feet. A brief attempt was made several years ago to determine the velocity of wave propagation on an ordinary resistance divider, using 2 dividers of approximately equal resistance (see figure 7*a*) but of different physical length both as regards actual length of wire and length of divider. The ends of these 2 types of dividers were connected through cables of equal lengths to the 2 pairs of plates of the cathode-ray oscillograph.

If, as expected the current must be established in a divider of this type by traveling along the wire only, the pattern obtained should have been of the form shown on figure 7*b*, i.e., the voltage at the plates connected to the short divider should have increased first and approximately one microsecond later, assuming a velocity equal to the speed of light, the voltage at the other pair of plates should have increased. However, the actual oscillogram obtained was of the form as shown on figure 7*c*. The wave used for this test is shown on figure 7*d* and had a front of approximately 0.2 microseconds.

This test seems to indicate that the voltage transmission on a divider of this type is a wave phenomenon of somewhat the nature of a space wave traveling along the divider. An exact physical interpretation of this phenomenon has not been attempted on account of the more urgent problem of finding a divider which could be used with confidence to measure impulse voltage with steep fronts. It is, however, an intriguing problem and well worth while of study.

Standards for determining the accuracy of dividers for measuring steep wave fronts are not available, as pointed out by Mr. McEachron. Three methods have been used to obtain proofs for the correctness of the

Figure 7




solution: First, the use of the spark-over of a sphere gap strongly irradicated (figure 1 of paper) represents a relative proof, since the actual wave front is not known. The fact, that a spark-over of the sphere occurs after the crest, which is reached in 0.1 microsecond, shows that the divider will be suitable for measuring fronts of 0.4 microsecond or longer, which represent the output of large high-voltage generators. Second, a comparison between a calculated wave and waves measured with 3 different resistance dividers as shown on figure 8. The calculated waves measured with shielded and the low resistance divider check fairly well. The third method consists in checking the input and output voltages of the shielded divider by means of the electrical transient analyzer, and comparing the result with other types of dividers such as a small capacitance divider. The waves applied during such tests have fronts of approximately 0.05 microsecond.

Messrs. Rorden and Ross show a divider shielded by the impulse generator and claim that the voltage distribution along the divider is practically uniform. It is gratifying to know that the author's results on sphere gaps are checked with this arrangement. Without knowing how this distribution was measured and with what type of wave, it is not possible to interpret this result correctly.

There are several objections: (1) The divider has to be used in this one position requiring relatively long leads between divider and testpiece; (2) the shielding cannot be checked conveniently and the divider may be under- or overcompensated.

For elimination of inductance $L_g$ in the ground leads compromises have to be made, since for spark-over tests on the range of 0.5 microsecond or less voltages of the order of 1,000 kv will occur across a wire of 30-foot length.

All are agreed that it is well to arrange discharge circuit to obtain an essentially straight voltage rise, thus eliminating one of

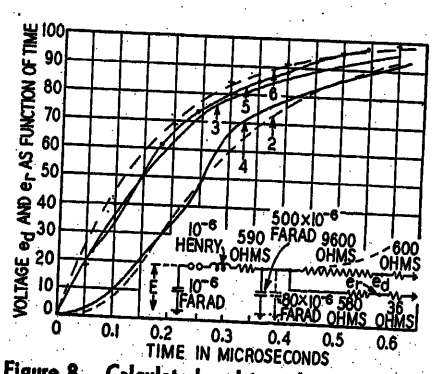



**Figure 8. Calculated and tested wave shapes with resistance divider**

1— $1/\varepsilon\times\infty$ wave (calculated)
2—Resulting voltage $e_d$ of high-resistance divider (calculated)
6—Positive wave calculated for circuit constants shown below
3—Measured with 580-ohm resistance divider (*EL*-1079-106)
4—Measured with standard 10,000-ohm divider (*EL*-1079-107)
5—Measured with shielded 10,000-ohm divider (*EL*-1079-108)

the variables of the problem of front of wave testing. Mr. Bellaschi shows in his table I the values of rate of rise of several oscillograms obtained by 3 methods. Differences between method 1 and 2 are of the order of 10 per cent while differences between 1, 2, and method 3 as proposed in the paper are as much as 30 per cent. The reason for the large differences is the bending over of the wave near the crest. In the cases where 1, 2, and 3 agree the front is probably straight, in the other cases bending over occurs. This bending over is,

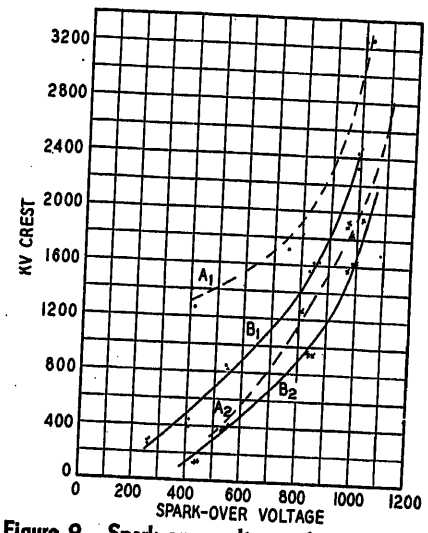



**Figure 9. Spark-over voltage of a 22.5-inch rod gap**

$A_1$, $A_2$—Series resistance is zero
$B_1$, $B_2$—Series resistance 1,500 and 2,000 ohms
Curves 1—Kilovolts/microseconds determined as kv crest divided by the time given by the intersection of a line drawn through the 10-per cent and 90-per cent points with the zero axis and the kv-crest axis
Curve 2—Kilovolts/microseconds determined is kv crest divided by time to spark-over

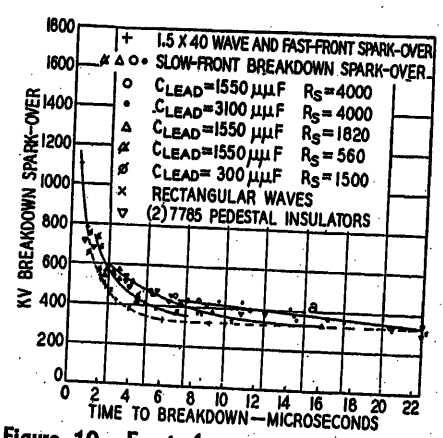



**Figure 10. Front-of-wave tests on 20-inch rod gaps**

Positive polarity, standard conditions

however, not as confusing as it appears as is shown on figure 9 of this discussion. Curves $A_1$ and $B_1$ were plotted using conventional methods of definition of kv/μs rise, for $A_2$ and $B_2$. The method proposed in the paper was used. Spark-over without series resistance ($A_1$ and $A_2$) took place partly on the tail of the wave at about one microsecond, while at short times to spark-over (0.25 microsecond) the voltage rise was straight with a sharp breakdown point. The waves

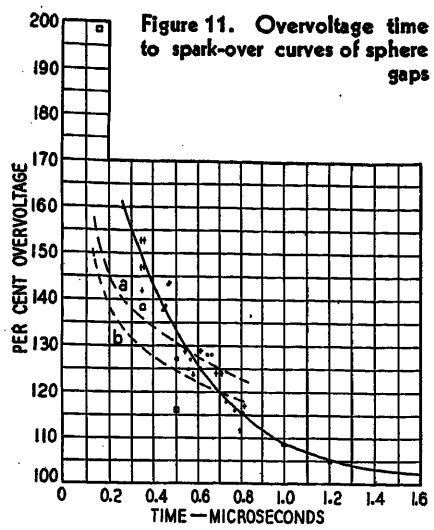



**Figure 11. Overvoltage time to spark-over curves of sphere gaps**

Solid curves—Average for 25-centimeter and 100-centimeter spheres; tests with shielded divider
+—Positive polarity; 50-centimeter sphere; 16.7-centimeter spacing
•—Negative polarity; 50-centimeter sphere; 16.7-centimeter spacing
o—Average of 100-centimeter sphere; 23- to 40-centimeter spacing
Nuttal (*Journal* of the Institution of Electrical Engineers, February 1936), direct measurements without divider
Dotted curves—Bellaschi; 25-centimeter sphere; 4-centimeter spacing
(*a*)—Capacitance divider
(*b*)—Resistance divider

of curves $B_1$ and $B_2$ showed the bending-over effect shortly before spark-over occurred. In spite of the different nature of the waves used to arrive at these curves, curves $A_2$ and $B_2$ practically fall together, and are checked with waves having straight voltage rise at all rates of rise. It appears therefore that the method of average rate of rise would produce more consistent results.

Neither definition, however, seems to fit conditions for spark-over on the front of the wave, when spark-over takes place at a time in excess of one microsecond. Figure 10 shows spark-over of a 20-inch rod gap when waves with slow exponential fronts are applied. Two limits appear to exist: (*a*) spark-over due to a rectangular wave (or practically speaking a 1.5x40 wave) and (*b*) the spark-over due to straight line rise of voltage (or practically curve *a* with a time constant, $RC$ = 12 microseconds). That waves with such slow rates of voltage rise cause arc-over on transmission system has been shown by Berger (Lightning Investigation During 1932 and 1933 in Switzerland, K. Berger. ASE Bulletin No. 9, April 27, 1934). For slow wave front tests it appears desirable to indicate rate of rise by the time constant of the wave front to permit comparison between results obtained by different investigators.

Concerning comparison of results published by Mr. Bellaschi and his associates and in the paper, it appears that the differences of rod-gap spark-over obtained are of the order of 10 to 20 per cent for larger spacings, i.e., spark-over values obtained with the shielded divider are higher by about that amount, when compared on the same basis (average rate of voltage rise). The values obtained with the shielded divider usually check within 10 per cent under entirely different test conditions, with different generators, oscillograms, and operating personnel. That the differences in results between the 2 laboratories is not greater than 10 to 20 per cent is undoubtedly due to the fact, that Mr. Bellaschi uses a 1.5x40 wave. For a front of such relatively slow rise the distortion effect of the nonshielded resistance divider is relatively small. However, as pointed out in the paper, the 1.5-microsecond front cannot economically be used for front-of-wave tests on gaps in excess of 30 inches and it should, therefore, be expected that results for the larger gaps should show greater differences.

It is not quite clear why it should be desirable to use an identical generator setup for both the 1.5x40 wave and the steep-fronted impulse. A standardized front is desirable for full-wave test and expecially the elimination of oscillations superimposed on the crest of the wave is of great importance; for front-of-wave tests, however, limitations on the actual front used should not be imposed except to specify the rate of voltage rise, or the time to spark-over. The removal of the series resistance does not materially increase testing difficulties provided the divider is connected directly to the testpiece.

Much greater differences in results, are found when comparing the spark-over of sphere gaps, as pointed out by Mr. Bellaschi. From figure 3 and figure 6 obtained by Mr. Bellaschi using a resistance type and capacitance divider it appears that spark-over voltages obtained with the capacitance divider are consistently higher than those obtained with the resistance divider which seems to indicate that even a resistance divider of as low a value as 3,300 ohms will not reproduce correctly the true rate of rise. In figure 5 of this paper is replotted an average curve obtained recently on a 50-centimeter sphere gap with 16.7-centimeters or 33.4-per cent spacing with points indicating negative polarity and crosses positive polarity. The large circles on this curve represent average values obtained from tests on a 100-centimeter sphere gap with spacing varying between 23 and 40 centimeters. Other recent data obtained with a 25-centimeter sphere gap fall within 10 per cent of the plotted curve. The squares indicate the points published in Mr. Nuttal's paper similar to those in figure 6 of Mr. Bellaschi's discussion. Finally the 2 dotted curves represent values of figure 3 of Mr. Bellaschi's discussion for 4-centimeter spacing. A comparison of the overvoltage values of the 50-centimeter and 100-centimeter sphere seems to indicate that the characteristic spark-over curves of the 2 sizes of gaps agree very well, also Nuttal's results obtained on a much smaller gap of 12.5-centimeter diameter indicate the same general trend. The curves of figure 1 of Mr. Bellaschi's paper, especially the values obtained with the capacitance divider agree fairly well in the region for spark-over times of 0.4 microseconds and longer. In the region of short-time spark-over the curves do not check, which possibly is due to the distorting effect of the resistance divider and possibly due to the effect of the resistance divider on the field in the capacitance divider, which apparently were placed quite close as shown in figure 5 of Mr. Bellaschi's discussion.

In conclusion the author wishes to emphasize the point brought out by Mr. McEachron that the paper should not be interpreted as advocating the use of increasingly steeper fronts for impulse testing. It is merely intended to discuss the problem of voltage measurement and to show the effect of steep wave fronts on the spark-over of the component parts of transmission systems.

A much greater amount of field data would be required to justify testing with fronts having rates of rise in excess of 1,000 kv per microsecond.

## Currents and Potentials Along Leaky Ground-Return Conductors

**Discussion of a paper by E. D. Sunde published in the December 1936 issue, pages 1338–46, and presented for oral discussion at the communication session of the winter convention, New York, N. Y., January 25, 1937.**

K. L. Maurer (Bell Telephone Laboratories, Incorporated, New York, N. Y.): The earth as a conductor of electricity has long been a puzzling and troublesome subject because of its great extent, its amorphous structural arrangement, and its general lack of homogeneity. The tendency upon the part of the engineer dealing with practical problems involving the earth as a conductor, has been to get around the uncertainties either by ignoring them or by idealizations often more consistent with convenience than with the facts. Fortunately, in many types of circuit problems, propagation rates are slow enough to admit rather sweeping idealizations of the electrical behavior of the earth. In other types of circuit problems, some of which are mentioned in the paper, and in particular, those involving differences in potential between points on the ground itself, recognition of what actually takes place in the earth cannot be avoided. In the past 10 years or so, a great deal of work

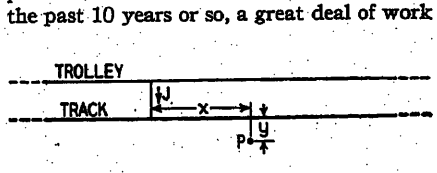



**Figure 1**

on this subject has been done by a number of investigators, as a result of which many of the difficulties have been resolved, and to this work Mr. Sunde's paper is an important contribution.

The formidable appearance of the expressions for voltage and current may, at first glance, give the impression that the formulas are too unwieldy for practical use. As a matter of fact, in most practical applications it will be found that the expressions can be considerably simplified without overstepping the limits of engineering accuracy, because it is rarely if ever that all of the factors in a circuit problem involving the earth can be determined with enough assurance to justify carrying out all of the steps called for in the formulas. The main factor of uncertainty, of course, is the character of the earth in the locality in question. As may be seen from the formulas in table II, the earth resistivity, although of secondary impor-

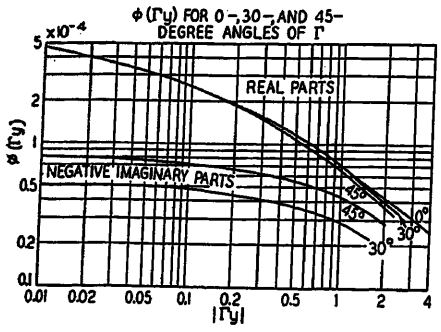



Figure 2

tance in the expressions for the conductor current and voltage, is an extremely important factor in determining ground potential since the latter is almost directly proportional to the resistivity. Since it is known by experience that the earth, particularly at the surface, usually is far from homogeneous, and since it is practically impossible to determine the variations in resistivity over the entire area involved in a particular problem, the question of the reliability of the formulas in practical work naturally arises.

To answer this question, a rather extensive series of tests was undertaken in the summer of 1935. The leaky ground-return conductor for these tests consisted of a single electrified railway track, and particular attention was given to the investigation of ground potentials, such as might affect communication circuits in the vicinity. From the results of these tests, which are described in another discussion of this paper, and from several other experimental checks, it appears that in the average case, a reasonably good fit between the formulas and the experimental data can be expected with relatively simple hypotheses as to the earth's structure.

As an example of the extent to which the formulas in the paper can be simplified for engineering use, consider the expression on page 1343 for ground potential produced by an electrified railway, as at point $P$ in figure 1 of this discussion. Since ground potentials are largest close to the track, it is of practical interest to examine this formula for small values of separation. By means of the expressions in table II, the ground potential for small values of $y$ may be written (using the notation of the paper):

$$V_e(x, y) = \frac{J\rho\Gamma}{4\pi}(1 - \mu) \times \left[K(x) + 2e^{-\Gamma x}\log_e \frac{1.12}{\Gamma y}\right] \text{volts} \quad (1)$$

in which $K(x)$ is a quantity, independent of the separation which is found to vary only slightly over the practical range of values of $\Gamma x$. In obtaining the difference in ground potential between 2 points at a given value of $x$, the quantity $K(x)$ cancels out and in obtaining the difference in ground potential between 2 points at different values of $x$, the difference between the 2 values of $K(x)$ is small compared to the difference between the 2 values of the remaining term, since the latter varies exponentially with $x$. Therefore, for close separations (up to about 500 feet in the average case), it is permissible to ignore $K(x)$.

Since the largest values of ground potential at a given separation occur opposite the current source or the load, it is also of practical interest to examine the formula in the paper for small values of $x$. In this vicinity, the ground potential may be written as

$$V_e(x, y) = J\rho\Gamma(1 - \mu)e^{-\Gamma x}\phi(\Gamma y) \text{ volts} \quad (2)$$

For convenience in practical work the terms of equation 2 are defined as follows:

$J$ = trolley current, amperes

$\rho$ = earth resistivity, meter-ohms

$\mu = M/Z$ = ratio of mutual impedance of trolley and return system to return system self-impedance, both on an earth return basis

$x$ = distance along track from point opposite electrode at which ground potential is taken, to point at which current enters tracks, miles

$y$ = separation, normal to track, between electrode and track, miles

$\Gamma = \sqrt{G \cdot Z}$ = track-return-system propagation constant, per mile

$G = (g \cdot g_1)/(g + g_1)$ = track-return-system leakage conductance mhos per mile

$g$ = leakage conductance of ties, track ballast, and other leaks, such as catenary structure footings, etc. For tracks, this quantity has been found to vary between 0.5 and 2 mhos per mile per track for dry and wet weather conditions, respectively. One mho per mile per track is frequently used as a representative value

$g_1$ = "leakage conductance" relating to the earth in the vicinity of track. This quantity may be taken as $1{,}000/\rho$ mhos per mile, regardless of the number of tracks

$\phi(\Gamma y)$ = a function of the return-system propagation constant and electrode separation, containing factors for conversion of distances from meters to miles. This function is shown in the accompanying figure

At $x = 0$ equation 2 is valid for a large range of values of $\Gamma y$. As $x$ increases, however, the range of values of $\Gamma y$ for which the equation is accurate becomes narrower. For $\Gamma x$ larger than about 2 in the average case, the equation is restricted to separations about the same as those for equation 1. At large values of $\Gamma x$, however, the ground potential ordinarily is so small compared to that at small values of $\Gamma x$, that its accurate determination is of less practical importance.

The ground potential produced by current leaving the track, as at a substation, is calculated in the same way, but has reversed sign. The total ground potential produced by current entering the track at one point and leaving at another, as in a section between a load and a substation, is the algebraic sum of the potentials calculated for each point separately. The difference in ground potential between 2 electrodes is the difference between the ground potentials calculated in this way for each point independently.

**P. Goldstone** (Gibbs & Hill, Inc., New York, N. Y.): In the preceding discussion reference was made to certain tests to obtain experimental checks on the analysis given in the paper. In these tests, in which I was interested from the railroad viewpoint, in addition to the study of ground potentials, measurements were also made of track currents and potentials, which are of interest to the railroad engineer.

The test arrangements are shown in figure 3. The circuit, which represents the trolley-track circuit of an electrified railway, consisted of a single overhead wire with return in a single bonded track. The tests were made at one end of the circuit and circuit lengths of 1, 2, 3, and 4 miles were used.

Figure 3 shows observations of the following quantities as the length of the energized section was varied: (*a*) track potential measured between the track and a ground rod located at the edge of the ballast, (*b*) difference in ground potential between the ground rod at the edge of the ballast and a ground rod situated about 9,000 feet away on a line at right angles to the track, (*c*) track current flowing away from the energized section. (This current is of course equal to the earth current at the end of the section.) The results indicate that all 3 quantities vary in substantially the same manner as the section length is changed. It will be seen that the track potential changed considerably with weather conditions due to the fact that the moisture increased the track ballast leakage conductance. The effect of weather conditions upon the ground potential, however, was negligible. The ground potentials at points near the track are seen in this case to be of the same order of magnitude as the track potential.

On figure 4 are shown observed differences in ground potential measured between the ground rod at the edge of the ballast and ground rods at various separations from the track along a right angle line. The energized circuit in this case was 4 miles long. Three calculated curves also are shown on this figure. Curves *A* and *B* were calculated by methods described in the paper assuming homogeneous earth having values of resistivity of 1,600 and 200 meter-ohms, respectively. Curve *C* was calculated for a resistivity variable with depth. Comparison of the experimental with the calculated curves brings out the effect of nonhomogeneous earth upon the variation of ground potential with separation. Measurements of earth resistivity by the usual d-c method in the vicinity of the end of the energized section indicated roughly a 2-layer earth structure, in which the resistivity of the upper layer was on the order of 1,600 meter-ohms, while at greater depth the resistivity was on the order of 200 meter-ohms. This condition required extending the formulas given in the paper, which are based on homogeneous earth, to correspond to the case of re-

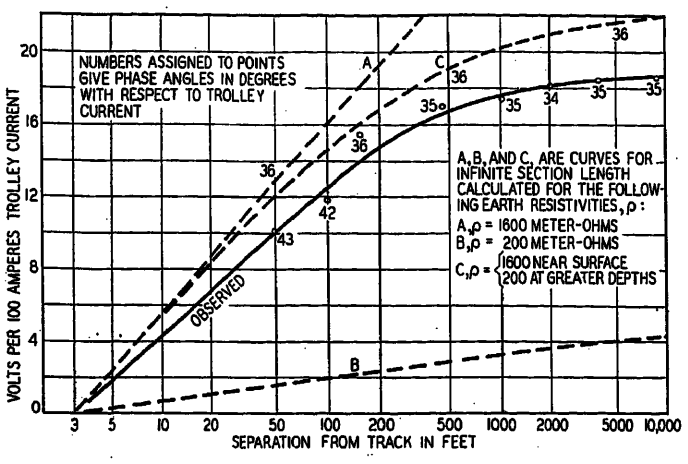



**Figure 3. 28-cycle tests on single-track railroad; earth potentials at end of 4-mile section referred to a ground near track**

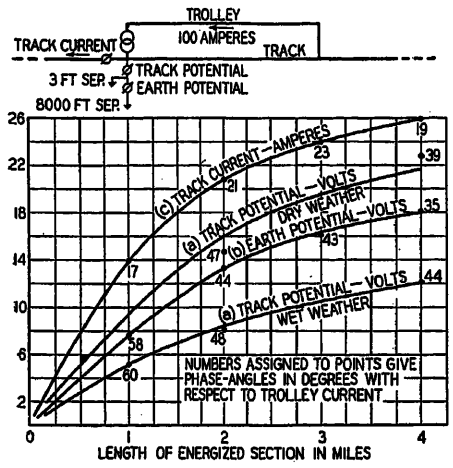



**Figure 4. 28-cycle tests on single-track railroad**

sistivity variable with depth and curve *C* on figure 4 is based on this assumption. The calculated curves are based on the assumption of infinite length of the energized circuit whereas the actual circuit was only 4 miles long. This fact accounts for some of the difference between the observed results and the calculated curve *C*.

Curve *C* was calculated by the author of the original paper in the following manner. Assume the variation in apparent earth resistivity $\rho'$, with electrode separation $r$ to be given by the formula:

$$\rho' = \rho(1 + ke^{-\beta r})$$

where $\rho$ is the earth resistivity measured for large electrode spacings, $(1 + k)\,\rho$ the earth resistivity for small spacings and $\beta$ a properly chosen constant. The earth potential is then approximated by calculating the earth potential for homogeneous ground of resistivity $\rho$ for 2 separations $y$, and

$$y' = y\sqrt{1 + \left(\frac{\beta}{\Gamma}\right)^2};$$

where $\Gamma$ is the propagation constant of the track for the unit length used for $r$. The latter earth potential is multiplied by $k$ and added to the first. It was found that the earth resistivities measured in these tests could be approximated by taking $\rho = 200$ per foot, $k = 7$, and $\beta = 0.015$ per foot, and curve *C* of figure 4 is based on these assumptions.

The following conclusions may be drawn from the experiments:

1. Ground potentials, track potentials and earth current at one end of a traction circuit (at which point the potentials normally are largest) vary with the circuit length $s$ nearly as $1 - e^{-\Gamma s}$ and decrease with distance $x$, along the track from one end of the section toward the center nearly as $e^{-\Gamma x}$
2. If the earth is not homogeneous, but has a resistivity decreasing with depth, the ground potential difference between 2 electrodes, one of which is near the track, increases less rapidly, as the other electrode is moved away from the track, than if the earth is homogeneous
3. With the track energized across a track break (as in case 1 of the paper) the track current propagation is nearly exponential for a considerable distance. This was found to be the case over the entire section (3 miles) used in the tests.

# Inductive Co-ordination of Common-Neutral Power-Distribution Systems and Telephone Circuits

**Discussion and authors' closure of a paper by J. O'R. Coleman and R. F. Davis published in the January 1937 issue, pages 17–26, and presented for oral discussion at the communication session of the winter convention, New York, N. Y., January 25, 1937.**

**Sidney Withington** (The New York, New Haven and Hartford Railroad Company, New Haven, Conn.): The co-operation which has been accomplished between the power and telephone interests, implied in this paper, I believe should be emphasized.

Reference is made in the paper to the co-ordination between the National Electric Light Association and the Bell Telephone system. Attention is called to the joint effort of the Edison Electric Institute and Association of American Railroads, resulting also in general agreement as to principles and practices, which should avoid a great deal of unprofitable controversy in the future.

Work of this kind which insures that decisions will be based upon engineering principles, is incomparably more desirable than permitting contests in the courts, where decisions by nontechnical individuals may be based upon cleverness of presentation by brilliant lawyers, regardless of engineering merits or economic factors, rather than upon logical analysis founded upon facts.

Instances of this kind have unfortunately occurred in the past, and it speaks well for the engineering profession that means have been taken to keep such discussion out of the courts in the future.

**T. A. Taylor** (Bell Telephone Laboratories, Incorporated, New York, N. Y.): The paper by Messrs. Coleman and Davis discusses the factors which must be considered in the inductive co-ordination of common neutral power distribution systems and telephone circuits operating in urban areas. As pointed out in the paper, there has been a recent trend toward the use of multigrounded or common-neutral systems in rural areas and in view of this trend, it may be of interest to compare briefly the co-ordination problems presented in rural areas with those discussed in the paper. This discussion is based upon the results of field studies of this problem carried out during the past 2 years by the joint subcommittee on development and research—EEI and Bell system. A comprehensive report on this work is now being prepared.

As the authors have indicated, rural power circuits are generally longer, operate at lower load densities and frequently at higher voltages than those in urban areas. As a result, it has been found, particularly in the case of rural lines operating at the higher voltages, that the ground-return charging current components are apt to be more important in contributing to their inductive influence than either the load current or transformer exciting current components, which generally control the influence of the lower voltage urban circuits. These "capacitive" or charging-current components return, at least in part, in the ground, regardless of whether the circuit is operated isolated, or with a single-grounded or multigrounded neutral. The results of tests in a number of locations indicate that while multigrounding the neutral of these longer circuits increases the 60- and 180-cycle ground-return components, it, on the average, makes no substantial change in the components of higher frequency, although in individual cases they may be increased or decreased. Measurements of noise on rural telephone circuits exposed to these power circuits have shown that these higher frequency components tend to control the noise whether the power circuits are unigrounded or multigrounded. On the average, therefore, on circuits exposed to rural power lines operating at 7,600 volts and above, the noise is not materially different whether the power circuit neutral is uni- or multigrounded.

In the case of short low-voltage rural power lines, the charging currents are of relatively small importance compared to the transformer exciting currents and load components. The behavior of such circuits, when multigrounded, is therefore similar to that of the urban circuits discussed in the paper, although differences in the influence under the unigrounded and multigrounded conditions may not be as great.

The studies of the committee have disclosed no new co-ordinative measures which may be applied to rural power and telephone circuits but indicate that certain of the measures outlined in the Coleman-Davis paper are applicable in rural areas. Since the ground-return charging current components are of particular interest, measures which tend to limit their magnitudes are relatively more important than those which primarily affect the transformer exciting current or load current components.

Experience has shown that the magnitudes of the charging currents may be affected in either the unigrounded or multigrounded cases by resonant conditions and propagation effects which occur in the longer circuits used in rural areas. The importance of these effects depends upon the voltage wave shape impressed on the circuit. The charging currents may therefore be reduced by improvement in the wave-shape conditions. The ground-return components of the charging currents on 3-phase lines may also be reduced by maintaining the greatest practicable degree of balance-to-ground of the system, by equalizing the lengths of single-phase extensions connected to each phase.

Since most of the rural telephone plant is of open-wire construction, the use of adequately co-ordinated telephone transpositions and the avoidance of severe unbalances in the open-wire conductors may often be a practicable and effective co-ordinative measure.

The method of co-operative planning of routes by both parties to avoid severe exposure conditions, which has been found effective in urban areas, is sometimes more difficult to employ in planning rural extensions, since the power and telephone circuits frequently must be carried along the same highways. Therefore, co-operative advance planning must usually be directed toward limiting the influence of the power system and the susceptiveness of the telephone system.

The paper points out that in many cases desirable magnetic shielding effects may be obtained by grounding the sheaths of exposed telephone cables. The joint subcommittee has found from tests in 2 urban areas that such grounds may often be practicably provided by bonding the cable sheath to the multigrounded neutral of the power-distribution system. Since the neutrals in these urban areas were very well grounded the degree of shielding so obtained was found to be comparable to that observed with other low-impedance grounds.

**J. J. Smith** (General Electric Company, Schenectady, N. Y.): This paper illustrates well the benefits to be derived from co-operative studies by power and telephone engineers of the mutual problems which arise between their respective systems. My recollection is that in the days when the use of the common-neutral system was first considered on a large scale, some engineers thought that it would considerably increase the influence of power circuits on paralleling telephone systems while other engineers felt that it would not. In order to arrive at the facts, experimental studies were undertaken which over the succeeding years brought forth the results given in this paper. The results described indicate that while the use of the common-neutral system without any reference to inductive co-ordination might give rise to noise difficulties, these can largely be avoided by co-operative procedure with regard to certain features of both the power and communication systems.

The experimental studies led to the breaking down of the over-all noise into its component parts. The tables given in the paper show well the effects of the wave shape of the power system and of the unbalances on the telephone system. The section on inductive coupling, however, refers only to factors which generally influence the type of construction used, whether the systems use the same pole jointly or are at highway separation. I feel that a table or curve giving a comparison of the effects of these types of construction in an average case would be a worthwhile addition to the paper. I should also like to suggest the inclusion in the paper of a comparison of open-wire and cable telephone circuits showing the results to be expected on each in some typical average case.

At the bottom of page 24 it is stated that "direct metallic-circuit induction can be greatly reduced by systematic transpositions in the telephone circuit." This agrees with the results in table 9 where variations of 5 to 1 up to 20 to 1 are given for the contributions to the noise from open-wire sections. These variations are attributed to the effectiveness of the transpositions. On page 24, however, the further statement is made that "due to the physical limitations in a practical layout of telephone transpositions the reduction in metallic-circuit induction is on the average from 60 to 80 per cent on nonpole pairs and about 90 per cent on pole pairs." These reductions, ranging from 2 to 1 up to 5 to 1, do not seem to agree very well with the previous statement or with the result given in table 9. I should like to have the authors clarify this point.

**Coleman and Davis:** On the first page of the paper reference is made to the start of this system in Minneapolis. Although this was the first extensive use in this country the system was developed and installed in Toronto, Canada by Mr. Hood prior to its installation in Minneapolis.

Mr. Smith raises 2 technical points that appear to require slight elaboration to answer.

Effectiveness of transpositions in exchange lines cited on page 24 are average values based on tests made by the joint subcommittee on development and research on several lines and published in volume 2 of "Engineering Reports," table IX, page 102. Under favorable conditions greater effectiveness than the average can of course be obtained. In table IX, page 25, the lower values of the noise contributed by the open wire is for a transposed nonpole pair and the higher value is for a nontransposed pair. Consequently the range shown is greater than that obtaining for a particular pair when transposed and nontransposed.

"Engineering Reports" 13 and 17, (volume II and III) show complete information on coupling and since there are many factors such as direct metallic and longitudinal coupling for both the balanced and residual components of both current and voltage each varying differently with separation it does not seem feasible to prepare a summary curve.

For distribution circuits induction from residual currents and voltages is frequently the controlling factor. The table I shows the order of magnitude of the ratios between joint use and roadway separation for residual coupling.

Table I

| Type of Telephone Construction | Component of Noise | Relative Noise: Joint Use About 6 Feet Separation | 40 Feet Separation | 75 Feet Separation |
|---|---|---|---|---|
| Open wire | Direct Metallic | | | |
| | 1. From voltages | 100 | 20 | 7 |
| | 2. From currents | 100 | 20 | 12 |
| | Longitudinal | | | |
| | 1. From voltages | 100 | 28 | 12 |
| | 2. From currents | 100 | 54 | 39 |
| Cable | Direct Metallic | | Negligible | |
| | Longitudinal | | | |
| | 1. From voltages† | | Negligible | |
| | 2. From currents† | 100 approximately | 54 | 39 |

† Assuming cable sheath grounded at one point only.

## Calorimetric Measurement of Dielectric Losses in Solids

**Discussion and authors' closure of a paper by H. H. Race and S. C. Leonard published in the December 1936 issue, pages 1347–56, and presented for oral discussion at the communication session of the winter convention New York, N. Y., January 25, 1937.**

**P. M. Lincoln** (Cornell University, Ithaca, N. Y.): The paper by Messrs. H. H. Race and S. C. Leonard, describing calorimetric measurement of dielectric losses in solids is an interesting one.

The general theory of the procedure is perfectly sound. This theory is that a certain known power applied to a given mass of material during a given time will raise that material to a certain determinable temperature at the end of that time. The temperature at the end of the power application is inferred from the cooling rate, details of which are fully described in the paper. If then power is applied to a similar mass of material at an unknown rate, the power can

be inferred by determining the temperature elevation after a given short time.

The method is perfectly sound in theory, but there are a number of discrepancies which appear in the data submitted in this paper which I believe deserve further explanation.

In the first place the points at which the wattage is applied to the samples under test, and to the calibrating sample are quite different. In the test samples the wattage is applied presumably at a uniform rate throughout the mass of the material. In the calibrating sample, however, the wattage is applied to the exterior surface of the sample, and it is an open question whether or not the temperatures measured by the method indicated are a true relative measure of the energy input in the 2 cases. In the case of the calibrating sample there must necessarily be a flow of heat from the point of generation to the point of measurement, and it is highly questionable whether or not the heat is uniformly distributed throughout the sample at the end of the short time of the calibration sample test run.

The method of measuring temperature of both the calibrating sample and the test sample is such that it gives essentially the temperature gradient at the surface of the piece under test. This temperature gradient is in turn a measure of the cooling rate. One of the things in this paper, for which I see no explanation, is the decided difference in the cooling rate for the calibration sample, as compared to the test sample which presumably is identical in every respect, except that the calibration sample is covered with a thin coating of conducting material. An analysis of figure 8, for instance, showing the cooling curves taken during the d-c calibration on the fused-quartz calibration sample, shows that the rate of cooling is such that the temperature falls to $^1/_2$ the initial temperature in approximately 100 seconds as a minimum and 150 seconds as a maximum. These cooling rates are shown by the slope of the cooling curves. The slopes of all curves in figure 8 are not the same. The slope of the curve starting at the maximum temperature is approximately 50 per cent greater than that of the curve which starts at the minimum temperature. This is as might be expected, since it is well known that the rate of cooling due to natural convection decreases with temperature elevation, and the above result might have been anticipated. However, when we come to compare the rates of cooling shown in figure 8 on the calibration sample, with the rates shown in figure 13 on a test sample, which is presumably a duplicate of the sample of figure 8 except that it has no surface conductor, we find a rate of cooling entirely different. In figure 13 the rate of cooling is such that $^1/_2$ the initial temperature is reached in from 220 to 250 seconds, or, in other words, the rate of cooling is only about $^1/_2$ of what we find on the calibration sample. I should like to ask Mr. Race if there is any known reason for this rather remarkable difference in the cooling rates of the 2 presumably duplicate samples.

If now we compare figure 10, which shows the cooling curves of the Isolantite calibration sample, with those of figure 14 which shows the cooling curves for test sample of the same material, we find that a very similar condition exists. In figure 10 $^1/_2$ of the initial temperature is reached in 75 to 110 seconds, while in figure 14 we find that it requires 130–150 seconds to arrive at $^1/_2$ the initial temperature. Why should there be this difference?

If I may be permitted, I should like to suggest one possible explanation for these discrepancies. It is quite possible that the temperature of the rather heavy masses at the ends of the samples under test was quite different during the test upon the calibration sample, and the test upon the test sample. Analysis will show that a very considerable portion of the heat applied to these samples will escape by thermal conduction, and of course the rate of heat escape by thermal conduction will depend upon temperature difference between the rather heavy metallic terminals on the samples and the temperature at the midpoint of the sample. I do not find that Mr. Race made any attempt to determine the temperature of these terminals. I am informed by those more familiar with high-frequency radio matters than I, that there is a possibility during the application of the high voltage, high frequency test, that some heat will be developed in the rather heavy terminals on the test sample. If this is the case, it would explain the difference in cooling rates that I have pointed out above.

If, as I suspect, a very considerable part of the heat in both the calibrating and the test samples is carried away by thermal conduction, the question of thermal conductivity of the materials under test will have a very decided bearing upon the results attained. Thermal conductivity of materials such as Mr. Race is experimenting with, varies over a very wide range. For instance, reference to the Smithsonion Physical Tables, confirmed by the International Critical Tables, give values as follows:

For crystalline quartz perpendicular to axis of 0 degrees centigrade

$k_t = 0.0173$

For crystalline quartz parallel to axis, same temperature, the value of $k$ is 0.0325. For hard rubber at 0 degrees centigrade the value of $k$ is 0.00037, being thus about 1 per cent of that for crystalline quartz. I can find no values of this constant for fused quartz, but I understand it to be of the order of 10 per cent or 15 per cent of that of crystalline quartz.

For Isolantite the value of $k$ is 0.00175. It will thus be noted that the thermal conductivity of the materials which were tested by Mr. Race vary over a very wide range. For instance, crystalline quartz parallel to the axis has a thermal conductivity, which is approximately $3^1/_2$ per cent of copper, while hard rubber has only about 0.04 per cent of that of copper, a variation of nearly 100 to 1. If, as I suspect, there is an appreciable dissipation of heat by thermal conduction during the 2 minute application of high potential, high frequency, to the test samples, will not this variation in thermal conductivity lead to results which are far from accurate?

The methods which Mr. Race is proposing in this paper certainly are interesting, and are worthy of additional study, but I would question whether the results so far obtained are of a very high degree of accuracy. I believe that if Mr. Race had taken his cooling curves between the center of his sample and the metallic terminals thereof his results might have led to determinations quite different from those cited in his paper.

There is one other point that might be mentioned before closing this discussion. If the information which I have received is correct, namely, that heat is developed in the metallic terminals during the high-potential high-frequency voltage application, this very fact would cause the results as reported in the paper to be quite erroneous. I should like to inquire whether or not any tests have been made to determine if there is such a loss in the metallic terminals during the period of high-potential high-frequency application.

**C. L. Dawes** (Harvard University, Cambridge, Mass.): To my mind the authors have developed a new and valuable technique in the methods of measuring dielectric losses. It permits measurement of such losses at high voltages simultaneously with high frequencies, which would otherwise be quite difficult. Also, because of the rapidity with which measurements can be made, the method is valuable not only for control work but for the rapid comparison of different dielectric materials. In the method as it has so far been developed, there are some possible sources of error. In figures 8 and 10, which give the cooling curve for the calibrating samples with fused quartz and Isolantite, the rate of cooling is much greater than with the test samples, as given by figures 13 and 14. This is explained, I believe, by the fact that with the calibrating samples the power is applied only to the surface. On cooling, some of the heat flows inward toward the center, thus producing a more rapid rate of cooling than with the test sample. With the latter, heat is produced throughout the body of the sample and the heat flow must necessarily be outward toward the surface. This gives a lesser rate of surface cooling than for the calibrating sample. Also it is questionable whether or not the placing of the thermocouple on the surface of the sample not covered by the surface layer of resistor material gives a true criterion of the cooling of the calibrating sample itself. Heat must flow over more or less irregular paths from the heated surface to the point of contact of the thermocouple. To my mind, these 2 difficulties might be overcome by calibrating with steady-state measurements, using the method of Baldwin.

Moreover, in calorimetric measurements the losses over the surface as well as the internal losses of the sample are measured. That is, surface losses cannot be eliminated by the usual guard electrodes, as in electrical measurements. Also the potential difference is applied between the 2 ends of a sample the length of which is considerable in comparison with the diameter. Hence the field between the electrodes will not be uniform and the dielectric lines will diverge outward as they leave the electrodes. This makes the stress per unit volume less at the midzone of the sample than at the ends. Hence the loss per unit volume throughout the sample is not constant. This, however, probably would have little or no effect so far as the comparison of samples of similar geometry is concerned.

The authors have attempted a very difficult problem and in their first attempt may not be expected to have brought the method

to perfection. They should be complimented on having obtained such rational results under very critical and difficult conditions.

**L. A. Burckmyer, Jr.** (Cornell University, Ithaca, N. Y.): This paper is very outstanding in its clear and full presentation of the test data. However the authors seem to have given only a small amount of attention to the interpretation of these data.

There is evidence that temperature conditions were not governed by the simple heat-storage relations that the authors relied on in determining the loss of a sample by the use of a calibrating resistor of different material. Thus equation 4 states, in effect, that the quartz calibrating resistor requires 0.25 watts (per cubic centimeter) per degree per calorie per cubic centimeter, on a 120-second test, or 30 watt-seconds per calorie, instead of 4.186, or the temperature difference $\Delta T_0$ is about $1/7$ the temperature rise that would occur with no heat loss.

There are 2 possible explanations:

(*a*). The values $\Delta T_0$ do not represent actual temperature rise, or
(*b*). The heat lost plays a very important part in the temperature attained.

Both of these are true, as can be shown by analysis of the cooling curves of, say, the quartz calibrating resistor. The uppermost curve (figure 8) shows a thermal time constant of about 150 seconds, indicating a heat loss which should have resulted in a temperature rise of about 2 degrees, or about 5 times $\Delta T_0$, during the heating period. (With no heat loss, the rise would be about 3 degrees.)

In view of the construction of the apparatus, it would not be unreasonable to assume that $\Delta T_0$ represents only about $1/5$ the actual rise, but to justify extrapolation of the cooling curves by drawing them as straight lines it is essential that $\Delta T_0$ be a *constant* fraction of the true rise. However, the slopes of the cooling curves on the quartz calibrating resistor differ by as much as 1.6 to one, and the average of these is about twice as great as the slope of the cooling curves on the quartz test sample, raising a question as to the significance of the results even when the calibrator and sample are made of the same material. As it is unreasonable to ascribe these variations to inconstant coefficients of heat transfer over the narrow range of working temperatures, it seems likely that $\Delta T_0$ does not even represent a fixed fraction of the true temperature rise; or, in other words, that the assumption of a linear cooling curve is arbitrary and unjustified.

The heat loss of the quartz calibrating resistor is about 6 times as large as can be accounted for by even black-body radiation. This discrepancy persists for any assumed ratio of actual temperature rise to $\Delta T_0$. Hence the temperatures must have been controlled largely by conduction, presumably to the massive metallic end pieces. If this is so, the inferred losses on all materials other than fused quartz and Isolantite can have little significance, for the conduction effects were not taken into account and would be entirely different in the calibrating resistor and in the test sample.

In the absence of any published defense of the construction of the calibrating resistor, with its surface heating and with temperature measurement made at the middle of a bare $1/4$-inch strip, any close agreement between the thermal behavior of the calibrating resistor and the test sample must be regarded as a fortunate accident. Certainly conduction plays a part in the heating of the bare strip, and it seems incredible that a radical change in the width of this strip would not have materially affected the calibration data.

With elimination of conduction effects and with a calibrating resistor that simulates the test specimen in all essential respects, it is likely that this method would be capable of yielding accurate results in measurements on dielectrics.

**H. H. Race** and **S. C. Leonard:** Before answering specific questions raised regarding this paper, we should like to make this general comment: The ranges of voltage and frequency over which bridge and substitution measurements can be used to measure dielectric constant and dielectric loss of solid insulating materials is shown in figure 1. Such methods cannot be used at high voltage high frequency, whereas calorimetric methods should be possible at frequencies and voltages equal to or higher than those we have used if a measurable power supply is available. The major disadvantage of previous calorimetric methods has been the time required to reach steady state. This paper reports progress in a 3 months attempt to use a transient calorimeter in this hitherto unexplored field of loss measurements on solid dielectrics. There is need for further refinement of the method which was presented with the hope of stimulating other workers to try transient calorimetry.

Specific questions can be separated into 3 classes:

(A). Thermal Conduction From the Ends of the Samples

When we started this work we planned to use samples 6 inches long with the hope that axial conduction would have a negligible effect upon the temperature of the midpoint. Our first measurements showed that with the maximum voltage available the gradient in long samples of low-loss material was insufficient to produce a measurable temperature difference. Therefore the samples were shortened to $1\frac{1}{2}$ and 2 inches with recognized attendant increases in the effects of axial thermal conduction. Preliminary calculations from the experimental data showed that about 80 to 85 per cent of the heat generated during a 2-minute heating period was being dissipated through the metal electrodes. Therefore, the theoretical thermal characteristics of our specific calorimeter were calculated by Doctor H. Poritsky of our engineering general department.

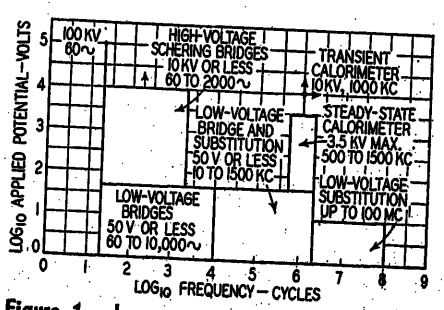



**Figure 1. Loss measurements, solid dielectrics**

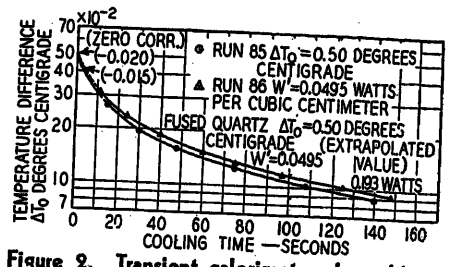



**Figure 2. Transient calorimeter d-c calibration with solid carborundum resistor, 2-minute runs**

His results indicated that (*a*) *assuming zero end conduction, the time constant of radial convection and radiation should be* about 725 seconds, and (*b*) *assuming the metal ends to be infinite heat sumps, the time constant of axial conduction should be about 150 seconds.* This latter value is of the same order as the measured time constants, indicating that the major portion of the heat is being dissipated axially. Because of space limitation, these mathematical studies of heat flow could not be included in the paper, but are available in report form. The fact that a major portion of the heat is dissipated axially should not prevent the use of the differential thermocouple to measure total heat if the thermal circuits have constant coefficients and if the test piece and calibrator are made of the same materials. When the test piece and calibrator are not of the same material the estimation of total heat is certainly less accurate.

(B). Time Function of Temperature Relaxation

We have not used the time constants of the temperature measurements to indicate heat generated, but have extrapolated the data to the time of removal of potential to obtain $\Delta T_0$. We have observed that the time constant of temperature relaxation changes with experimental conditions and that if the ambient temperature is changing the relaxation curves may not have the same slope or may not be exponential in form, however, we found that the extrapolated values of $\Delta T_0$ are effected much less than the time constants by such changes in ambient conditions. Considerable more work must be done to determine the ultimate accuracy of this method. The paper shows the check obtained for the absolute value of loss factor of fused quartz.

(C). Type of Calibrator

Since thermal conductivity of a sample is important, it was considered necessary to make the calibrator of the same material as the test piece or of a material having comparable thermal conductivity. No materials are available having sufficiently high volume electrical conductivity so that they could be used as calibrators which also have the same thermal properties as the materials being tested. A one-point calibration was obtained using a solid carborundum calibrator as shown in figure 2. The cooling curves were not exponential functions and the steepness of the initial slopes caused by its greater thermal conductivity made it difficult to determine the extrapolated value of $\Delta T_0$. Variations as great as 30 per cent could be made in this extrapolation. The value of $\Delta T_0$ as extrapolated in figure 2 when corrected for specific heat and density

agreed with the value of $\Delta T_0$ obtained from the fused quartz calibration curve for the same value of watts per cubic centimeter input.

Since the surface type calibrators gave more consistent data, we asked Doctor Poritsky to make a mathematical analysis of the temperature rise at the center of the uncoated portion assuming uniform heat input to the remaining surface and zero heat loss. The mathematics are too involved to be included here, but indicated a heat rise at this point of 2.8 degrees centigrade for a total heat input of 0.2 watts for 2 minutes. Likewise, if we assume uniform volume heating at 0.2 watts for 2 minutes and zero heat loss the average temperature rise should be 3.0 degrees centigrade. Therefore, the error resulting from surface heating is given by the ratio of 2.8 to 3.0 degrees centigrade. On the other hand we have already shown that heat dissipation to the ends is a much more important factor. This is again indicated by the fact that the measured value of $\Delta T_0$ was only 0.42 degrees centigrade for these conditions.

Whether or not this ratio of 0.42 to 2.8 remains constant is one of the important factors to be investigated more thoroughly. The independent check obtained in the case of fused quartz and the fact that measurements on other low-loss samples give consistent results between different samples of similar materials and yield loss factors of the order of magnitude anticipated indicates that the variation in this ratio may not be as serious as has been assumed.

Case II under "Calculations" was presented as a possible method of determining a value for loss factor for a material that was different from that of the calibrating body. Calibrators were made of several different bodies other than the quartz and Isolantite units described in the paper and correlation of the experimental data thus obtained led to the presentation of case II. We realize that this method is based on a limited amount of experimental data and that case I is the preferable method.

On the whole we are pleased with the initial results obtained with the transient calorimeter as reported in this paper. The complete development of a measuring technique built around this method obviously will require a large variety of samples. In the meantime we believe that with adequate manipulation and analysis that satisfactory results are obtainable.

## Automatic Boosters on Distribution Circuits

**Discussion and author's closure of a paper by Leonard M. Olmsted published in the October 1936 issue, pages 1083–96, and presented for oral discussion at the power distribution session of the winter convention, New York, N. Y., January 26, 1937.**

J. A. Brooks (New York and Queens Electric Light and Power Company, Flushing, N. Y.): The author has discussed in detail the application of automatic step boosters on 4-kv distribution feeders. I am inclined to agree with his views in the case of most rural circuits. That is, I feel that an automatic booster controlled by voltage relays is the solution to low-voltage problems where neither the feeder nor the bus to which the feeder is connected are regulated. In such a case, the voltage on the feeder is determined not only by the load on the feeder but by external conditions quite remote from the feeder itself. As a consequence, the feeder voltage is likely to have a large spread and voltage control for the booster must necessarily be the choice.

However, in the cases which the author describes, where the feeder voltage is held substantially constant at some feed point by induction regulators in the station, it appears to me that the possibility of current control for the boosters has been dismissed too lightly. The author states that current control operates on the principle that the voltage drop in the line is directly proportional to the current flowing. Actually, of course, the voltage drop depends upon 3 factors, they are: (1) The impedance of the circuit; (2) the current flowing in the circuit, and (3) the power factor of this load current. Of these 3 factors, the circuit impedance is a known constant and I submit that, for a circuit which feeds a suburban load, the power factor is also a constant for any given time of the day. With these 2 factors constant the only variable remaining is the load current. In my opinion, therefore, the assumption on which current control is based is accurate.

In the case which the author cites for a $2^1/_2$ per cent single step booster controlled by voltage relays it is shown that, due to an expected one per cent error in relay accuracy the effective boost obtained is only 1.5 per cent. This amounts to a reduction of 40 per cent in terms of the booster rating. If current control were used in this case and the relay error was the same—one per cent—the effective boost would be lowered by only one per cent of the voltage drop. Since the booster rating will be of the order of magnitude of the voltage drop, the relay error would result in a reduction in booster effectiveness of only one per cent in terms of the booster rating or one fortieth of that when voltage control was used.

P. E. Benner (General Electric Company, Schenectady, N. Y.): Mr. Olmsted has made a very interesting analysis of the application of boosters to the distribution circuits of the Duquesne Light Company. It should be noted that his particular problem was not one of economically regulating small loads and low-capacity feeders but consisted of supplementing the regulation of the feeder induction regulators at the substation. In this connection it would be well to differentiate between the low-capacity low-cost 10-per cent-range regulator and the low-range supplementary booster used in connection with the usual station-type feeder regulator. As shown by figure 1 the pole-type induction regulator and the small 4-step regulator were developed to make it possible to economically regulate small loads and low-capacity circuits. By means of these regulators, capacities as low as 10-kva can be obtained at approximately the same cost per kilovolt-ampere as the larger station-type regulators.

The booster on the other hand is strictly a supplementary device. A one-step booster can be readily arranged to give one $2^1/_2$-per cent fixed boost and one $2^1/_2$-per cent automatic boost. By following through the author's method of analysis, it will be seen that this arrangement gives exactly the same results as a booster having 2 automatic steps because theoretically the first step is always in. Therefore, there is no particular advantage in having the first step automatic. Moreover, the one step device lends itself to a much simpler control and should be especially attractive for this reason. Figure 2 shows several curves similar to those plotted in the author's figure 6. The curve on the one $2^1/_2$-per cent fixed and one $2^1/_2$-per cent automatic step booster has been extended to cover the same range as the $2—2^1/_2$-step booster inasmuch as the analysis shows it will produce the same results. It will be noted that the curves have been terminated so as to indicate the useful range of the device in question. Extending the curves horizontally to the right-hand margin might easily give the impression that the device was economically applicable for the entire variation of primary voltage, whereas it is believed that it would be very questionable to say the least to use a device which did not make full use of the permissible primary-voltage variation.

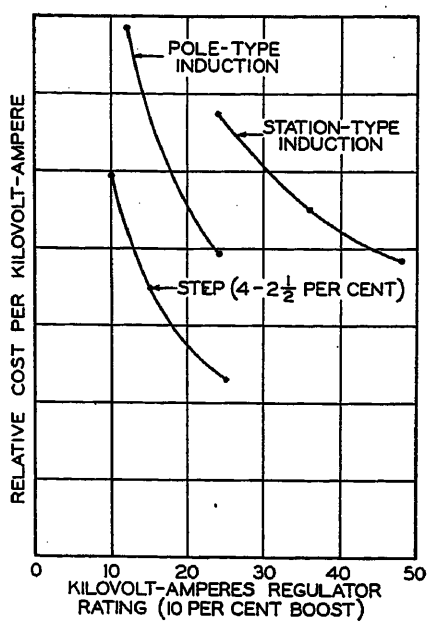



Figure 1

It is believed that further consideration should be given to the analysis by which the author concluded that the 2—1.33-per cent step booster would give the most economical operation for a primary voltage variation of 5 per cent. Figure 3 shows the factors entering into this analysis. The primary voltage varies from 100 per cent to 105 per cent. The booster is selected on the basis that its range plus the band width of its control is equal to 5 per cent. As shown, the band width figures to be plus or minus 1.17 per cent and the range 2.66 per cent. It will be noted that at full load when the incoming primary voltage is 100 per cent, the booster would attempt to hold the outgoing primary voltage within the band width for which the control was adjusted. Ordinarily the voltage held would average somewhere near the center of the band-width setting. However, in this case because of the limited range the maximum voltage which could be held approximates the lower limit of the

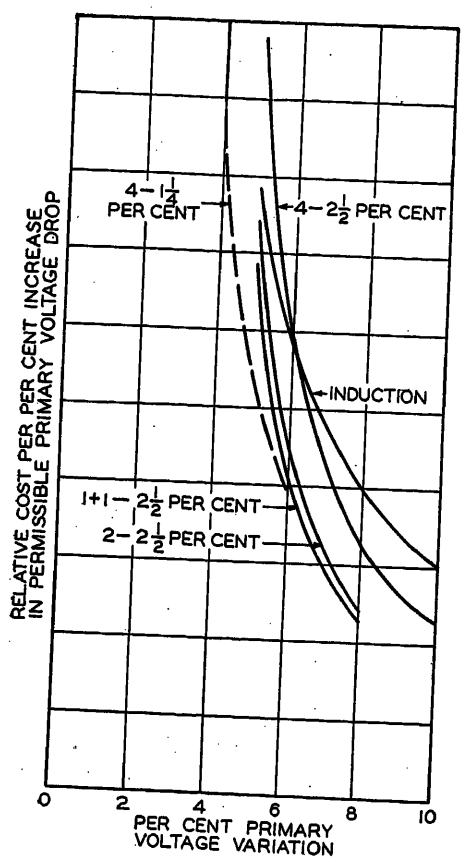



**Figure 2**

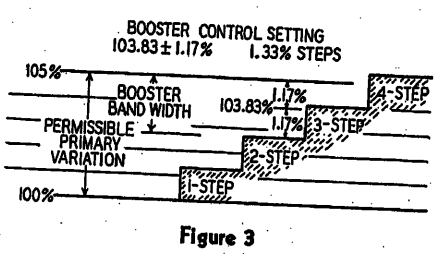



**Figure 3**

band which is a full one per cent lower than would be held if the booster had an additional one or 2 steps. It is believed that this extra one per cent in outgoing voltage is easily worth the extra cost of the larger range device. Referred to the cost of the device itself, if the first 2 steps is represented by 100 per cent the next 2 could be had for approximately an additional 30 per cent. In other words 2 additional steps, one of which as shown by the analysis would be in service at full load, would cost only about 60 per cent as much as each of the first 2 steps.

In view of this analysis it is believed that from the theoretical as well as the practical standpoint rule number 2 governing the selection of boosters should be changed to read, "The voltage range of the booster should be approximately the same as the permissible primary voltage variation in order to allow the booster to hold the maximum voltage possible."

The author has admittedly been conservative in regard to the amount of primary voltage variation permissible. It can be readily seen that the 5 per cent variation used in the analysis could easily be extended to 7½ per cent by assuming the difference in drop between the heaviest and lightest loaded transformers and secondaries to be 2½ per cent instead of 5 per cent. It should be noted that line-drop compensation would be necessary to take advantage of this increase in range from 5 per cent to 7½ per cent. That is, the booster or regulating device would hold voltage not at the point where it was located, but it would compensate for a portion of the distribution transformer and secondary drop.

From a practical standpoint it is obviously desirable wherever possible to use a regulator or booster having a range and size of step applicable to average rather than specific feeder conditions in order to permit a degree of standardization which will justify the low price levels desired on this type of equipment.

**L. H. Hill** (Allis-Chalmers Manufacturing Company, Milwaukee, Wis.): Mr. Olmsted is to be congratulated on having presented a paper which includes considerably more fundametal data than would be indicated by the title of his paper. Ever since the introduction of step voltage regulators, there has been considerable discussion concerning the use of time delay in the control; and Mr. Olmsted shows conclusively that the use of time delay will give good results from a regulation point of view. He also considers the effect of primary relay setting on the number of operations and also the size of step that can be used. His analysis of the effect of size of step on the range of regulation is general and would apply to any type of regulator.

It might be pointed out in connection with figure 5 that since Mr. Olmsted's conclusions are drawn on the basis of a regulator with 5-per cent range, the 8-step regulator would provide a ⅝-per cent step instead of a 1¼-per cent step for this application, in which case the relative effectiveness curve would have been above the curve for the induction regulator.

Naturally since Mr. Olmsted's conclusions are based on a total of 5 per cent regulation, it is necessary to point out that other conclusions might be reached for regulators of the conventional 10-per cent range, such as are needed on more rural-type lines.

It should also be pointed out in connection with figure 6 concerning the relative costs of various automatic voltage boosters the conclusion might be drawn that the size of step were the only variable. As a matter of fact, these costs must be based on equipments made by different manufacturers, and it cannot be assumed that the cost of the various mechanisms is comparable. Actually, there is considerable difference in the quality of mechanism in booster regulators of various steps. There seems to be an impression abroad on the part of some designers—and also operators, for that matter—that the tap-changing mechanism in a branch feeder regulator can be something light and flimsy, simply because it is used for branch regulation. It might be admitted for sake of argument that a regulator on branch service may not operate as frequently as one used for station type service; however, the branch type regulator will undoubtedly operate for much longer periods of time without inspection. The very nature of the application—mounted on poles in more or less inaccessible places—means that inspection and maintenance will be at a minimum; and it will not be unreasonable to expect that branch feeder regulators in many cases will operate for long periods of time without any inspection or maintenance whatever. Accordingly, it is my opinion that the mechanisms used in branch feeder regulators must be of the same order of quality as the tap changing mechanisms used in station-type regulators.

**L. M. Olmsted:** Before replying to the discussions, I wish to correct 2 errors in the published article. In figure 8, the per cent regulation from *B* to *C* should be 3.00 per cent instead of 2.66 per cent. In table II, the relay-band widths should read ±1.00, ±1.10, ±1.25 and ±1.38. It is well to observe also that table II presents estimated data and that a series of experiments intended to check them is under way but not yet completed.

I agree with Mr. Brooks' statement that voltage drop in a distribution feeder depends upon (1) impedance of the circuit, (2) current flowing in the circuit, and (3) power factor of the current. It must be observed, however, that the purpose of a booster on a regulated feeder is to correct for voltage drop between the feeding point and the booster. If there is no load tapped off the circuit between these points, then the current through the booster provides a fairly accurate measure of this voltage drop and could be used to control the booster. Usually most of the load is fed from the circuit between the feeding point and the booster, however, and a considerable part of the voltage drop is caused by load current which does not pass through the booster. In such cases the current through the booster is not an accurate measure of the voltage drop and could be used to control the booster only if the characteristics of loading on the circuit are such that the current flowing through the booster is always proportional to the voltage drop between the feeding point and the booster. For example, assume a circuit passing through an industrial section and into a residential area; voltage is low in the residential area and a current-controlled booster is installed between the 2 areas to correct it. With the relay adjusted to give satisfactory night-time voltage, the residential area might continue to get low voltage during the daytime because its day load might be too light to operate the booster to correct for the voltage drop caused by the low-power factor day-time industrial load between the feeding point and the booster.

It is quite true that the great spread between light-load current requiring no boost and heavy-load current requiring boost might permit a relay setting which would sacrifice less than one per cent of the circuit voltage, but the necessity to allow for disproportionality between booster current and voltage drop could very easily eradicate this advantage. Such considerations led the author to write that "the accuracy with which the voltage is regulated (by current control) depends upon the consistency with which the distribution of load along the circuit is duplicated from day to day. This limitation is overcome by voltage control. . . . . ."

Mr. Benner has advocated the use of boosters having one permanent step and one automatic step in place of 2 automatic steps. Undoubtedly the first booster on a

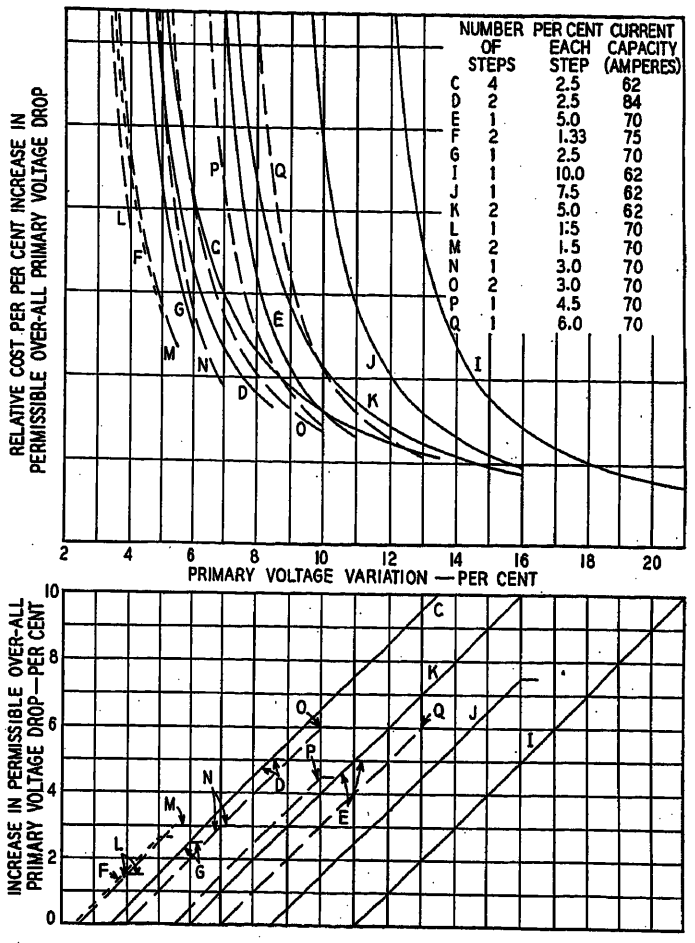



Figure 4

circuit could be of this type, but a second booster in series could not have a fixed step without causing high voltage during light-load periods. A booster having a permanent step cannot be set on neutral and bypassed out of service without interrupting customers beyond the booster. Furthermore, it is difficult to avoid some phase unbalance on long circuits, and a permanent booster might tend to increase the voltage on a phase already high on account of unbalance. The difference in cost is not large, and it is doubtful whether the savings offset the disadvantages.

Mr. Benner's criticism that the limited range of the 2—1.33 per cent step booster results in a full one per cent lower output voltage than could be secured by a 4-step booster is minimized by the fact that the input voltage of 100 per cent, upon which it is founded, actually is the lower limit of a 101 ± 1 per cent voltage band and would exist for comparatively short periods. It is well to note, however, that 4 0.8 per cent steps would hold the output voltage at 104.1 ± 0.9 volts with a lower limit 0.54 volts higher at a relative cost only a little higher than the 2 1.33 per cent steps. Of course 0.8 per cent is not a standard step, but as long as a 4-step regulator with a total range of 5 per cent or less is not standard anyway, I see no reason why the step size should not be selected for the application.

Obviously it is desirable to use a regulator or booster having a range and size of step applicable to average rather than specific feeder conditions. The very fact that these standard ratings have been found so grossly inadequate for applications having limits admittedly close but not unusual leads one to wonder whether a more generally applicable set of standards might be developed. Mr. Benner has noted that the problem "consisted of supplementing the regulation of the feeder induction regulators at the substation" and that the booster was developed for this purpose. Why, then, was a total range of 10 per cent incorporated into the design? The diagrams show the curves of figures 5 and 6 of the paper (corrected for price changes) extended to show the full range of each device. Note that a primary voltage variation of 21 per cent is necessary to secure the full effectiveness of a 1–10 per cent step booster. Surely so great a variation in primary voltage is excessive for any system. If we limit the primary voltage variation to 14 per cent, which certainly could not be considered too close, we find the 1–10 per cent step booster completely outclassed, both in effectiveness and in relative cost, by the 1–7.5 per cent and the 2–50 per cent step boosters although neither is used to its maximum effectiveness.

Boosters of somewhat less range designed for maximum effectiveness at 14 per cent primary voltage variation would have either 1–6.5 per cent step or 2–4.33 per cent steps and the relative cost, taking the price as that of the corresponding standard ratings, would be from 10 to 18 per cent lower because of the increased effectiveness. Following the present established practice of having taps at the quarter points on the one-step design, and of having a series-parallel connection on the 2-step, we would find steps of 1.62, 3.25, 4.88, and 6.50 per cent on the one and steps of 2.16 and 4.33 per cent on the other. These steps are somewhat more adaptable to the close limitations discussed in the paper than are the steps at present available on standard equipment, and indicate that compromise ratings might be found which would prove entirely satisfactory for both types of application. It is suggested that this compromise rating have 1.5, 3.0, 4.5, and 6.0 per cent taps, with a choice of one-step or 2-step tap changers. People requiring close regulation could use 2–1.5 per cent steps to secure a maximum of 3.0 per cent increase within a primary voltage variation of 5.5 per cent. People requiring maximum correction at minimum cost could use 1–6.0 per cent step to secure an increase of 6.0 per cent within a primary voltage variation of 13.0 per cent. Intermediate requirements could be satisfied by 1–3.0 per cent or 1–4.5 per cent step, or 2–3.0 per cent steps. The dashed curves based upon prices of corresponding capacity in standard ratings, show that these proposed steps lower the relative cost of booster operation within 5.0 per cent limits practically to the 2–1.33 per cent special design, and yet can be applied to the wider limits for which the present standard designs are suitable with no increase in relative cost.

Inasmuch as the amount of boost has been reduced, the largest rating of booster in the 2,400-volt class would be 104 amperes at 6.0 per cent or 15 kva, permitting standardization upon the 3 capacities of 5, 10, and 15 kva in place of the present 4. It is my opinion that such a change would be of decided benefit to the industry.

I agree with Mr. Hill's suggestion that 8–$^5/_8$ per cent steps would be more suitable than 8–1$^1/_4$ per cent for the application discussed in the paper. It would not lower the relative cost as much, however, as the one- and 2-step boosters with a total range of 6.0 per cent. Automatic voltage boosters do not receive the same attention in service as the station-type voltage regulators, consequently must be simple and sturdy, approaching as nearly as possible the reliability of distribution transformers. In my opinion time delay is valuable in that it tends to reduce the number of operations, thereby minimizing wear and increasing the time which can be allowed between inspections. Recently a spot welder has been connected on the single-phase extension of the booster application described in the paper, which varies the primary voltage almost 3 volts, and the time delay has proved very desirable.

## Trends in Distribution Overcurrent Protection

**Discussion and authors' closure of a paper by G. F. Lincks and P. E. Benner published in the January 1937 issue, pages 138–52, and presented for oral discussion at the power distribution session of the winter convention, New York, N. Y., January 26, 1937.**

H. P. Seelye (The Detroit Edison Company, Detroit, Mich.): At several points in this excellent presentation of the subject of co-ordination of overcurrent protection, the authors have mentioned the importance of economic considerations and of the rela-

tive amount of customer outage in determining the proper combination of devices. Some light on these factors has been gained from a recent study of outages on the Detroit Edison system.

The Detroit system is divided into 2 sections in which somewhat different conditions prevail. In the suburban part which includes a large number of smaller cities and towns as well as rural territory, the transformers are radial, that is each serving its own separate length of secondary, and are protected by primary fuse cutouts only. In selecting fuse sizes the emphasis has been placed on service continuity rather than protection to the equipment. The smallest primary fuse used is one of 8-ampere rating. This corresponds fairly well with the minimum of 5 amperes for a 20-to-1 ratio system which the authors of this paper have mentioned as giving proper co-ordination with the larger household fuses. The fuse itself is a cartridge fuse of special Detroit Edison design which has an appreciably greater inverse characteristic than the usual expulsion type shown in the curves of this paper. Over a 3-year period an average of only about 75 transformers per year out of a total of approximately 30,000 transformers have been burned out due to secondary short circuits or overload. This is about $^1/_4$ of one per cent. Of these, 38 per cent were $1^1/_2$ kva; 45 per cent, 5 kva; 15 per cent, 10 kva; 2 per cent, 15 kva; and a negligible amount of larger ones. The proportion between number burned out and total in service for each size is: $1^1/_2$ kva, 0.42 per cent; 5 kva, 0.29 per cent; 10 kva, 0.10 per cent; 15 kva, 0.08 per cent. It is evident that, for this system at least, the ratio of burnouts decreases rapidly with size and most of the burnouts occur on $1^1/_2$- and 5-kva sizes. For 15 kva and above the capacity seems to be large enough to burn off most faults.

An estimate of the cost of replacing and repairing burned-out transformers, compared with the cost of using secondary fuses for increased protection, showed that to accomplish any saving such a fuse must cost less than an amount ranging from 75 cents for a $1^1/_2$-kva down to 35 cents for a 10-kva including incidental material and labor of installation. A study of the curves given in this paper shows that it would be rather difficult with the conventional fuses to get much protection from such a fuse on the smaller transformers. As to the benefit to be gained in service continuity, on this system most of the $1^1/_2$- and 5-kva transformers serve only one customer so the loss of service due to their burnouts is not great. Also, the records available indicate that only about $^1/_2$ of the faults which would blow a secondary fuse, and hence interrupt service, do burn out the transformer, the other half clearing, whereas with fuse protection these would be likely to cause interruption.

In the city of Detroit, transformers are banked, that is, the secondaries tied solidly together and the transformers protected by both primary and secondary fuses in their leads. The paper points out the advantages of banking (page 147) in reducing voltage variations and the emergency duty thrown on any transformer and its protective equipment. It apparently favors the "loose" bank, however, with fuses midway between transformers rather than the solid bank, giving a number of reasons, most of which are not as serious in practice as they appear from a distance. It is true that solid banking requires somewhat more care in design than loose banking—for example, primary rings are quite a necessary accompaniment of large banks—but 30 years successful operation of this scheme in Detroit has shown conclusively that it is economical and effective in decreasing customer outage. Its advantage over the loose bank, in addition to maintaining service in case one transformer develops a fault, is that the capacity of 2 or more adjacent transformers is available to burn off a secondary short whereas, with the loose bank, the intermediate fuses are likely to blow, leaving conditions the same as for a radial system. Although cascading of a whole bank in such a case is a possibility which is frequently mentioned as a serious disadvantage, it actually occurs in relatively few cases.

A careful record of all fuses blown on the Detroit banked system over a period of 18 months, and involving about 20,000 transformers, showed only 5 cases of cascading in banks containing more than 4 transformers and in each of these only one side of the $^{115}/_{230}$-volt secondary was involved. Of the remaining cases, 50 per cent had only 2 transformers in bank, the remaining 50 per cent being about equally divided between those with 3 transformers and those with 4. In nearly all of these, the transformers were small and also usually only one side of the secondary went out. On the whole system, 267 transformers, or about $^9/_{10}$ of one per cent per year were involved in these outages but the actual service outage amounted to only half that in transformer-secondary units or $^{45}/_{100}$ of one per cent. The conclusion is evident that the bigger banks do burn off most of the faults which occur and that the best banks have more than four transformers, although of course it is not always practical to make them. Further study of this record showed that the solid banks allowed about 65 per cent less actual interruption than would probably have been experienced with a radial system, and 50 per cent less than with loose banks. Considering the small banks of 2, 3, or 4 transformers alone, the indications were that the solid bank was at least as good in this regard and probably a little better than either of the other schemes, there being many cases in which only one or two fuses were found blown without any service interruption, even where only two transformers were tied together. Transformer burnouts due to service shorts or overloads in this area are negligible.

This is not intended to disparage the "loose bank," which no doubt has its field. It is wished to emphasize what the authors have indicated in their paper that banking of transformers is an important means of improving protection to service and to point out that solid banking is practical and effective where it can be properly applied.

**E. J. Burnham** (General Electric Company, Schenectady, N. Y.): The paper by Lincks and Benner brings out facts and information which throw considerable light on the problems of overcurrent protection. By using these facts and studying the results much can be gained from the standpoint of the user and fromthe standpoint of the manufacturer.

Being somewhat familiar with the work which the New York Power and Light Corporation has done and is doing along the lines suggested in this paper, the following comments may be in order. Over the past 2 years this company has put in much hard work and effort studying their distribution system by districts to find ways and means of improving service to customers and doing it economically.

In studying a district the plan has been to first inspect the lines and make recommendations as to putting them into first class physical shape. This would include tree trimming where desirable, and seeing that crossarms, braces, and equipment on the poles were installed properly.

Secondly, decision would be made as to the type, rating, and location of overcurrent devices for each circuit in a district. This would usually mean several changes and some additional devices. Time-current characteristics were plotted for the fuses and devices, in manner shown in the authors' paper. Selections were made only after it was reasonably certain as shown by the curves plotted, that no fuse blowing would cause damage to another fuse or incorrectly cause a relay to operate and thereby trip a circuit unnecessarily.

This program has now been carried out over considerable time with what seems to be about 100 per cent results. In some of the long rural lines as many as 4 fuses have been placed in series. These might be rated for example—15, 25, 40, and 50 amperes. Some of the longer lines have been operating this way for about one year with good results as reported from the districts. However, steps are now being taken to improve the way of obtaining and reporting operating results to make sure the fuses and overcurrent devices are operating as expected. It is also the plan to obtain more information regarding the ratio of permanent to temporary faults for different circuits so the benefits to be derived from the use of reclosing devices may be determined. This seems to be a step in the right direction, because if it is worth while to spend much time and effort selecting and applying fuses and overcurrent devices, it certainly is worth while to get complete outage data and then analyze it to determine if the devices are operating as expected and also determine if any improvements can be made in the devices themselves or in the ways of using them.

**R. H. Earle** (Line Material Company, South Milwaukee, Wis.): There is a certain type of low-cost rural system now being built in different parts of the country which probably includes more of the interesting problems described by Messrs. Lincks and Benner than any other type of power distribution.

I refer to those systems in which power is delivered to individual farms through $1^1/_2$- or 3-kva transformers supplied by 4,800-volt or 6,900-volt single-phase grounded branch lines or subbranch lines. At the customer's service entrance 60-ampere fuse boxes are provided. The transformers have internal fuses and have spill-over gaps instead of lightning arresters. All branch lines have repeater fuses or reclosing breakers where the line branches off from the main feeder. When one of the gaps flashes over due to lightning the branch-line

fuse blows to clear the circuit. After a momentary interruption the next fuse of the repeater comes into the circuit and power is restored.

The 60-ampere fuse which it is possible for the customer to insert in the service box is considerably oversize for the initial load, which the customer is expected to provide and this 60-ampere fuse is, of course, too large to afford much overload protection to the transformer. The likelihood of this load increasing, however, warrants the large service fuse although first cost prohibits the installation of a larger transformer.

If the transformer fuse is installed inside the tank, it is important that the fuse co-ordinate with the 60-ampere secondary fuse and that it blow only in case of dire necessity because of the inconvenience of replacing the link. As a result the size of this link is selected so as to blow in case of a short circuit between service wires leading to the customer's house but to let the 60-ampere secondary fuse take care of less serious trouble.

The spill-over gaps that are used instead of lightning arresters require the system to be broken up into as small sections as possible so that when one of these gaps flashes over and blows a branch line fuse, only a few customers will be affected. This sectionalizing requires that the fuse links on the various branches and subbranches be spaced closer together than is ordinarily permissible. The result is that certain values of fault current will blow not only the nearest fuse but will also take out the next larger fuse in the series. A larger number of customers are affected than is entirely desirable, but since all fuses are of the repeater type the interruption of service is momentary.

A system of this kind obviously makes certain sacrifices in quality of service in order to reduce the cost of the lines to a point where it is possible to build them, and is a good example of the increasing demand being made on fuses for greater accuracy in co-ordination.

manent line faults varying from 64 to 85 per cent, 3 companies from 5.7 to 7.5 per cent, and in the case of the ninth company there seems to be more permanent faults than total faults on the circuits.

It would be very interesting to know more about the differences in conditions existing between 5 companies with high percentages of permanent faults and the 3 companies with low percentages. A great number of conditions might be responsible, such as nature of area served, type of construction, tree conditions, relay protection, etc. The differences are so great, however, that there should be some apparent reason for them.

The idea of instantaneous tripout on initial fault and time delay on reclosure is especially attractive from the standpoint of preventing permanent damage. It would be interesting to know from those companies using it, whether it has had any influence in this respect.

**L. M. Olmsted** (Duquesne Light Company, Pittsburgh, Pa.): Mr. Lincks and Mr. Benner have presented a very good account of the technique of co-ordinating overcurrent protection on a distribution system.

Similar studies by the Duquesne Light Company have indicated several difficulties, however, which might well be considered at this time.

The diagram below shows curves for a 10-kva 2,400-volt transformer serving an individual consumer. Full-load current on the secondary is 42 amperes, and inasmuch as it is common practice to permit loading up to 150 per cent of rating, this current may be as great as 63 amperes. The next larger commercial size of fuse is 100 amperes which size is taken as the basis of co-ordination. The secondary connections are 3-wire grounded-neutral and practically all of the consumers' load is connected line-to-neutral, consequently short circuits are practically all from one line to netural. This gives a transformation ratio of 2,300 to 115, so that 20 amperes primary current is equivalent to 400 amperes of secondary short-circuit current. Curves for 3 different types of 100 ampere secondary fuses are shown on this basis.

There seems to be a growing trend toward thermally tripped circuit breakers, however, and it is advisable to compare their characteristics with the curves of the fuses which they replace. The commercial size next larger than the 63 amperes load current for this 10-kva transformer is 70 amperes; corresponding curves are shown on the diagram. It is very evident that these devices are much slower blowing than fuses, which has permitted the sales feature of being less subject to tripping by motor-starting currents. The co-ordination of primary fuses, however, must be with the circuit breaker rather than fuses.

In order to provide some degree of protection to the transformer and secondary system, it is desirable to use a primary fuse of about 15 amperes continuous rating. The curves for four such fuses, each one rated for 100 per cent current and 3 of them universal, are shown as *A*-15, *B*-15, *C*-15, and *D*-15. *A*-15 co-ordinates with ample margin but has a rather high continuous carrying capacity. *B*-15 is very close at heavy currents but probably co-ordinates satisfactorily and has a more reasonable continuous-carrying capacity. *C*-15 and *D*-15 fail to co-ordinate for short circuits exceeding approximately 6 times full-load current. This comparison demonstrates the marked difference in characteristics for supposedly interchangeable fuses of different manufacture.

The comparatively recent agreement among fuse manufacturers to rate fuses for continuous operation at 100 per cent current might seem to offer some hope that the characteristics of fuses gradually will be brought into closer agreement. In that light it is unfortunate that manufacturers *B* and *C* both superseded a fuse with characteristics which would have co-ordinated

**G. B. Dodds** (Duquesne Light Company, Pittsburgh, Pa.): The authors have correlated a great amount of information relative to the protection of distribution circuits. The information they have obtained regarding outage data of various companies is particularly interesting.

As the authors have pointed out, there is a wide variation between the companies in the frequency and nature of outages. However, in one respect there is a disappointing similarity. This is in regard to the permanent line outages (per 100 miles of line) as shown in line 1, table II. Although the numbers vary greatly for the different companies, when they are compared with the total outages due to line troubles (per 100 miles of line) on line 1 of table I and expressed on a per cent basis of the total line faults, the results are alarmingly consistent for some of the companies. For example, comparing line 1 of table I with line 1 of table II, it is seen that of the total line faults, the following percentages are permanent for the various companies: 64 per cent, 61 per cent, 6 per cent, 65 per cent, 70 per cent, 7.5 per cent, 85 per cent, and 5.7 per cent.

It appears from these figures that 5 of the 9 companies have percentages of per-

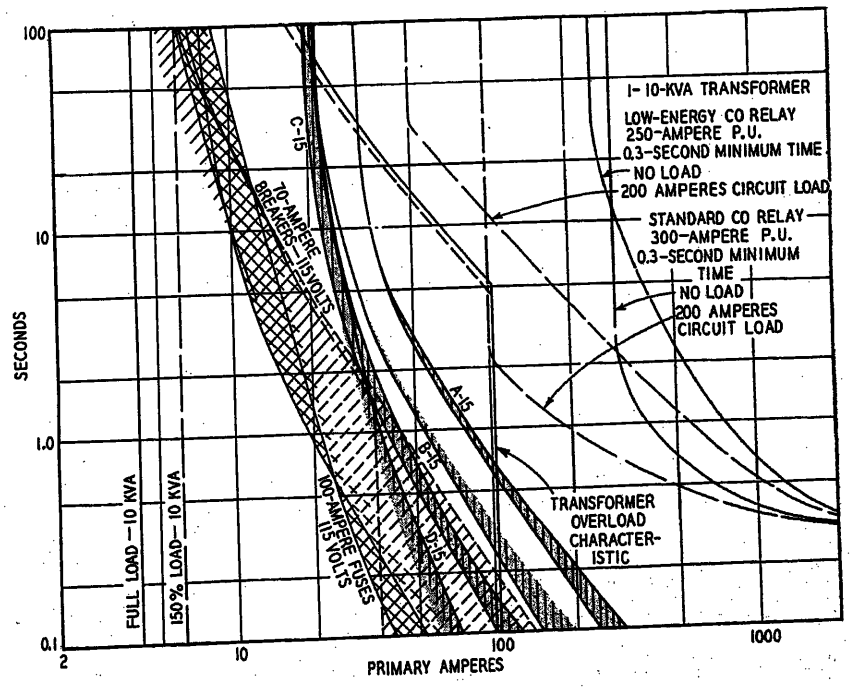



Figure 1

more satisfactorily when they introduced *B*-15 and *C*-15. There seems to be a decided trend toward "fast blowing" primary fuses, probably intended to afford better selective action between transformer fuses and line sectionalizing fuses. This trend is entirely opposite to the trend of consumers' overload protection and seriously complicates the co-ordination of primary and secondary protective devices.

**G. F. Lincks and P. E. Benner:** The authors greatly appreciate the contributions made by those discussing this paper. This should enhance its value for those interested in the improvement of service continuity on distribution systems.

It is assumed that the 100-ampere fuse and 70-ampere circuit breakers referred to by Mr. L. M. Olmsted, are those located at the meter board on the consumer's premises.

The design of the fuse links referred to as "*C*15" in Mr. Olmsted's discussion, was made to fit a scientifically developed set of time-current curves as shown in figure 4 of the published paper. In developing these, each fuse link was made to blow within 5 minutes at as low a percentage above the rating as possible and still carry the rating continuously and without exceeding a temperature rise of 30 degrees centigrade above an ambient temperature of 40 degrees centigrade. Motor starting acceleration time-current curves were plotted for motors representing 75 per cent of full-load current of a transformer fused with a fuse link rated at 2 times the full-load current, which is the lowest of the fusing practices developed and quite generally used by the utilities for the primary of distribution transformers. These practices apply to fuse links rated to blow at 150 per cent of their ratings within 5 minutes and a similar application was made in the development of the curves in figure 4

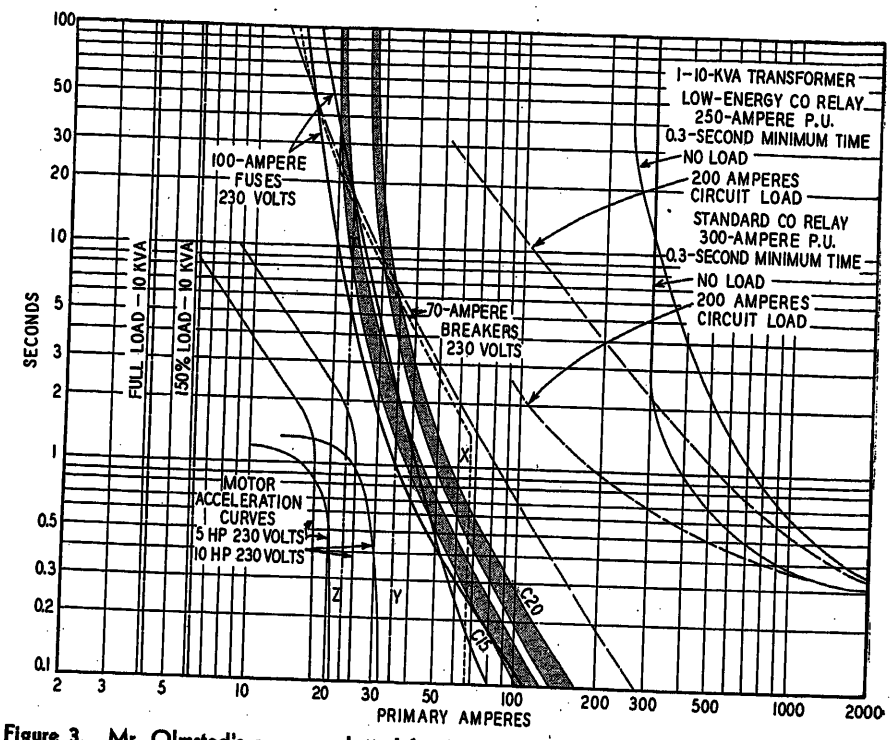



**Figure 3. Mr. Olmsted's curves replotted for 230-volt fault conditions and with 5- and 10-horsepower 230-volt motor acceleration curves**

of the published paper, although some fuse links were renamed later in order to meet the new 100 per cent continuous current carrying rating standards. Induction type relay curves approach these motor starting current curves in the range between one and 3 seconds, thus quite definitely locating the one-to-3-second range of the time-current curves for the fuse links best adapted to co-ordinate with both. The shorter-time, higher-current range of the fuse-link curves was made to co-ordinate with plunger-type relays of which there are many in service and with the interrupting rating of the fuse cutout for which the fuse links are designed. The curves for all ratings were made to parallel each other as closely as possible so the smaller fuse links will protect the larger fuse links to the highest currents possible when connected in series for line sectionalizing. The design of the actual fuse links was made so as to produce these scientifically developed curves.

In figure 2, the full-load full-voltage motor-starting-acceleration time-current curves for 3- and 5-horsepower 115-volt motors are plotted with a duplicate of Mr. Olmsted's curves for the 100-ampere fuses, the 70-ampere circuit breakers and the "*C*15" 15-ampere fuses. The 3-horsepower motor has a full-load current of 28 amperes or 65 per cent of the full-load current of the 10-kva transformer, thus closely approximating that used in the development of the "*C*15" curves. The full-load current of the 5-horsepower motor and 10-kva transformer are approximately equal. It can be seen that both of these motor-starting curves indicate successful co-ordination with the 100-ampere fuse, while the less inverse curves of the circuit breakers allow an excessively wide range above the motor-starting curves. As a result, these slower—less inverse—characteristics of the breaker prevent reasonably close co-ordination with branch-line plug or cartridge fuses (connected on either the line or load side) on the consumer's premises and, as Mr. Olmsted points out, interfere with the application of the primary fuse links scientifically developed to provide close co-ordination with both induction relays and motor-starting currents. Actual studies by the engineers of several utility companies have shown that slower (less inverse) primary fuse link characteristics than the "*C*15" curves will necessitate higher feeder circuit breaker relay settings, which

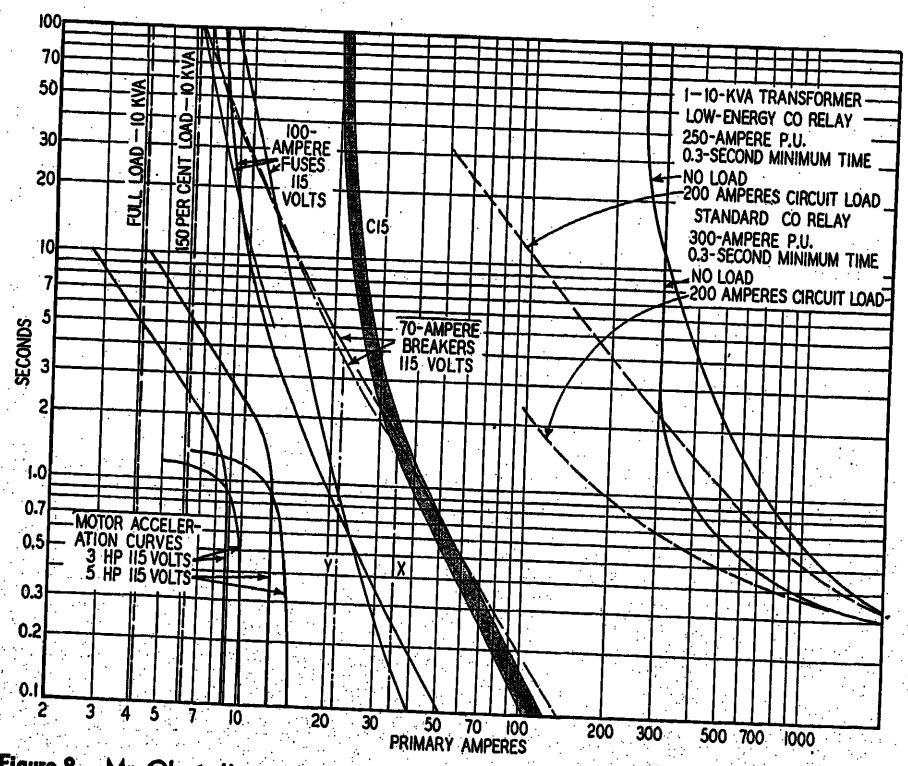



**Figure 2. Mr. Olmsted's curves replotted (115-volt faults) with 3- and 5-horsepower 115-volt motor acceleration curves**

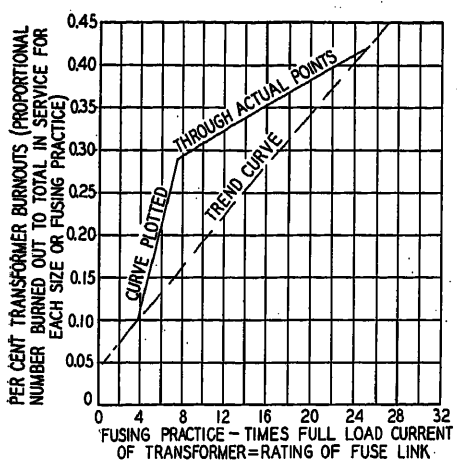



**Figure 4. Primary fusing practice—transformer burnout curve**

Based on using an 8-ampere fuse link with 1 1/2-, 5-, 10-, and 15-kva 4,800-volt transformers which Mr. Seelye states is the practice for the transformers to which the data in his discussion applies.

| Transformer Rating | Fusing Practice × Full Load | Per Cent Burnouts Per Size Installed |
|---|---|---|
| 1 1/2 | 25.0 | 0.42 |
| 5 | 7.2 | 0.29 |
| 10 | 3.8 | 0.10 |
| 15 | 2.5 | 0.08 |

in turn will interfere with the protection on the transmission system. This indicates the need for making the time-current characteristics of the secondary circuit breakers more inverse.

Mr. Olmsted has chosen the less conservative example on the basis that the majority of faults will occur between line and neutral (115 volts) where the transformation ratio for short circuit and surge currents is 20 to 1. Figure 3 illustrates the effect of line-to-line 230-volt faults for the same installation except with 5-horsepower and 10-horsepower, 230-volt motors having full-load currents of 23 and 43 amperes, respectively. It can be seen that a 20-ampere primary fuse link "*C*20" figure 3 is necessary instead of the 15-ampere fuse link "*C*15" in order to be protected by the 100-ampere cartridge fuse. However, this is not unreasonable when one considers that with the wide variation in the many different makes of cartridge fuses purchased on the open market out of the control of the utility engineer, the 100-ampere rating, in meeting the Fire Underwriters' specifications, blows at 150 amperes secondary current or 15 amperes primary current (150 per cent of its rating) within 4 minutes, while most 15-ampere primary fuse links blow at 22.5 amperes primary current (150 per cent of its rating) within 5 minutes. The curves in figure 3 show the conditions of figure 2 made worse by the lower transformation ratio, thus accentuating the need for speeding up (making more inverse) the characteristics of secondary circuit breakers for use on the consumers' premises, in order that as a comparatively new device entering the field, it may better line up with existing conditions and equipment.

The instantaneous trip shown by Mr. Olmsted for one of the 70-ampere circuit breakers, see curve *X* figures 2 and 3, as taken from Mr. Olmsted's curves, might be helpful on 115-volt faults if set to cut off at lower currents, see curve *Y* figure 2. However, as shown by curve *Y* figure 3, this does not appear to offer a solution on 230-volt faults, where the full-load current of the 230-volt motors closely approximates the full-load current of the transformer. With smaller 230-volt motors having full-load currents approximately 75 per cent of that for the transformer or even large 115-volt motors, the setting of the instantaneous trip might be made low enough, curve *Z* figure 3, to permit co-ordination with the motor acceleration curves and the "*C*20" primary fuse links of figure 3 but the co-ordination of branch line, plug, or cartridge fuses might prove difficult with such an installation.

With this background and to more directly answer Mr. Olmsted's question, the trend has been to faster time-current characteristics for primary fuse links during the past years,[1,2] so as to permit the closer co-ordination with existing induction type relays which many utility engineers have declared a vital necessity.

Mr. H. D. Seelye has made a real contribution in enlarging on the economies of secondary protection for individual transformers and outlining the advantages of the secondary banking, which he calls "solid," meaning with fuses in the secondary leads and not everything solidly tied together as is being used by another utility pioneering in this phase of secondary protection.[3] Mr. Seelye's data confirms that given in table I and II of the paper in showing that the normal primary fusing practices just mentioned are affording a high degree of protection to the transformer except for the lower kva ratings where the ratio of fuse rating to transformer full load current is much higher. The curve figure 4 shows how the percentage of transformer burnouts per size installed, as taken from the tabulation in Mr. Seelye's discussion, varies with the fusing practice. It is of interest to note that 3 of the points fall on a straight curve, indicating a trend which, of course, may or may not apply to higher-rated transformers. Mr. Seelye's records of the types of loading and any other causes for the higher percentages of burnouts with 5-kva transformers would be of value. Possibly, the increased use of 5-kva transformers for range and hot-water heating loads might be an explanation for the higher percentage of burnouts which, if true, would also raise the percentage of burnouts for 3-kva transformers above such a trend curve plotted for other utilities' systems where they are using these for similar loads. As Mr. Seelye indicates, the use of secondary protection depends on the degree of improvement in protection which can be secured and a comparison of the savings made possible thereby *vs.* the cost of securing these savings for the particular conditions pertaining on each specific system.

It was not the intent of the authors to favor the "sectionalized" or "loose" banking or any of the other types of protection covered in the published paper, but rather to investigate the effect of each of the trends in distribution protection so utility engineers may be better enabled to decide which best suits his requirements. If emphasis was placed on the "sectionalized" banking, it was because this method appears to predominate in the installations known to the authors and because it does permit securing the benefits without increasing the primary fusing practice. Actual service experience has proved that this latter is important for those wishing to sectionalize the lines now or in the future. Mr. Seelye points out that the so-called "solid" banking is best adapted to ring feeders where the secondaries of a large number of transformers are connected together which he states is not always practical to adapt to existing systems. He rates the "solid" and "sectionalized" or "loose" banking as equal where 2, 3, or 4 transformers are connected together, although having previously discounted the effect of each on line sectionalizing as discussed in the paper since he believes this is not a serious operating problem.

Mr. E. J. Burnham's discussion of the experiences of the New York Power and Light Corporation with fused line sectionalizing, which includes not only straight radial circuits but those that are more complicated and interconnected, exemplifies the growing trend toward this effective method of reducing consumer minutes outage. The improvements embodied in modern fuse cutouts and fuse links[1,2] along with the protective characteristic charts,[4] the total clearing time-current curves and the simplified methods of calculating the currents in primary line short circuits[5] now available have made primary-line sectionalizing with fuses practical even to a much greater degree than heretofore. Mr. Burnham supports the paper in stating that more actual operating data expressed in numerical terms are necessary to help toward the more effective application of this and other methods of distribution protection. However, as exemplified in Mr. Burnham's discussion, the practical and more general knowledge of utility engineers on the reductions in line outages by line sectionalizing when applied according to modern methods has placed this method of line protection beyond the experimental stage. In addition to the benefits mentioned by Mr. Burnham and in the paper, fused sectionalizing when applied in accordance with figure 12 of the published paper can be made effective in extending protection to the lines out beyond the point where the line impedance limits fault currents to values below the minimum pickup current setting of the feeder circuit breaker relay. Permanent faults might otherwise anneal the copper or actually burn down the lines.

Mr. G. B. Dodds has brought out an important point in regard to permanent *vs.* temporary faults. He appears to favor a system on which temporary faults predominate, whereas some other utility engineers have expressed their belief that the causes of temporary faults are subject to correction and thus believe permanent faults should predominate. Possibly this variance in viewpoint may influence the system design, which, along with the other conditions Mr. Dodds suggests, might be responsible for the difference between the 5 companies having a percentage of permanent faults varying from 64 per cent to 85 per cent and the 3 companies varying from 5.7 per cent to 7.5 per cent.

The authors appreciate Mr. Dodds calling attention to the misplaced decimal point in table II. In checking this table, other similar errors suggest reprinting the data in correct form.

Mr. Dodds expressed interest in the idea of instantaneous tripout on initial opening

**Table II. Comparison of Permanent Primary Line Outages with Distribution Transformer and Secondary Outages (Reprinted to Include Corrections)**

| Company | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 |
|---|---|---|---|---|---|---|---|---|---|
| 1....Permanent line outages (per 100 miles of lines) | 18.65 | 8.3 | 2.54 | 35.0 | 14.0 | 1.0 | 34.0 | 1.7 | 0.4 |
| 2....Distribution transformer and secondary outages (per 100 distribution transformers) | 7.2 | 4.1 | 8.7 | 5.6 | 8.1 | 0.9 | 7.8 | 3.0 | 11.6 |
| 3....Transformers per mile | 11.9 | 9.5 | 13.5 | | 10.7 | | 7.9 | | 8.9 |
| 4....Transformer outages for one mile of line due to permanent line faults | 2.22 | 0.79 | 3.43 | | 1.5 | | 2.68 | | 0.36 |
| 5....Transformer outages for a one-mile line due to transformer and secondary faults | 0.86 | 0.39 | 1.73 | | 0.87 | | 0.63 | | 1.03 |
| 6....Transformer outages for a 1/2-mile line due to permanent line faults | 0.505 | 0.20 | 0.83 | | 0.38 | | 0.07 | | 0.09 |
| 7....Transformer outages for a 1/2-mile line due to transformer and secondary faults | 0.43 | 0.20 | 0.86 | | 0.44 | | 0.31 | | 0.62 |

of the feeder circuit breaker and time delay on reclosure so as to permit branch line fuses to isolate permanent faults. The Toledo Edison Company have reported very favorably on their experiences which we believe extend over a period of several years. One or 2 other companies in that district have also adopted this scheme. Without doubt many engineers would welcome the publishing of any operating data they have accumulated.

Mr. R. H. Earle brings out an interesting trend in rural distribution with respect to a practice of wiring residences with 60-ampere meter switches and receptacles for future needs while installing low kva transformers rated for the present load. He states that the internal transformer fuses are selected to blow on short circuits between the service wires leading to the house. However, from the available published data, internal transformer fuses in the primary leads are usually rated too high to blow even on secondary line faults close to the transformer. Thus a secondary protective device is required if faults are to be cleared between the service entrance fuse and the transformer. As shown by curves $I'$ and $I''$, figure 9 of the paper, the rating of the internal transformer fuses is generally so high that there is very little, if any, range for sectionalizing the primary line even at one point. Thus the breaking up of the line into many sections even with the overlapping of fuse blowing as suggested by Mr. Earle, if possible at all, could only be accomplished by an extremely high setting of the feeder circuit breaker relay. On the other hand, the spillover gaps used for lightning protection require the positioning of the time-current characteristic curve for the relay, recloser or sectionalizing fuse, so it always functions on the lowest dynamic follow current at the gap furthest out on the line with sufficient speed to protect the gap. In many instances, this time-current characteristic curve is to the left of (faster than) the curve for the internal primary fuses in the transformer so the relay, recloser, or fuse on the primary lines operates ahead of the internal fuses. Under such conditions, all permanent transformer and line faults interrupt service on the entire feeder or the sectionalized portion. As explained in the paper some utilities, using the recloser for such service, shunt it manually with a fused cutout and fuse link rated high enough to permit the internal fuses to blow first when checking to determine whether the fault that caused the recloser to lock-out is on the line or in a transformer. Counters on such reclosers have indicated as high as 25 or more operations without lock-out in one lightning storm, evidently due to gap flashovers. Such operation would make impractical two or three reclosures on repeating fuses. The experiences of any utilities employing such fuses on this type of rural circuit would be valuable.

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## Pole Flexibility as a Factor in Line Design

**Discussion and authors' closure of a paper by Howard P. Seelye and Myron Zucker published in the January 1937 issue, pages 91–100, and presented for oral discussion at the power distribution session of the winter convention, New York, N. Y., January 26, 1937.**

F. W. Deck (Philadelphia Electric Company, Philadelphia, Pa.): This paper is a distinct contribution to the advancement of our theoretical knowledge in a field where practice has heretofore been based almost entirely upon experience and established precedent. It will be very helpful to those engineers whose problems permit the use of this theoretical knowledge of pole flexibility, to have available a theoretical basis upon which they can establish well-defined rules for the use of the men in the field. In some localities it may not be possible, due to the particular conditions involved, to utilize these theories, or it may not be necessary since their utilization is not demanded by the conditions encountered.

Within the Philadelphia Electric Company area, our engineering and operating forces have not so far encountered the need for a concentrated study of methods such as Messrs. Seelye and Zucker have developed, due to the fact that there has been a lack of the particular problem which the authors describe as existent in the Detroit district. In the development of standards for pole line construction, we have utilized the higher stress values which have been developed in the regulations and codes within recent years, and these values are leading to the use of smaller poles. It has not been necessary to make frequent use of the smaller size poles of other utilities as guy stubs.

Sometimes we "rake" the end poles of a line to a specified amount so that when the wire loads reach the normal tension at 60 degrees Fahrenheit the pole tops are in a vertical position. Of course, when heavy ice loads are applied, there is an additional deflection of the pole; but the pole, even designed thus as a semirigid structure, is not called upon to withstand a greater load than 60 per cent of the ultimate strength of the wire.

If the fixity of the pole in the ground can be precisely determined, and if no loads occur during either the period of construction or actual service which would cause a stretching of the wire to a point outside of the range covered by the initial modulus of elasticity, then the method of design prescribed in the paper can be used with accuracy. These factors, however, deserve attention and must be thoroughly taken into consideration in the application of the method described by the authors. If the pole in question is blocked against foundation movement, the likelihood of any considerable variation in its position at the base, from the fixed vertical, is very slight. However, it may not always be possible to block or concrete the base of these poles, and in such cases it is well to remember that the change of position of the top of the pole due to movement of the pole in the ground may lead to as great or even greater change in the span length, with the accompanying tensional changes in the wires than the actual flexing of the pole itself. Even if the pole is blocked below the ground line, freezing and thawing of the soil at the ground line is responsible for a difference in the resistance to movement of the base of the pole.

Also, if for some reason or other the wire is stretched during the construction to a point greater than the average tension sustained under normal conditions, the computation may be considerably in error unless some allowance for this change has been made in the selection of the wire modulus used. Heavy loading would also cause a plastic extension of the wire material and have something of the same effect. These wire effects are, however, much less pronounced in copper than in aluminum or in composite cables where aluminum is present.

A pole system is not necessarily constructed with such refinements that the effects of unequal construction loads can be entirely eliminated, and therefore it is possible that flexibility in the poles might be an

important contributing factor in this type of design, extending farther back into the line than the 2 poles of the span considered.

Wood as a material cannot be subjected to the ordinary principles of design with the same freedom as materials such as steel and concrete. The fibrous composition of wood raises shear to a much greater importance than in materials having a more crystalline and homogeneous construction. Longitudinal shear or shear parallel with the fiber, together with effect of defects in the wood on the distribution of shear are of the utmost importance in some types of wood design; and while they do not achieve nearly the importance in the cantilever pole used to support wires as they do in the horizontal beam, still they are factors not to be lightly dismissed. Their effect upon the section modulus to be used and consequently upon the proper cross section of the pole is worth while considering. Poles may when newly erected, and more frequently after they have been in service for some time, have a central section which is not of full value. The unit stresses allowed take care of these considerations to some extent, but not entirely so. The articles written by Mr. J. A. Newlin, of the Forest Products Laboratory, United States Department of Agriculture, are interesting in regard to these last points since they are the result of Mr. Newlin's long and varied experience in testing, designing, and using wood in all kinds of work.

With regard to the methods which are developed in the paper in determining the bending in the pole and the final position of equilibrium, it is well to remember that in cases where lateral as well as transverse loads come upon the same pole, sometimes at different levels, the "deflection constant $p$" is affected and should be either a partial constant for each direction of bending or else a combination constant for the resultant direction of bending. If these loads are applied at different levels, the determination of the combined bending effect is somewhat more involved, but some answer to this question must be determined, or else only a part of the stress in the pole will have been considered and hence the computations may be in error.

This paper should arouse great interest among those who have to do with the design and construction of wood-pole lines, and should encourage studies and experiments to determine the movement of a pole in the ground when the pole is not blocked, and where average types of soil are encountered. Further studies should also be developed to show the combined effects of vertical and horizontal longitudinal and transverse loads occurring simultaneously. Also, in this connection it would be interesting to know the magnitude of the actual guying effect which the supported wires provide against lateral transverse deflection in the individual poles in a long line of poles.

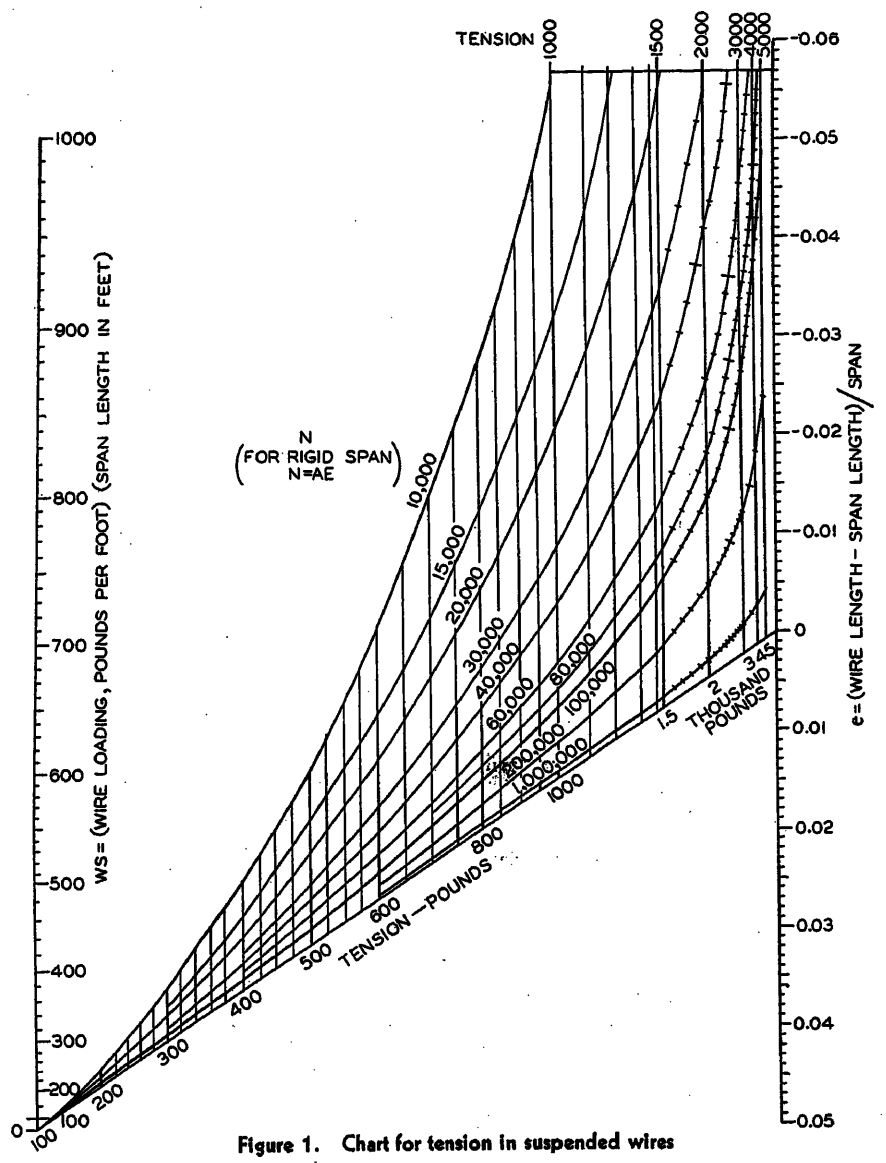



Figure 1. Chart for tension in suspended wires

**A. B. Campbell** (Edison Electric Institute, New York, N. Y.): The presentation of this paper offers a needed opportunity to discuss wood-pole flexibility in connection with the design of overhead lines. Since the second edition of the National Electrical Safety Code was published about 20 years ago, it has contained a general requirement that did not permit taking into account the deformation or deflexion of any part of a supporting structure in the calculation of stresses. This requirement has been included in subsequent editions. Inasmuch as this code forms the basis for the minimum construction requirements in force by several state regulatory commissions, the requirement just mentioned is given legal status where this part of the code has been adopted.

Actually, flexibility is oftentimes desirable in the supporting structure of an overhead line, particularly when these supports are wood poles. It constitutes one of the greatest assets of a structure in resisting ice and wind loads, and probably is the explanation why many lines have not failed when theoretically they might have been expected to do so.

The code requirement referred to above has made it necessary to assume a wood pole as a rigid structure. Compliance with this assumption has usually been obtained by the use of guys or braces, some of which have in themselves introduced electrical conditions that have resulted in conductor failures which the installation of the guys were intended to prevent. Furthermore an attempt to make a wood pole into a rigid structure by the use of guys which are not required to support a constantly unbalanced load, is likely to introduce a mechanical condition which prevents the distribution and equalization of stresses throughout the pole and thus causes failure at or near the point where stresses are concentrated. There is little doubt but that a rigidly guyed pole is less capable of withstanding impact loads than one which is free to deflect within reasonable limits under load and then return to its normal position when the load is removed.

This is one phase of the problem. Another is that no generally accepted method has been developed which would make possible a precise solution. Attempts have been made and considerable thought given to the problem but several factors are involved which make an exact solution impossible. For example, the effect of moisture content in the pole and the varying conditions in earth settings are not only difficult to evaluate but vary from day to day. It is well known that a relatively small longitudinal movement of a pole top can result in excessive conductor tensions or greatly reduced clearances. Since this effect would vary quantitatively with weather conditions, no exact method of calculating this effect seems possible. Therefore the code rule previously

referred to was perhaps the best method known at the time the code was formulated to hold variations in sags, tensions, and clearances within desired limits.

The past several years have furnished a wide experience in the performance of wood poles under normal loading and storm conditions. In my opinion some of the conditions for which guys are used seldom occur and when they do the guyed pole, when properly selected, seems to possess the ability to equalize stresses and remain unbroken. For this reason I favor the omission of unnecessary guys and the use of an approximate method such as the authors of this paper have developed whereby a reasonable advantage may be taken of the inherent flexibility of a wood pole structure. It is to be hoped that further attention will be given to the subject covered by this paper and an effort made to co-ordinate loadings with the flexible characteristics of wood pole structures.

**H. P. Seelye and Myron Zucker:** Mr. Deck has summarized the elements that must be considered in designing flexible spans. However, it must be emphasized that while such items as load distribution up the pole, strength of pole foundations, elastic limit of the wire, and pole constants enter into the problem, they are by no means indeterminate.

In discussing these variables, the governing fact is this: a relatively great variation in deflection constant will cause but little change in the relation between stringing and loaded tensions. Therefore, pole and foundation movement per unit load need be determined only with reasonable accuracy. The 2 elements of uncertainty in pole flexure are variation of fiber stiffness, and vertical distribution of load. The former is admittedly a variable, although not to quite the extent that might be indicated by tests on small specimens. Deflection constants derived from tests on 15 full-size poles have agreed within ±25 per cent of calculated values. As to the latter, a reasonable approximation may be made, for wires in the same zone, by using the deflection constant for a load height equal to the square root of the sum of individual heights squared. For more widely separated loads or loads in different directions an analysis of deflections may be made. It is relatively complicated and requires solution by successive approximations as described in the paper for joint-use leads.

As to foundation movement, the results of several short-time and numerous long-time full-size tests have enabled us to specify foundation designs for various types of soil and ranges of load, so that poles may be held with a negligible or reasonably predictable foundation yield. Considering the relative unimportance of deflection constant, mentioned at the beginning of this paragraph, the accuracy is well within the limits assumed for standard loading conditions.

It is of course possible to stretch wires past their elastic limit. However, the tendency for this to happen is less in flexible spans than in rigid spans where the effect is generally neglected. In addition, a study of $N$ will show that the wire stretching is generally a minor factor compared with pole bending.

Straight-grained woods are greatly to be preferred for holding dead-end loads, since their moduli are more consistent and they yield less initially and over a period of time than do knotty poles, due to the large bending effect in the latter when moderate loads straighten out the curved fibers surrounding the knots.

Informal discussion has shown that a chart in terms of tension instead of sag is needed for convenience in calculation. Substituting equation 6 in equation 5 gives the relation

$$e = \frac{w^2S^2}{24T^2} - \frac{T}{AE} \qquad (5a)$$

This may be charted as in figure 1, which is manipulated in the same manner as figure 9. Thus, with $w_1S$, $N$, and $T_1$ known $e$ is found; appropriate changes are made in $e$ for temperature variation and external forces; and then with $e'$, $N$, and $w_2S$ known, $T_2$ is read. The chart may be used whenever tensions are involved, and is especially valuable when tension is specified under one set of conditions and is to be found for another set. The range of figure 1 may be extended by using any desired scale multiplier on the $wS$, $T$, and $N$ values (not affecting $e$).

Mr. Campbell mentions some variables—moisture content and pole setting—which are difficult to evaluate. This difficulty must be admitted, but it applies equally well (as do the points enumerated by Mr. Deck) to the design of poles for transverse loads. The uncertainty of actual loads and the judgment needed in specifying safety factors overshadow the other unknowns in both cases. At any rate, satisfactory results have been obtained with numerous special cases of flexible dead ends designed according to the principles outlined in the paper.

Mr. Campbell's comments bring out the advantage of flexibility under certain conditions and point to the fallacy of the common idea of "being on the safe side." This reinforces the thesis of the paper: that calculation of dead ends on the assumption of rigidity may actually make some elements in the line undersize. Regardless of the merits of unguyed poles, it is certain that where they *are* used, the design should be based on the fact of flexibility rather than the fiction of immobility.

## A Review of Overhead Secondary Distribution

**Discussion and author's closure of a paper by W. P. Holben published in the January 1937 issue, pages 114–22, and presented for oral discussion at the power distribution session of the winter convention, New York, N. Y., January 26, 1937.**

**Harold Cole** (The Detroit Edison Company, Detroit, Mich.): Mr. Holben's paper is, I think, a valuable addition to the technical information on the matter of secondary-distribution economics. The secondary wires and their associated transformers form such a large proportion of the investment of an electrical distribution system that the importance of sound engineering in this field cannot be overemphasized. The comparison of the results of studies made on 5 large systems shows very little difference in conclusions, despite some rather wide variations of assumptions as to cost factors. The interesting thing is that the investigators agree that wire sizes from number 4 to number 2 are the most economical for the densities of load found largely in urban districts, and that through a rather large range of load densities there is not a great variation in the relative cost of the secondary distribution system, no matter whether number 4, number 3, or number 2 wire is selected, providing, of course, that the transformer size and spacing is selected to give the minimum cost of the combination of the 2. If the smaller wires are installed initially, the later cost of more frequent relocation of transformers or of secondary replacement, or both, offsets the initial saving in investment to a greater or lesser extent, depending on the rate of growth of load.

All of this would indicate that a rather wide latitude is possible in the proportioning of secondary copper and transformers without affecting greatly the over-all economy. The important thing to my mind, therefore, is that a program of development is laid out that is best suited to the conditions in the particular area under consideration and that it is carried out under intelligent supervision. Haphazard development results in costly rearrangements later on or else perpetuates uneconomical layouts made in an effort to take care of the immediate necessity at the least cost without consideration of over-all economy.

An effective way of providing for an orderly development of the distribution system is to draw up master plans which show the location of all poles, transformers, secondary and primary mains in all areas which have been subdivided into city lots. If the facilities are built as required in accordance with these plans, the cost of the initial extensions may be slightly higher than would be possible with expedients which take account only of the cost of providing service to the few scattered customers first applying, but in an area which is expected to build up solidly in a few years, the added cost of later rearrangement of facilities amply justifies the slightly higher first cost.

In my own company we have prepared such master plans, not only for undeveloped areas but for the older sections of the city where replacement of poles will be required in the future. In this way, the relocation of transformers and replacement of wires may often be carried out at time of pole replacement at a minimum of expense. The planning of these layouts is supervised by an engineer of long experience in distribution design and every effort is made to adapt the layout to the type of load which may be expected to develop in that area.

In residential areas we have adopted number 2 copper wire as standard for secondary mains and initial transformer spacings are usually 700 to 800 feet. The initial transformers may be as small as 5 kva but where development is expected to be rapid or where range load will probably develop, we will use the 10-kva size. A spacing of about 800 feet is necessary with these small transformers if noticeable voltage dips caused by starting of small household appliance motors are to be avoided. Ability to give adequate voltage for electric ranges in the early development stages also requires spacings of this order. The same secondary

wire and transformer spacing will be adequate for load densities up to about 50 kw per 1,000 feet. It is only necessary to change transformer sizes as the load requires. We feel that any possible saving in the use of wire smaller than number 2 in the early development stages would not justify the poorer quality of service which would result, especially in view of the present trend to more complete home electrification with the increased use of appliances equipped with electric motors as well as the larger heating appliances which will ultimately result in much greater load densities. On the other hand, the use of conductors larger than number 2 does not seem to be required in residential areas, even with the increased load densities to be expected, as a relocation of transformers on number 2 secondaries will permit going to much higher densities when they develop before the system becomes uneconomical.

Incidentally, the banking of transformers on a more or less continuous secondary main, such as practiced in Detroit and now being rapidly extended to other parts of our system where conditions are at all favorable, is very helpful in many ways to the economical development of the system. Steady state voltages are more easily maintained on the secondaries and voltage dips due to motor starting are much less troublesome, to say nothing of decreased outages due to transformer failures and less transformer capacity required.

I want to emphasize that the orderly development of a distribution system requires a trained personnel to supervise that development. The men who are responsible for this development should be men of engineering training, and should not be burdened with so much detailed routine work that they do not have time to adequately study the engineering problems involved in additions to or changes in the system. The use of master plans, however, will be of much aid to these men in helping them to make rapid decisions and still not overlook some important considerations which would not escape one who had sufficient time to study all of the conditions involved. The field engineer need then only concern himself with situations where new considerations develop which make it desirable or necessary to modify the original plans.

I want also to urge the importance of making studies such as those reviewed by Mr. Holben for each particular system. I do not wish to minimize the value of the presentation of such a review but there is some danger, I think, that some of the general conclusions may be misinterpreted by those who have not carefully studied all aspects of the problem. A study which takes account of all of the local field conditions and operating practices will make certain that development plans will be adopted which are best suited to the particular system.

W. P. Holben: Mr. Harold Cole, in his discussion of the paper "A Review of Overhead Secondary Distribution," has presented a number of points that are worthy of serious consideration. In fact, I am heartily in accord with these items as well as the results to be obtained by using his recommendations and will therefore repeat them in outline form.

1. Importance of sound engineering to include studies for each particular system
   - *a.* To account for all local conditions
   - *b.* To avoid misinterpretation of the general conclusions
2. Need for a program of development
   - *a.* Intelligent and experienced supervision
   - *b.* Master plans with future steps indicated
   - *c.* Procedure in new developments

The summary and conclusions, included in the paper, have stated some necessary exceptions to the principles recommended by the respective authors. There are other natural differences of opinion and local operating practices that will probably affect the application of these principles of design on various systems. Further study therefore along the following lines should provide valuable information and knowledge on the subject of overhead secondary distribution.

1. A classified list of necessary exceptions with the best engineering solution for the principal classifications
2. Flicker conditions and economical solutions.
3. Transformer loading practice and a summary of experience records especially for the higher per cent loadings
4. Banking transformers, single-phase, and 3-phase, for large appliance load to meet capacity and flicker conditions

Mr. Cole has referred to the practice of banking transformers in Detroit. He reports improved voltage conditions, decreased outages and less transformer capacity required for areas served in this manner. It is apparent therefore that such advantages warrant a thorough study of this type of a secondary system. Mr. Sweetman and Mr. Arnold have contributed the suggestion that the new development in transformer design and use of a secondary breaker for transformer protection warrants further development of secondaries with banked transformers at least on a trial basis. With a probable increase of flicker complaints as the appliance load increases, it follows that banking should be considered as a possible solution since this method cuts sudden voltage variations to approximately half of that experienced on radial secondaries under similar conditions.

## Negative-Sequence Reactance of Synchronous Machines

**Discussion and author's closure of a paper by W. A. Thomas published in the December 1936 issue, pages 1378–85, and presented for oral discussion at the synchronous machinery session of the winter convention, New York, N. Y., January 27, 1937.**

S. B. Crary (General Electric Company, Schenectady, N. Y.): This paper presents a very complete theoretical and experimental analysis of the AIEE method of measuring the negative-phase-sequence reactance and should result in a more accurate description of the method of testing by the AIEE.

Figure 1 of this discussion presents in a little different way than in the paper, the

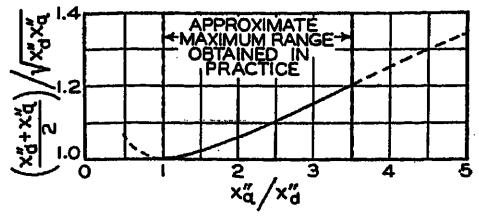



**Figure 1. Ratio of the 2 expressions for $x_2$ as a function of the ratio of the subtransient reactances. Full line indicates approximately the maximum range obtained in practice**

variation between the 2 limiting values of negative-phase-sequence reactance as a function of the ratio between $x_q''$ and $x_d''$. In this figure the approximate maximum range to be expected in practice is indicated by a solid line. As seen from this curve the maximum variation to be expected is about 20 per cent for a ratio of $x_q''$ to $x_d''$ of 3.5. This variation, of course, would decrease quite rapidly with increase in the amount of external reactance. Accordingly, the value $(x_d'' + x_q'')/2$ can be used for most practical purposes in system calculations involving this reactance.

J. C. Balsbaugh (Massachusetts Institute of Technology, Cambridge): Reference is made to the application of the negative-sequence reactance of synchronous machines to the study of power system fault currents. I should like to add several significant factors in the application of this reactance.

For a line-to-line fault in a power system as viewed from a generator, the negative-sequence reactance is given in general by the equation

$$x_2 = \sqrt{x_d'' x_q''}$$

in which $x_2$ is the equivalent negative-sequence impedance from and including the generator to the fault, $x_d''$ and $x_q''$ are the sum of the generator subtransient reactances $x_{dg}''$ and $x_{pq}''$, respectively, and the equivalent external reactance $x_e$. The negative sequence reactance $x_{2g}$ of the generator, is equal to $x_2 - x_e$ and is equal to the geometric mean of the generator subtransient reactance with $x_e = 0$, and approaches the arithmetic mean of the generator subtransient reactances with $x_e$ large relative to $x_{dg}''$ and $x_{qg}''$. The equivalent external reactance $x_e$ is not in general the reactance from the machine to the point of fault, but in a power system with a group of machines feeding into a fault through a network, it is the equivalent reactance as viewed from the generator terminals.

It is further important that the foregoing negative-sequence reactance does not apply in general to all line-to-line faults in a power system, but only those faults that are line-to-line faults as viewed from the generator terminals. Thus consider an individual generator tied to a line through a Δ-Y grounded transformer and a ground fault on the line. In this case a line-to-ground fault on the line becomes an equivalent line-to-line fault on the generator and $x_{2g}$ is determined as given in the foregoing, and $x_e$ must be determined as an equivalent impedance as viewed from the generator terminals.

It can also be shown that the negative-sequence reactance in general for a line-to-

**Table I. Definitions of Negative-Sequence Reactance**

| Method | Analytical Expressions | | Numerical Value $x_d' = 0.35$ $x_q = 0.70$ $x_d = 1.0$ | |
|---|---|---|---|---|
| | Fundamental | Root-Mean-Square | Fundamental | Root-Mean-Square |
| (1) Application of sinusoidal negative-sequence voltage | $\frac{2x_d' x_q}{x_q + x_d'}$ | $\frac{\sqrt{2}x_d' x_q}{\sqrt{x_q^2 + x_d'^2}}$ | 0.47 | 0.44 |
| (2) Application of sinusoidal negative-sequence current | $\frac{x_q + x_d'}{2}$ | $\frac{1}{2}\sqrt{(x_q + x_d')^2 + 9(x_q - x_d')^2}$ | 0.53 | 0.74 |
| (3) Initial symmetrical component of sudden single-phase short-circuit current | $\sqrt{x_d' x_q}$ | $x_d'(\sqrt{1-b^2}-1) + \sqrt{x_d' x_q}\times\sqrt{1-b^2}$ | | |
| (4) Sustained single-phase short-circuit current | $\sqrt{x_d' x_q}$ | $x_d(\sqrt{1-b^2}-1) + \sqrt{x_d' x_q}\times\sqrt{1-b^2}$ | 0.50 | 0.48 |
| (5) Same as (4) with 0.35 p.u. external reactance | | | 0.50 | 0.47 |
| (6) AIEE | | $\frac{x_q + x_d'}{2}$ | | 0.50 |
| | | | | 0.53 |

ground fault (as viewed from the generator terminals) in a power system is

$$x_2 = \sqrt{\left(x_d'' + \frac{x_0}{2}\right)\left(x_q'' + \frac{x_0}{2}\right)} - \frac{x_0}{2}$$

in which $x_2$ is the equivalent negative-sequence reactance from and including the generator to the fault, $x_d''$ and $x_q''$ are the sum of the generator subtransient reactances $x_{d0}''$ and $x_{q0}''$, respectively, and the equivalent external reactance $x_e$ and $x_0$ is the equivalent zero-sequence impedance from and including the generator to the fault and is equal to sum of the generator zero-sequence impedance $x_{0g}$ plus the equivalent zero-sequence external impedance $x_{E0}$ to the fault. The negative-sequence reactance of the generator $x_{2g}$ for the condition is equal to $x_2 - x_e$.

Thus it is seen that accurate determinations of negative-sequence impedances of generators for use in connection with fault studies in power systems involves the circuit connections and other system impedances. These and other considerations should be taken into account in the measurement of negative-sequence impedances of synchronous machines and in their application.

**C. F. Wagner** (Westinghouse Electric & Manufacturing Company, East Pittsburgh, Pa.): Mr. Thomas is to be congratulated in raising the general question of the nature of the negative-sequence reactance of synchronous machines. A particularly valuable contribution is his analytical proof that the AIEE method of measuring the negative-sequence reactance gives a quantity equal to the arithmetic mean of the reactances in the 2 axes.

In reading this paper I have been prompted to make a table to show some of the methods that might be suggested to measure the negative-sequence reactance. In preparing this table a salient-pole machine without amortisseurs has been considered because the effects in question should be pronounced in such a machine. Resistances will be neglected. The first method consists in applying a sinusoidal set of negative-sequence voltages to the machine. Using the fundamental component of current in defining the reactance results in the expression[5]

$$\frac{2x_d' x_q}{x_q + x_d}$$

but if $x_2$ be defined in terms of the root-mean-square values the reactance is equal to

$$\frac{\sqrt{2}\,x_d' x_q}{\sqrt{x_q^2 + x_d'^2}}$$

However, if a sinusoidal set of negative-sequence currents be made to flow through the machine a fundamental and third harmonic voltage are set up across the armature. In terms of the fundamental component $x_2$[5] is equal to $x_q + x_d'/2$ and in terms of the root-mean-square values is equal to

$$\frac{1}{2}\sqrt{(x_q + x_d')^2 + 9(x_q - x_d')^2}$$

If $x_2$ be defined as such a quantity which with $x_d'$ will give, upon applying symmetrical components, the proper fundamental component of current for the initial a-c component of a suddenly applied single-phase short-circuit current, then $x_2$ is

$$\sqrt{x_d' x_q}$$

and to give the proper root-mean-square value of current $x_2$ is

$$x_d'(\sqrt{1-b^2} - 1) + \sqrt{x_d' x_q}\,\sqrt{1-b^2}$$

This is the method described in paragraph 184 of the Preliminary Report on a Proposed Test Code for Synchronous Machines (January 1937).

If $x_2$ be defined as that quantity which will give the proper fundamental component of sustained single-phase short-circuit current when the method of symmetrical components is used, then $x_2$ is again

$$\sqrt{x_d' x_q}$$

and to give the proper root-mean-square value of current, $x_2$ should be

$$x_d(\sqrt{1-b^2} - 1) + \sqrt{x_d' x_q}\,\sqrt{1-b^2}$$

The AIEE method which is also based upon the sustained single-phase short-circuit test but with different metering connections gives, as Mr. Thomas has shown, the value of $x_2$ as $(x_q + x_d')/2$.

It is difficult to draw conclusions of the relative merits of the different expressions until numerical values are inserted. To this end a typical machine was chosen having the constants

$x_d' = 0.35$
$x_q = 0.70$
$x_d = 1.0$

and the numerical values corresponding to the different analytical expressions were tabulated on the right-hand side of the table.

Let us now analyze these results in view of the utility of the quantity and the applicability of the method as a testing means. The greatest use of $x_2$ is in connection with short-circuit and stability studies. It would appear then that the results obtained by the root-mean-square values for the single-phase short-circuit tests, would be the most important, preference being given to the sustained value because it results in a somewhat smaller value of reactance and also, because it does not require an oscillograph, is an easier method to apply. The AIEE method gives a value of $x_2$ somewhat greater than the value obtained by the single-phase short-circuit test. With regard to the ease in making the test it will be noted that the only difference between the single-phase short-circuit method and the AIEE method is that the latter requires an extra wattmeter whereas the former requires a previous knowledge of the synchronous reactance. The difficulty of obtaining either a sinusoidal negative-sequence voltage or current would eliminate the first 2 methods as test methods.

I am therefore submitting this discussion for your consideration. It would appear that the sustained single-phase short-circuit test for root-mean-square values is a better test for salient-pole machines than the present AIEE method. In terms of the test values this quantity is expressed by the equation

$$x_2 = \frac{\sqrt{3}\,E}{I} - x_d$$

where

$I$ = root-mean-square value of armature current in the short-circuited phase
$E$ = open-circuit voltage before the short circuit is applied or the no-load voltage corresponding to the field current at which $I$ is read

For turbogenerators saturation introduces variables of such greater magnitude that the appropriate method of measuring the unsaturated value becomes inconsequential. Perhaps the best solution for turbogenerators is to simply use the subtransient reactance.

**W. A. Thomas:** I wish to emphasize the need of agreement on the use or abandonment of the per-unit system of notation. I have deliberately avoided throughout my paper such short-hand systems as per-unit or per-cent notation.

To a large group of engineers and especially to students who are reading the literature for applications of fundamental principles, such special systems are not easily understood. Some equations when written in a per-unit system lose their dimensional check and thus invite confusion.

May I suggest a return, in all synchronous-machine papers, to the use of fundamental units of voltage, current, and reactance?

# Two-Reaction Theory of Synchronous Machines

**Discussion and author's closure of a paper by S. B. Crary published in the January 1937 issue, pages 27–31, and presented for oral discussion at the synchronous machinery session of the winter convention, New York, N. Y., January 27, 1937.**

W. V. Lyon (Massachusetts Institute of Technology, Cambridge): Mr. Crary's method of analysis is particularly suited to transient conditions of operation. For some cases of steady-state operation a simpler method of analysis may be preferred. The criterion for self-excitation of a salient-pole machine when it is running synchronously ($s = 0$) with the field circuit open and delivering current to a balanced capacitive load having series constants of $R$ and $X$ was given in my discussion of "Synchronous Machines—I," by Doherty and Nickle, AIEE, page 947, 1926). In this discussion I said:

"There is a problem of some interest that the authors did not mention. It is that of a synchronous generator which, when feeding an open-circuited transmission line, loses its field excitation. If $R$ and $X$ represent the equivalent resistance and reactance of such a line on open circuit then it is readily shown for this case that

$$(R + r)^2 = -(X + x_q)(X + x_d) \qquad (1)$$

This shows that $X$ is capacitive and lies between $x_q$ and $x_d$. Since the values of $x_q$ and $x_d$ depend upon the saturation, a graphical solution of the foregoing relation can be made which will determine the saturation, and from that the terminal voltage can be found."

This equation 1 is derived from the equations which apply to the steady-state operation of a salient-pole synchronous machine.

$$\left.\begin{aligned} E &= (R + r) I_q - (X + x_d) I_d \\ 0 &= (R + r) I_d + (X + x_q) I_q \end{aligned}\right\} \qquad (2)$$

where $E$ is the excitation electromotive force due to the d-c field and $R$ and $X$ are the series resistance and reactance of the capacitive load ($X$ is inherently negative).

If $E = 0$ it follows that

$$(R + r)^2 = -(X + x_q)(X + x_d)$$

from which the critical value of $X$ for self-excitation is

$$X = \frac{-(x_d + x_q) \pm \sqrt{(x_d - x_q)^2 - 4(R + r)^2}}{2}$$

This agrees with Mr. Crary's equation 24. The greatest value of $X$ for which self-excitation can occur is determined by substituting for $x_d$ and $x_q$ their *unsaturated* values. If it be assumed that there is *no* resistance in the circuit, either $(X + x_d)$ or $(X + x_q)$ equals zero. Due to the effect of the reluctance toque, the machine will undoubtedly operate stably so that $I_q = 0$ and hence it is $(X + x_d)$ that equals zero. The synchronous reactance in the direct axis equals $x_m/k + x_a$, where $x_m$ is the unsaturated value of the magnetizing reactance in the direct axis and $k$ is the saturation factor (see "Saturated Synchronous Reactance," C. Kingsley, Jr., AIEE, March 1935). Consequently

$$|X| = \frac{x_m}{k} + x_a$$

or

$$k = \frac{x_m}{|X| - x_a} \qquad (3)$$

Since $x_m$ and $x_a$ are both constant, the value of the saturation factor for any value of $X$ numerically less than $(x_m + x_a)$ but numerically greater than $x_a$ can be found, and hence the electromotive force $E_a$ due to the resultant air-gap flux can be determined. The terminal potential $V$ is

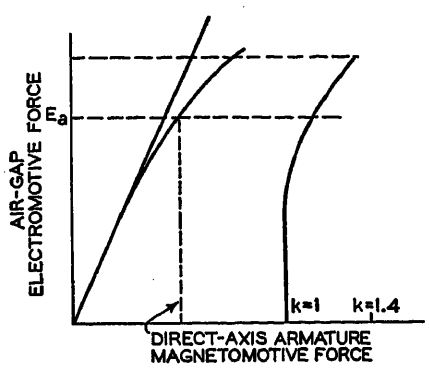



Figure 1

$$V = \frac{|X|}{|X| - x_a} E_a \qquad (4)$$

The resistance $(R + r)$ can be taken into account if desired, but the expressions are not as simple. In this case the stable operating point depends both upon the direct-axis synchronous reactance and upon the quadrature-axis synchronous reactance. It is necessary to assume in what manner *each* of these reactances is affected by saturation. As a first approximation assume that the magnetizing reactances in each axis are affected *equally* by saturation. That is, assume that

$$x_d = \frac{x_{md}}{k} + x_a \qquad (5)$$

$$x_q = \frac{x_{mq}}{k} + x_a \qquad (6)$$

This approximation is better when the resistance, $(R + r)$, in the circuit is well below its limiting value of $\frac{x_d - x_q}{2}$ for which condition the internal power-factor angle is 45 degrees and $I_d$ equals $I_q$. If these values of $x_d$ and $x_q$ are substituted in equation 1,

$$\frac{1}{k} = \frac{-(X + x_a)(x_{md} + x_{mq})}{2x_{md}\,x_{mq}} \pm \sqrt{\frac{(X + x_a)^2 (x_{md} - x_{mq})^2 - 4x_{md}\,x_{mq}(R + r)^2}{2x_{md}\,x_{mq}}} \qquad (7)$$

It follows that the greatest numerical value of

$$\frac{R + r}{X + x_a}$$

is

$$\frac{x_{md} - x_{mq}}{2\sqrt{x_{md}x_{mq}}}$$

This determines the greatest value of the power factor at the air gap in terms of the unsaturated values of the magnetizing reactances in the 2 axes. The sign before the radical in equation 7 must be taken so that $k$ is greater than one. If both values of $k$ are greater than one, the larger value should be chosen, since the flux will stabilize itself nearer the direct axis than the quadrature axis.

Consider the following numerical case: Let

$x_{md} = 0.85$ $\qquad X = -0.80$
$x_{mq} = 0.40$ $\qquad R + r = 0.20$
$x_a = 0.15$

Whence, using the minus sign before the radical, $k = 1.07$. If the plus sign is used before the radical, $k = 0.764$. The greatest value of $(R + r)/(X + x_a)$ is 0.386. From equation 2, since $E = 0$,

$$\frac{I_q}{I_d} = \frac{R + r}{X + x_q}$$

The tangent of the angle between the axis of the field pole and the axis of the fundamental component of the armature flux is

$$\frac{I_q\,x_{mq}}{I_d\,x_{md}}$$

and in this numerical example is

$$\frac{0.20}{-0.80 + \frac{0.40}{1.07} + 0.15} \times \frac{0.40}{0.85} = 0.341$$

The displacement of the armature flux with respect to the field poles is 20 degrees. This small displacement tends to justify the assumption that saturation affects the magnetizing reactances in the two axes equally.

There is another point that I wish Mr. Crary would discuss. It is well known that an induction generator may self-excite on a capacitive load. With a cylindrical rotor there is no tendency of the rotor to occupy one position rather than another with respect to the rotating armature magnetomotive force. On the other hand, there is a strong tendency for the rotor of a salient-pole machine to lock with the rotating armature magnetomotive force and run so that the quadrature component of the armature current is just sufficient to satisfy the condition that the power developed $I_d I_q (x_d - x_q)$ is sufficient to carry the load $I^2(R + r)$. What is the criterion which determines whether the machine will run as an induction or as a synchronous generator? If the resistance, $(R + r)$, in the circuit is greater than its critical value of $(x_d - x_q)/2$ so that the machine cannot operate stably as a synchronous generator, will the machine operate stably as an induction generator at a slip sufficient for the development of the necessary power?

C. Concordia (General Electric Company, Schenectady, N. Y.): We have recently had occasion to apply the methods given by Crary to the determination of the stable and unstable regions of operation of an induction motor when operating with series capacitance. Curves have been determined for induction motors similar to figure 1 of the paper. In this case only the unshaded portion of the unstable region of figure 1 appears since the ordinary induction motor has a symmetric rotor. Takahashi (reference 4 of the paper) has given similar induction motor curves for some cases and our results have been in complete agreement with his.

Also by a simple extension of the theory to the case of a resistor in shunt with the series capacitor we have shown that for this extended case, the final equations 14 and 15 of the paper will still apply if only the first $p$ in each of these equations is replaced by

$$\left(p + \frac{x_c}{R}\right)$$

where $R$ is the shunt resistance. The complexity of the equations is therefore not increased and the only change is in the introduction of the quanity $x_c/R$, which may be interpreted as the reciprocal of the time constant of the capacitor-resistor circuit considered by itself. Using these extended equations the regions of stable and unstable operation of induction motors have been determined as affected by the value of shunt resistance. It has been found that if $x_c/R$ be plotted as a function of $x_c$ just as the series resistance $r$ was plotted in figure 1 of the paper, the unstable regions in the 2 cases are very similar in both form and magnitude.

S. B. Crary: Professor Lyon has made an analysis of the phenomena of self-excitation based upon the steady state equations, that is, $i_d$ and $i_q$ are constants for any given set of circuit conditions. The phenomena cannot be properly described by such an analysis, as self-excitation is produced under the conditions when the armature magnetomotive force is pulsating with respect to the direct and quadrature axes, $i_d$ and $i_q$ are varying with time. From the steady state equations for the direct and quadrature components of armature current (equations 33 and 34) one might suspect that the critical values of armature circuit capacitance ($x_c$) corresponds to the condition when the denominator of this expression equals zero. However, the denominator being equal to zero merely indicates that the steady state components of armature current would be very large at 2 definite values of capacitance (infinite neglecting saturation) if the field excitation or armature voltage is finite.

The condition when the denominator of the steady-state equations equals zero corresponds to the 2 points at which one of the roots of equation 21 (with $T_0 = 0$) is zero. This corresponds to the points at which the roots change sign. The time constant of build-up of the armature current is infinite. Accordingly, the transient and steady-state equations are in agreement at these 2 critical points, but the steady-state equations do not by themselves indicate the region of self-excitation.

In order to explain why self-excitation will occur for values of $x_c$ from $x_d$ to zero, Professor Lyon says "Due to the effect of the reluctance torque the machine will undoubtedly operate stably so that $i_q = 0$ and hence it is $(X + x_q)$ that equals zero." No reluctance torque as ordinarily defined exists unless there is an applied armature voltage. If self-excitation exists $i_q$ will not be a constant value equal to zero, so that the explanation based upon the steady-state equations is misleading and unnecessary.

Professor Lyon asks about stability and "What is the criterion whether a machine will run as an induction or as a synchronous generator?" A machine will run as a synchronous generator when connected to an impedance load when there is a unidirectional field excitation corresponding to that produced by residual or d-c excitation. The machine will operate as an induction machine if the circuit constants and the speed are such as to produce self-excitation. Stability is determined by the balance between the electrical and mechanical torques. No electrical torque will be developed for the case when there is no field excitation or applied armature voltage unless the machine self-excites. If the machine self-excites the electrical torque after the currents have reached their maximum values as limited by saturation will pulsate if the machine is of salient pole construction, but will be constant if the rotor is symmetrical.

The results of Mr. Concordia's work, which he has only very briefly described in his discussion, constitute an important extension of the theory, as many cases occur in practice which do not correspond to the comparatively simple cases studied in this paper. It is hoped that his results will shortly be made generally available by presentation to the AIEE.

There is one point in regard to the derivation of equations 18 and 19 which it would be well to point out at this time. In the derivation of these equations for $i_d$ and $i_q$, the changes in field excitation were neglected, that is, $\Delta E_{fd} = \Delta E_{fq} = 0$. This assumption was of course unnecessary and the components of $i_d$ and $i_q$ due to the field excitation voltages, $E_{fd}$ and $E_{fq}$ can be determined in a similar manner to that used for determining these components due to $e_d$ and $e_q$. Since several readers of the paper have asked in regard to these components, it was deemed advisable that they be given in this closing discussion. The direct and quadrature axes components of armature current, including the components due to the field excitation are given below:

$$i_d = \frac{-\{[p^2 + (1-s)^2]Z_q(p) + px_c\}e_d - \{[p^2 + (1-s)^2](1-s)x_q(p) - (1-s)x_c\}e_q\{[(1-s)^2 + p^2]^2 x_q(p) + [(1-s)^2 + p^2]pr - [(1-s)^2 - p^2]x_c\} G_d(p)E_{fd} - (1-s)\{[(1-s)^2 + p^2]r + 2px_c\}G_q(p)E_{qd}}{A(p)} \quad (18a)$$

$$i_q = \frac{+\{[p^2 + (1-s)^2](1-s)x_d(p) - (1-s)x_c\}e_d - \{[p^2 + (1-s)^2]Z_d(p) + px_c\}e_q + (1-s)\{[(1-s)^2 + p^2]r + 2px_c\}G_d(p)E_{fd} + \{[(1-s)^2 + p^2]^2 x_d(p) + [(1-s)^2 + p^2]pr - [(1-s)^2 - p^2]x_c\}G_q(p)E_{fq}}{A(p)} \quad (19a)$$

It will be noted that all of the components of current have the same denominator $A(p)$. It can be further shown that when these expressions are rationalized the resulting denominator which determines whether or not self-excitation will exist will be the same. This means therefore that the results presented in the paper apply equally well for small changes in the field excitation voltages, as well as for changes in the armature voltage.

## Synchronous Machine With Solid Cylindrical Rotor

**Discussion of a paper by C. Concordia and H. Poritsky published in the January 1937 issue, pages 49–58, and presented for oral discussion at the synchronous machinery session of the winter convention, New York, N. Y., January 27, 1937.**

S. B. Crary (General Electric Company, Schenectady, N. Y.): This paper represents a valuable contribution to the theory of synchronous machines in that the effect of eddy currents in the main flux path of the solid rotor are included in the general equations. This makes possible more accurate analyses than have heretofore been made of the effect of the solid rotor on the short-circuit current, the torque slip characteristics, running out of and pulling into step, etc. Additional information as to the effect of saturation is also made available as the authors included the permeability of the rotor as one of the factors entering into their equations. The mathematical analysis of the effect of rotor eddy currents and main-flux saturation which the authors have made was essential in order that a better qualitative and quantitative understanding of the transient phenomenon involved in solid rotor synchronous machines be obtained.

The short-circuit current of turbogenerators has been calculated for some time based on rather empirical design constants which when compared with test data have not always checked very well. The reasons for these differences have been properly attributed to the difficulty in evaluating the effect of magnetic saturation and eddy currents in the magnetic parts.

It now seems desirable to consider in the light of the work by Concordia and Poritsky the present status of the problem of the determination of the magnitude of short-circuit currents of solid cylindrical rotor machines. They have found that the effect of main rotor body saturation and eddy currents is comparatively small, indicating that saturation and eddy currents in the leakage paths must play a predominant part in reducing the effective reactance to short circuit currents. In this analysis they assumed constant rotor permeability, an assumption which is likely to be questioned because the density actually may vary considerably. The importance of this assumption of constant permeability on the main flux path and the relative effect of leakage flux to main flux saturation may be more reasonably evaluated now on the basis of neglecting the effect of eddy currents, since Concordia and Poritsky have shown the relative unimportance of this factor in determining the short circuit current.

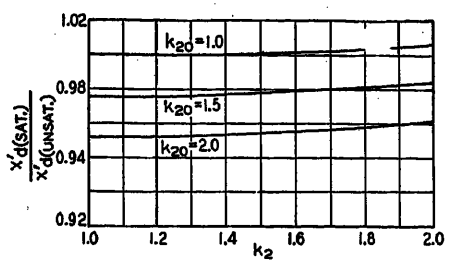



**Figure 1. Effect of rotor main-flux saturation**

If the effect of eddy currents is neglected, the comparative effect of main and leakage flux saturation can be approximately evaluated by equation 10 of a discussion given on page 1114 of the 1935 AIEE TRANSACTIONS. This equation is:

$$x_{d'(sat.)} = 2 \times \frac{\left(\frac{x_{afd}}{k_2} + x_l\right)\left(\frac{x_{afd}}{k_2} + \frac{x_{fld}}{k_3}\right) - \frac{x^2_{afd}}{k_2{}^2}}{\frac{1}{k_{20}}\left[\frac{x_{afd}}{k_2} + \frac{x_{fld}}{k_3}\right] + \frac{1}{k_2}\left[\frac{x_{afd}}{k_{20}} + \frac{x_{fld}}{k_{30}}\right]} \frac{1}{k_{20}}$$

$k_2$ = rotor main-flux saturation factor
$k_3$ = rotor leakage-flux saturation factor
$k_{20}$ = rotor initial main-flux saturation factor
$k_{30}$ = rotor initial leakage-flux saturation factor

Refer to the above mentioned discussion for more complete definitions of this and the remaining quantities.

Figure 1 of this discussion shows the ratio between $x_{d(satd.)}$ as calculated by this equation to $x_{d(unsat.)}'$ for the case when the leakage saturation is zero ($k_{30} = k_3 = 1.0$) for different conditions of initial saturation in the rotor main flux path ($k_{20} = 1.0, 1.5, 2.0$), while the saturation at the instant of maximum armature reaction varies ($k_2 = 1.0$ to 2.0). As shown by these results, the initial saturation in the main flux path has only a small effect, while changes in saturation from the initial to the value at the instant of maximum armature reaction has a still smaller effect. The magnitude of the effect of the initial saturation in the main flux path checks very well the results obtained by Kilgore ("Effects of Saturation on Machine Reactances," AIEE TRANSACTIONS., volume 54, pages 545–50, May 1935) and by Concordia and Poritsky for the laminated-rotor case. The additional fact, indicated by figure 1, that the effect of the change in rotor main-flux saturation is very small and tending to increase the effective reactance checks physical reasoning and further justifies the assumption of Concordia and Poritsky of constant permeability in the main flux path. Physically, increased saturation in the main flux paths under short-circuit conditions is due to an increase in density due to a required increase in the total flux near the base of the rotor teeth in the direct axis in order that constant field flux leakages be maintained. This interesting fact was pointed out sometime ago by Mr. P. L. Alger. Although this increase in density may increase the saturation in the rotor, it results in a very small increase in the effective transient reactance. This probably can be noticed more decidedly by its effect to increase the a-c component of induced field current rather than its effect on the magnitude of short-circuit current, the short-circuit current being limited chiefly by the leakage flux. Therefore, the conclusion is reached that the effect of rotor main-flux saturation on the magnitude of armature short-circuit current is small and that the effect of leakage-flux saturation is the important factor which should be further investigated.

Accordingly, letting $k_2 = k_{20} = 1.0$ in equation 1 and investigating the effect of changes in initial leakage saturation ($k_{30} = 1.0, 2.0$) and changes in leakage saturation at the instant of maximum armature reaction ($k_2 = 1.0$ to 4.0), the results shown in figure 2 of this discussion were obtained. It is seen from these results that the effect of saturation in leakage paths is appreciable.

These results indicate the very decided effect of saturation in the leakage flux paths in reducing the effective reactance, while very little effect is produced by saturation in the main flux path.

Because of the importance of saturation in the leakage flux paths on the short-circuit current, a possible explanation for the apparently inconsistent results sometimes obtained when attempting to obtain the transient and subtransient reactances from the oscillographic records presents itself. Maximum leakage flux exists when the rotor has moved 180 degrees after the instant at which the 3-phase short circuit was applied, this leakage flux decreasing to a minimum value at 360 degrees and then rising to a slightly reduced maximum value at 540 degrees, etc., until the d-c armature transients have died out. Therefore, if the envelope of the completely offset wave of armature current is measured, this effect will tend to yield lower values of short-circuit reactance than the envelopes which are not completely offset. If a completely offset wave is not obtained, the lowest possible value of short-circuit reactance may not be obtained. This leakage flux, which pulsates with respect to the rotor, disappears with the decay of the d-c components of armature current, so that if the d-c components of armature current have disappeared, the magnitudes of the envelopes of the different phases should be approximately equal and the saturation in the leakage paths considerably reduced even for the case of a long field time constant.

This suggests a modification of our present manner of defining and measuring subtransient and transient reactance of turbogenerators. Possibly, we should use the terms "maximum possible 3-phase short-circuit current" to apply to the first peak of the completely offset current wave and "transient symmetrical short-circuit current" to apply to the component of short-circuit current obtained from extending the slowly decaying components of armature current, after the d-c component of armature current has decayed, back to the zero time axis. These 2 values of current could have their corresponding values of reactance. The reactance determined after the d-c components of armature current had decayed could be used in calculating system short circuits where the d-c time constant is very small, which is practically true every place except on or just off a generator bus. This reactance could also be used in stability calculations.

The value of reactance used for determining "the maximum possible short-circuit current" could be used for determining the maximum short-circuit currents near or at the generator terminals. This method would have the advantage of giving more accurate answers and a clearer conception of the actual effect of saturation on the short-circuit current.

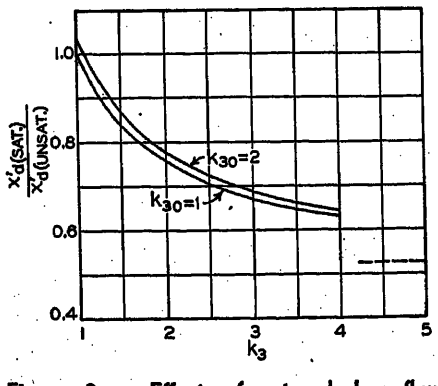



**Figure 2. Effect of rotor leakage-flux saturation**

## Contributions to Synchronous Machine Theory

**Discussion and author's closure of a paper by A. S. Langsdorf published in the January 1937 issue, pages 41–48, and presented for oral discussion at the synchronous machinery session of the winter convention, New York, N. Y., January 27, 1937.**

S. B. Crary (General Electric Company, Schenectady, N. Y.): Dean Langsdorf has presented an interesting paper which gives methods of obtaining the steady-state characteristics by graphical constructions. Such constructions have the advantage in that the work involved in calculating the steady-state performance of a machine may be materially decreased. The work that Dean Langsdorf has done suggests a further step, that of taking saturation more completely into account by modifying the present constructions based on no saturation. This would make the results considerably more practical as the steady-state performance of a machine is affected appreciably by saturation in the magnetic circuit under many normal and particularly under certain abnormal operating conditions. The effect of saturation on the steady-state performance is, in general, a more important factor than the effect of saliency.

If the effect of saturation is to be considered it is suggested that the assumptions in regard to it be critically reviewed. Saturation in the armature core is not negligible and there may arise conditions of operation in which saturation in the pole tip cannot be neglected. Dean Langsdorf presents in figure 16 a method for modifying V curves to account for the effect of saturation. This modification tacitly assumes that saturation in the field poles is only a function of the field excitation while actually saturation in the field poles is a function of the flux in the pole which is dependent on both the armature and field magnetomotive forces and not the field magnetomotive force alone.

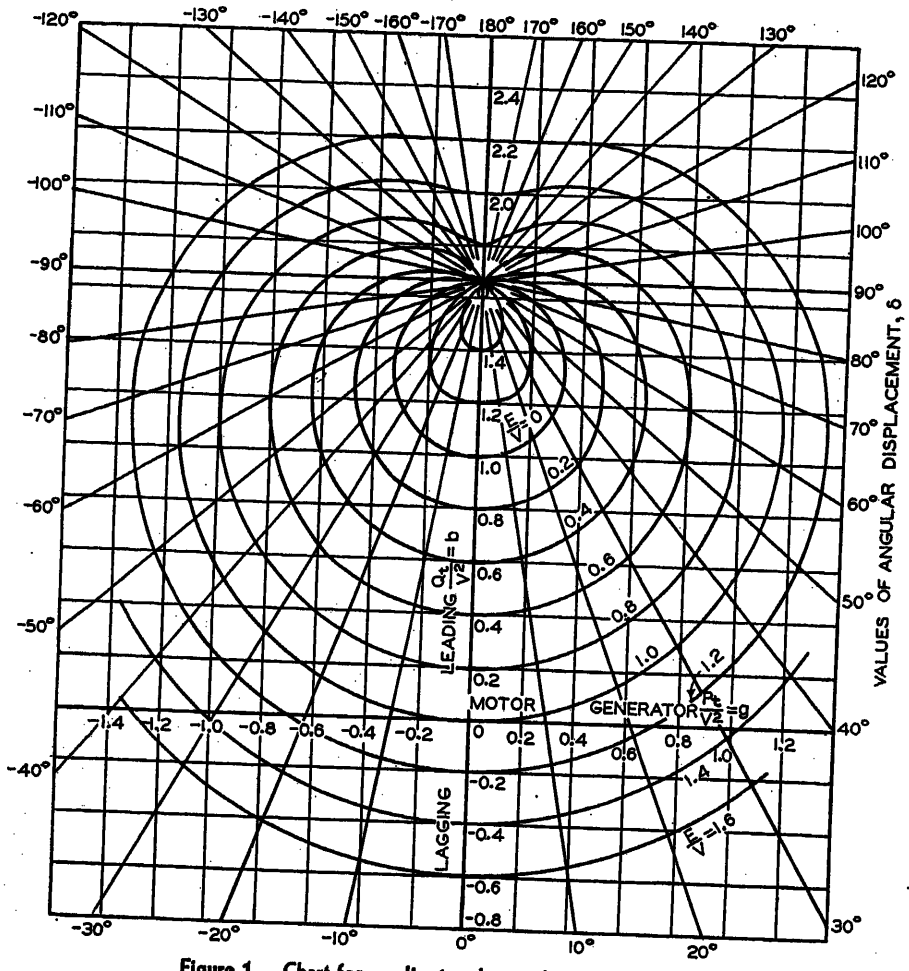



**Figure 1. Chart for a salient-pole synchronous machine**

$R_a = 0$ $X_d = 1.00$ $X_q = 0.60$

**H. E. Edgerton** and **Charles Kingsley, Jr.** (Massachusetts Institute of Technology, Cambridge): The writers, in collaboration with Professor W. L. Sullivan (now at Stevens Institute of Technology) developed several years ago a power chart for salient-pole synchronous machines which is very similar to the current chart, figure 10, of Professor Langsdorf's paper. The chart is illustrated in figure 1 of this discussion. The rectangular co-ordinates are

$$\frac{\text{power at the machine terminals}}{V^2} = \text{apparent conductance } g$$

= active component of armature current per-unit terminal voltage,

and

$$\frac{\text{reactive volt-amperes at the terminals}}{V^2} = \text{apparent susceptance } b$$

= reactive component of armature current per-unit terminal voltage.

Positive values of power are for generator action. Positive values of reactive volt-amperes are for leading-current generator action, or lagging-current motor action. The curves show the relation between the apparent conductance and susceptance for various constant values of the ratio $E/V$. The radial lines show various constant values of the load angle $\delta$. The chart shown is drawn for a machine having the following constants:

$R_a = 0$
$X_d = 1.0$ per unit
$X_q = 0.6$ per unit

The reactances are assumed to be constant, independent of saturation. This same assumption is made by Professor Langsdorf. Although resistance has been neglected in drawing this chart, it is not a difficult matter to include resistance, as will be shown subsequently in describing the method by which the chart is drawn. Practically, the effects of the resistance of the machine are usually very small.

This chart is very much like figure 10 of Professor Langsdorf's paper. In fact, if figure 10 of the paper were rotated counter-clockwise through 90 degrees, and the scale altered by dividing by the terminal voltage $V$, Professor Langsdorf would have obtained exactly these same curves for this machine. The advantage of altering the scale in this manner is that the chart now shows the vector loci of the armature current per unit terminal voltage. The chart can now be used at any terminal voltage, by correcting the readings taken from it in accordance with whatever the terminal voltage may be. This is a simple matter of multiplication. In addition to the curves for constant values of the ratio $E/V$, radial lines are drawn which show constant values of the load angle $\delta$.

The only essential differences between this chart and figure 10 of Professor Langsdorf's paper are the change of scale, making the chart applicable at any terminal voltage (saturation being neglected), and the addition of the radial angle lines. This chart can be used, as shown by Professor Langsdorf, to obtain practically any of the normal steady-state operating characteristics of the machine.

The chart is constructed by a different method than that used by Professor Langsdorf. The procedure is shown in figure 2 of this discussion. In this construction the armature resistance is included. The construction is as follows:

Compute the co-ordinates of the point $A$, which are

$$g = -\frac{R_a}{R_a^2 + X_q^2}$$

$$b = +\frac{X_q}{R_a^2 + X_q^2}$$

Draw the line $OA$, connecting point $A$ with the origin. Except for the change in scale and the rotation of the chart through 90 degrees, this line is the same as line $OC$ of Professor Langsdorf's figure 9 extended to the point $A$ where line $OC$ again intersects the reluctance circle.

Draw the perpendicular bisector of $OA$ and find point $G$, its intersection with the $b$-axis. The distance $OG$ should be equal to $\frac{1}{2} X_q$.

Draw the axis of symmetry $AGB$.

Draw the reluctance circle $ALC$ with its center $O'$ on the axis of symmetry $AGB$ and with its diameter equal to

$$\frac{X_d - X_q}{R_a^2 + X_d X_q}$$

Except for the change in scale, this is the same circle shown in figure 9 of the paper.

Draw in a number of radial lines $ALP$, $AL_1P_1$, etc., radiating from point $A$. These are the lines of constant load angle $\delta$. The load angle is equal to the angle which these lines make with the zero angle line $AO$.

From the intersections $L$, $L_1$, etc., of the angle lines with the reluctance circle, measure the distance $LP$, $L_1P_1$, etc., equal to

$$\frac{E}{V}\,\frac{Z_q}{R_a^2 + X_d X_q}, \text{ where } \frac{E}{V} \text{ is a chosen value.}$$

Draw the curve connecting points $P$, $P_1$, $P_2$, etc. This is the admittance locus for the particular chosen value of $E/V$.

By repeating this comparatively simple graphical construction for other chosen values of $E/V$, the complete chart can be constructed.

It can readily be shown by simple geometry that the points $L$, $L_1$, etc., are the same as the corresponding points which would be obtained by Professor Langsdorf's graphical construction.

Mathematically, the curves are limaçons, symmetrical about the line $AB$, and having the polar equation

$$\rho = a + b \cos\theta$$

where $a$ and $b$ are constants.

There have also been several articles

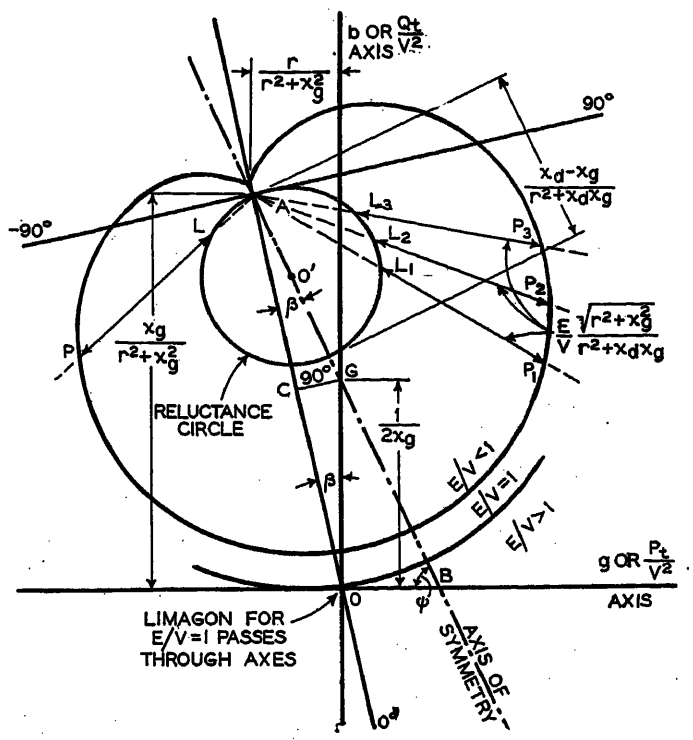



**Figure 2. Construction of the chart**

published in German ("Das Stromdiagramm der Synchronmaschine mit Ausgeprägten Polen in Symbolischer Behandlung," by Johannes Schammel, *Archiv für Elecktrotechnik*, volume 23, 1929, page 237). This article also gives a bibliography which may be of interest to those following the subject.

**Sterling Beckwith** (Allis-Chalmers Manufacturing Company, Milwaukee, Wis.): The relations and curves derived by Mr. Langsdorf are very interesting, and probably answer questions which have been wondered about by everyone who has worked with synchronous machines for any appreciable length of time.

There are 2 interpretations of the term "equivalent" impedance. One is the reactance which can be used to replace the varying reactance of a machine and which has the value that will give correct power limits for the machine when used with constant internal voltages in the usual formulas for power limits. Another is the reactance which will give the correct internal voltage of a machine. A point worth mentioning in connection with the 2 definitions, both of which appear in the literature on the subject, is that the first reactance will not give correct internal voltages, and that the second reactance will not give correct stability limits. In order to get correct stability results with the latter type of reactance, for example, it is necessary not only to take into account the magnitude of the reactance but also its rate of change and the rate of change of the internal voltage. Both reactances are useful for their purposes, but their shortcomings must not be overlooked.

Two questions occur to me after reading the article. One is whether the power circles in figure 10 are true circles, or whether they approximate circles as in the case of the circles for constant internal voltage $E$. The other is whether the assumption of negligible tooth saturation and the use of the no-load saturation curve in figure 16 are sufficiently accurate in view of the fact that stability is dependent on the rate of change of saturation.

**A. S. Langsdorf:** The excitation loci of figure 10, and their Cartesian representation in the manner indicated in figure 12, have been checked experimentally by slip tests made with a small 15-kva laboratory alternator. The accompanying oscillograms, all made by the usual slip-test method show the results of slip tests with zero excitation (curve number 9); with very small excitation (curve number 10); and with a larger, but less than normal, excitation (curve number 11).

In the case of oscillogram number 9, the theoretical polar current locus is the small reluctance circle $O'$ of figures 9 and 10. The current variation through the range from $\delta = 0$ to $\delta = 360$ degrees should theoretically show values of current which are less than the average through a range smaller than 180 degrees, and which are greater than the average through an angle of more than 180 degrees. This conclusion is amply supported by the oscillogram.

The second oscillogram, number 10, shows very clearly the humps predicted by figure 12 of the paper; and oscillogram number 11 shows how these humps are leveled with increasing excitation, and with the asymmetry to be expected because of the fact that the excitation loops of figure 10 extend below the zero-power circle more than they rise within it.

It is a further fact that the maximum power that can be developed by an unexcited motor (indicated by circle $P_1$, figure 10) is equal to the reluctance power

$$\frac{V^2(X_d - X_q)}{X_dX_q}$$

which appears as the coefficient of the second term of the coupling factor (equation 44), provided the resistance $R_a$ is neglected. The proof of this statement follows readily from the equations given in the paper.

There is no doubt that a critical study of the effect of saturation, as suggested by Mr. Crary, would be useful to designers, but it is nevertheless true (quoting from the original paper) that "the full effect of saturation of the magnetic circuit is apparently beyond the scope of any reasonably simple analysis." It was believed that such an open disclaimer, serving as an introduction to the "reasonably simple" construction of figure 16, constituted sufficient notice of the approximate nature of that construction. As a matter of fact, the approximations involved in figure 16 are precisely the same as those suggested in appendix *D* (part I) of Doherty and Nickle's paper,[1] (footnote refers to numbered references in the article) and which are there shown as modifications of the vector diagram, whereas the present author chose to represent them as modifications of the derived V curves. Mr. Crary is quite correct in his contention that saturation is not a function of field excitation alone; it is decidedly a function of the armature current and the phase displacement between current and voltage. If anyone knows how to bring these additional factors into the picture he has a clear field; pending the presentation of a complete analysis, it may merely be said that the method embodied in figure 16 tends in the right direction. In any case, the purpose of the paper was not to emphasize saturation effects, but (quoting from the opening paragraph of the paper) "to point out some features . . . which follow . . . from the 2-reaction theory." That theory is completely represented by the vector diagram figure 4, and any shortcomings in the deductions are inherent in the theory itself.

It is interesting to note that the method of Messrs. Edgerton and Kingsley leads to the same conclusions as those of the paper under discussion, though their analysis stops short of such deductions as those concerning the law of variation of reactance, the nature of the V curves, etc.

Mr. Beckwith mentions 2 different interpretations of the term "equivalent impedance," both of which refer to single-valued quantities. As the term is used in the paper, it refers to a variable impedance which is a function of the 2 constant reactances, $X_d$ and $X_q$, and of the variable phase angle $\psi$.

Mr. Beckwith raises the question whether the power circles of figure 10 are in reality true circles. Inasmuch as these circles are merely the geometrical representations of equation 1, the question is equivalent to asking (*a*) whether the power developed by the machine is really equal to the input minus the copper loss, and (*b*) whether the voltage $V$ and the current $I$ are the simple harmonic functions of time that they are tacitly assumed to be. The truth of (*a*) cannot be questioned, hence if (*b*) is satisfied the loci are truly circular, but with the understanding that $P$ represents power developed, not power usefully delivered at the shaft. The second question, concerning tooth saturation, has already been implicitly answered in reply to Mr. Crary; the method of figure 16 is confessedly somewhat approximate, that is, qualitative rather than quantitative.

# News

## Of Institute and Related Activities

# Pacific Coast Convention Includes All-Day Trip to Grand Coulee

TO THOSE who have looked forward to the time when they might profitably visit the Pacific Northwest, the 1937 AIEE Pacific Coast convention to be held in Spokane, Wash., August 31–September 3, offers an excellent opportunity to combine business with pleasure. Not only is the city of Spokane itself a recreational center, but also within easy reach are many fine trout streams and mountain lakes, and several famous national parks.

A special feature of the high-class technical program that has been arranged is a joint session with the Institute of Radio Engineers, which organization is concurrently holding its first Pacific Coast convention. Other attractions include an all-day inspection trip to the Grand Coulee project on the Columbia river, and the usual sports competitions and special entertainment.

### Spokane a Recreational Center

A mountain river flows through the center of Spokane, and a big proportion of its banks has been, and is being, converted into State and City park areas. City and adjacent State parks total 4,920 acres, which is said to be the largest park area per capita of any city in the United States. Five golf courses, play grounds, the sunken gardens of Manito, all provide pleasant recreation.

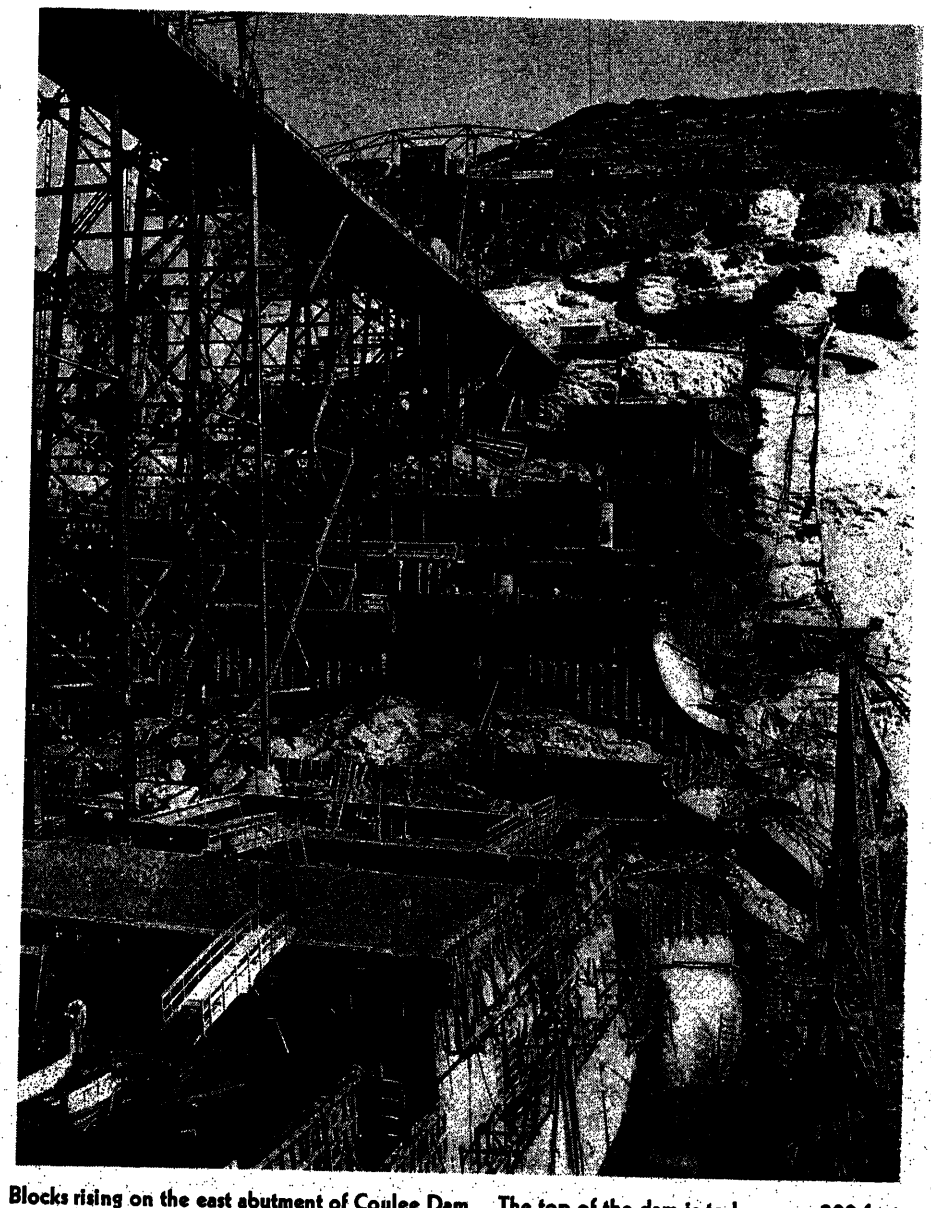
For those who will combine either all or part of their vacations with attendance at the convention, Spokane offers a surrounding recreational area of mountain scenery, fine trout streams, and lakes. Within 50 miles of Spokane are located 76 clear mountain lakes. Only a little farther away is the famous Coeur d'Alene mining district with the Sunshine Mine, the Bunker Hill Smelter, and other new and old producers. Only a little farther, and all within easy reach of Spokane, are the national parks, Glacier, Yellowstone, Craters of the Moon, Mount Rainier, Mount Baker, and others.

### Technical Program

The technical program is comprised of a wealth of material, and some of the papers will deal with recent problems in the Pacific Northwest. Five technical sessions and one conference session on electric house heating will be held. The communication session will be a joint session with the Institute of Radio Engineers and papers also will be presented by well-known members of the IRE. According to F. E. Terman (A'23, M'34) of Stanford University, Calif., chairman of the IRE convention committee, present tentative plans call for a 2-day IRE convention to be held September 1 and 2 in the same hotel as the AIEE convention. Registration will be on the morning of September 1, followed by a technical session that afternoon. The jointly sponsored session is scheduled for Thursday morning and will be followed by another IRE session in the afternoon. The joint session and the IRE convention should prove an additional attraction for electrical engineers.

### Interesting Inspection Trips

As a special feature, it is planned to devote one entire day to an inspection of Grand Coulee, the world's greatest dam, and an address on its electrical features by Alvin F. Darland of the United States Bureau of Reclamation. This dam, which



**Blocks rising on the east abutment of Coulee Dam. The top of the dam is to be some 300 feet above the top of the trestle shown. Openings to the inspection and grouting galleries may be seen in some of the blocks. Approximately 500 cubic yards of concrete are used for a 5-foot lift on each block**

being built for the dual purpose of irrigation and of power generation, is of great interest to all engineers. Grand Coulee is only 92 miles from Spokane.

What is said to be the world's tallest unguyed radio tower, which has just been completed in Spokane by station KHQ, also is on the inspection-trip program. The main tower is 803 feet tall with a short wave and television spire extending up to a total height of 828 feet.

Another "world's greatest" scheduled for inspection is the new pumping plant of the City of Spokane. Each of the 2 vertical turbine-type pumps is driven by a 900-horsepower 1,200-rpm vertical hollow-shaft motor built into the pump head, largest ever built of this construction.

### Some Facts Concerning Grand Coulee

The Grand Coulee project, perhaps the most extensive of its kind every attempted, embraces the construction of a dam, power plant, and pumping plant on the Columbia River; a reservoir in Grand Coulee; and main irrigation canals and water distribution system on the project lands. The estimated cost of the dam and power plant is $178,790,000; of the irrigation system, $197,841,000. The dam is of the straight gravity type and will rise to a height of 550 feet, second only to Boulder Dam which is 727 feet. Thickness of the dam at the base will be about 500 feet and at the top about 30 feet. Length along the crest will be approximately 4,200 feet.

Some 11,250,000 cubic yards of masonry and 65,000,000 pounds of reinforcing steel will be required for the dam, power plant, and appurtenant works. The reservoir created by the dam will cover an area of about 82,000 acres and will contain approximately 10,000,000 acre-feet of water.

There will be 2 power houses, one at each end of the dam, each about 765 feet long. Ultimately, 18 generating units will be installed, each consisting of a 150,000-horsepower vertical turbine and a 120,000-kva 60-cycle 13,800-volt generator. Water will reach the turbines through 18 penstocks, each 18 feet in diameter, under an average head of 335 feet.

The pumping plant, which ultimately will contain 12 pumps each having a capacity of 1,600 cubic feet per second and driven by a 65,000-horsepower motor, will be on the west bank of the river adjacent to the upstream side of the dam. Normal pumping head will be 295 feet; maximum, 367 feet. Water from this pumping plant will be used to irrigate about 1,200,000 acres of land on the east side of the Columbia river.

The entire project is being constructed by the United States Government under the direction of the Bureau of Reclamation of the Department of the Interior. Excavation was begun in December 1933, and the placing of concrete in December 1935. If the present rate of progress is maintained, the dam and power plant will be completed in 1941. Initially, only 3 generating units will be installed; these are expected to be in operation during 1942. Present plans provide for bringing in irrigation areas in small units only, at such times as there is a demand for additional land. According to estimates, the irrigation project will be finally completed at the end of about 40 years.

### Sports

As usual, the high light of the sports events will be the golf tournament for the John B. Fisken cup. An interesting feature of the sports program this year is that Mr. Fisken himself, a resident of Spokane, is chairman of the convention's sports subcommittee. A variety of other competitions will round out the sports program.

### Special Entertainment for Women

For the women guests at the convention, one of the most interesting features will be the gardens of Spokane. During 4 years of participation in the nationwide contest of the National Yard and Garden Contest Association of America, Spokane gardens have won 4 first prizes. This is said to be more "firsts" than have been won by any other American city—in fact, as many as ever have been won by all the gardens within any other entire state.

## Tentative Program

**In this program, reference to the issue and, in so far as possible, to the page in ELECTRICAL ENGINEERING is given for all papers**

### Tuesday: August 31

**10:00 a.m.—Opening of Convention**

**10:15 a.m.—Selected Subjects**

Lighting the San Francisco-Oakland Bay Bridge, C. R. Davis, Department of Public Works, State of California. Scheduled for August issue

Present Day and Probable Future Electrical Applications in Aircraft, W. V. Boughton, Douglas Aircraft Company, Inc. Scheduled for August issue

Proposals for the Administration of Federal Power in the Pacific Northwest, H. V. Carpenter, State College of Washington. Scheduled for August issue

**2:00 p.m.—Development of Protective Equipment**

Relay Operation During System Oscillations, C. R. Mason, General Electric Company. July issue, pages 823–32

A Comprehensive Method of Determining the Performance of Distance Relays, J. H. Neher, Philadelphia Electric Company. July issue, pages 833–44

The Ultra-High-Speed Reclosing Expulsion Oil Circuit Breaker, A. C. Schwager, Pacific Electric Manufacturing Corporation. Scheduled for August issue

Capacitance Control of Voltage Distribution in Multi-Break Breakers, R. C. Van Sickle, Westinghouse Electric & Manufacturing Company. Scheduled for August issue

**9:00 p.m.—Reception and Informal Dance**

### Wednesday, September 1

**9:00 a.m.—Power Transmission and Distribution**

Empirical Method of Calculating Corona Loss From High-Voltage Transmission Lines, J. S. Carroll, Stanford University, and Mabel Macferran Rockwell, consulting electrical engineer. May issue, pages 558–65

Distortion of Traveling Waves by Corona, H. H. Skilling, Stanford University, and P. de K. Dykes, Cambridge (England) University. July issue, pages 850–7

Analysis of Series Capacitor Application Problems, J. W. Butler and C. Concordia, General Electric Company. Scheduled for August issue

**2:00 p.m.—Student Technical Session —Golf**

**8:00 p.m.—Banquet; Presentation of Prizes**

### Thursday, September 2

**9:00 a.m.—Joint Communication Session With Institute of Radio Engineers**

Magnetic Generation of a Group of Harmonics, Eugene Peterson, J. M. Manley, and L. R. Wrathall, Bell Telephone Laboratories, Inc. Scheduled for August issue

Radiotelephone Noise Reduction by Voice Control at Receiver, C. C. Taylor, Bell Telephone Laboratories, Inc. Scheduled for August issue

The Vodas, S. B. Wright, Bell Telephone Laboratories, Inc. Scheduled for August issue

Transmission Lines at Very High Radio Frequencies, L. E. Reukema, University of California Scheduled for August issue

The Developmental Problems and Operating Characteristics of 2 New Ultrahigh-Frequency Triodes, Winfield G. Wagener, RCA Radiotron Company. IRE paper

High-Efficiency Grid-Modulated Amplifiers, F. E. Terman and John Woodyard, Stanford University. IRE paper

**2:00 p.m.—Student Technical Session —Session on Electrical Machinery**

Tooth-Frequency Eddy-Current Loss, Paul Narbutovskih, Stanford University. February issue, pages 253–56

The Saturated Synchronous Machine, B. L. Robertson, T. A. Rogers, and C. F. Dalziel, University of California. July issue, pages 858–63

Transformer Current and Power Inrushes Under Load, E. B. Kurtz, University of Iowa. Scheduled for August issue

**8:00 p.m.—Conference on Electric House Heating**

Electric Heating of Residences, C. E. Magnusson, University of Washington.

Electric Heating of Residences, H. V. Carpenter, State College of Washington.

### Friday, September 3

**Coulee Dam Trip**

Address: The Coulee Dam Project, Alvin F. Darland, United States Bureau of Reclamation.



**Lobby of the Davenport Hotel, Spokane, Wash., headquarters of the AIEE 1937 Pacific Coast convention**

There will be sight-seeing trips for the women, a bridge luncheon at the Country Club, golf, putting contests, and other entertainment.

HOTELS AND REGISTRATION

Convention headquarters will be at the Davenport Hotel where registration desks will be open from early Tuesday morning, August 31. Accommodations of all types are available at the Davenport at prices beginning at $3 per day.

Accommodations at the Spokane Hotel will range from $2 to $6. The Desert Hotel, across the street from the Davenport, and the Coeur d'Alene have accommodations ranging from $2.50 upward. All members desiring accommodations are urged to make their reservations early. Special arrangements are being made for economical accommodations for Enrolled Students.

COMMITTEES

In the following list are given the members of the 1937 Pacific Coast convention committee, which includes the 10 subcommittee chairmen, as indicated.

H. V. Carpenter, *chairman*
R. D. Sloan, *vice-chairman*
M. F. Hatch, *secretary*
Reinier Beeuwkes
S. E. Caldwell
J. B. Fisken
L. R. Gamble
J. C. Gaylord
C. R. Higson
N. B. Hinson
R. H. Hull
H. S. Lane
F. O. McMillan
H. L. Melvin
H. S. Osborne
George Quinan
C. E. Rogers
R. W. Sorensen
A. Vilstrup
L. R. Gamble, meetings and papers
J. S. McNair, finance
L. A. Traub, transportation
H. W. Webbe, housing
J. R. Murphy, entertainment
J. B. Fisken, sports
H. B. Hodgins, publicity
R. H. Hull, student activities
D. H. Olney, registration
Earl Baughn, inspection trips

**Electric Power Markets in Washington.** This is the title of a 40-page bulletin (No. 93) of the University of Washington Engineering Experiment Station, prepared by Doctor C. E. Magnusson, professor of electrical engineering at the university, and director of the Engineering Experiment Station. This bulletin presents, largely in tabular and graphical form, the results of an extensive study of the electric heating of residences in Seattle. It is listed as being available from the University at 40 cents per copy.

## AIEE Directors Meet at Institute Headquarters

The regular meeting of the board of directors of the American Institute of Electrical Engineers was held at Institute headquarters, New York, on May 24, 1937.

Present: *President*—A. M. MacCutcheon, Cleveland, Ohio. *Past-President*—H. P. Charlesworth, New York, N. Y. *Vice-Presidents*—C. V. Christie, Montreal, Canada; Mark Eldredge, Memphis, Tenn.; C. Francis Harding, Lafayette, Ind.; W. H. Harrison, New York, N. Y.; A. C. Stevens, Schenectady, N. Y. *Directors*—F. M. Farmer, New York, N. Y.; H. B. Gear, Chicago, Ill.; F. Ellis Johnson, Columbia, Mo.; C. R. Jones, New York, N. Y.; P. B. Juhnke, Chicago, Ill.; W. B. Kouwenhoven, Baltimore, Md.; Everett S. Lee, Schenectady, N. Y.; K. B. McEachron, Pittsfield, Mass.; C. A. Powel, East Pittsburgh, Pa.; R. W. Sorensen, Pasadena, Calif. *National Treasurer*—W. I. Slichter, New York, N. Y. *National Secretary*—H. H. Henline, New York, N. Y. Present by invitation during discussion of one item—Past-President A. W. Berresford, New York, N. Y.

Minutes were approved of meetings of the board of directors held January 26–27, 1937, and the executive committee on March 25, 1937.

Announcement was made of the vacancies in the board of directors caused by the deaths of Past-Presidents J. Allen Johnson and E. B. Meyer and the filling of these vacancies by Past-Presidents H. P. Charlesworth (to August 1, 1937) and J. B. Whitehead (to August 1, 1938), in accordance with the board's interpretation, in May 1936, of section 35 of the constitution to mean that the 2 most recent living past-presidents shall be members of the board of directors.

Actions of the executive committee on applications for admission, transfer, and Student enrollment were reported and confirmed, as follows: As of February 19, 1937—1 applicant elected and 5 applicants transferred to the grade of Fellow; 12 applicants elected and 13 applicants transferred to the grade of Member; 76 applicants elected to the grade of Associate; 81 Students enrolled. As of April 16, 1937—2 applicants transferred to the grade of Fellow; 6 applicants transferred and 11 elected to the grade of Member; 470 applicants elected to the grade of Associate; 68 Students enrolled.

Reports were presented and approved of meetings of the board of examiners held April 14 and May 12, 1937. Upon the recommendation of the board of examiners, the following actions were taken: 2 applicants were transferred to the grade of Fellow; 14 applicants were transferred and 27 were elected to the grade of Member; 342 applicants were elected to the grade of Associate; 164 Students were enrolled.

Monthly disbursements as follows were reported by the finance committee and approved: April, $18,714.91; May, $20,679.11.

Upon recommendation of the committee on electrophysics, the board authorized a change in name of that committee to "committee on basic sciences," without change in function.

Approval was given to a recommendation of the membership committee that each District vice-chairman of that committee be added to the executive committee of his geographical District, if not already a member of the executive committee in another capacity. The wording of revisions of sections 32 and 76 of the by-laws, to bring them into conformity with this policy, was referred to the committee on constitution and by-laws.

Approval was given to the appointment, upon nomination by the standards committee, of Institute representatives, as

## Future AIEE Meetings

**Pacific Coast Convention**
Spokane, Wash., Aug. 30–Sept. 3, 1937

**Middle Eastern District Meeting**
Akron, Ohio, Oct. 13–15, 1937

**Winter Convention**
New York, N. Y., January 24–28, 1938

**North Eastern District Meeting**
Pittsfield, Mass., Spring 1938

**Summer Convention**
Washington, D. C., June 20–24, 1938

follows: T. H. Haines, on Sectional Committee on National Electrical Safety Code, and W. C. Goodwin, on Sectional Committee on Safety Code for Mechanical Refrigeration.

H. B. Gear was appointed an Institute representative on the Commission of Washington Award, for the 2-year term beginning August 1, 1937, to succeed L. A. Ferguson, whose term will expire at that time.

The board confirmed applications made by the AIEE committee on research to The Engineering Foundation for financial support for the year 1937–38 of the following research projects: investigation of electric shock, stability of impregnated paper insulation, and work of welding research committee.

Upon recommendation of the committee on research, it was voted "that the board approves in principle the idea of a contribution by the AIEE toward the specific research projects which the board recommends to The Engineering Foundation for financial support, of not more than $500 for any one project in a year, the total amount appropriated for all such projects during a budget year not to exceed one-half of one per cent of the total gross income of the AIEE for the preceding fiscal year."

Appointment by the president of the following committee of tellers to canvass and report upon the ballots for the election of Institute officers was approved: W. E. Coover (chairman), John T. Binford, George C. Brown, M. S. Mason, L. M. McCullough, L. A. Nelson, and A. M. Schoettgen.

A report, transmitted by Chairman F. B. Jewett of the committee on Iwadare Foundation, from E. H. Colpitts, covering his Iwadare lectureship itinerary in Japan in the spring of 1937, was received and ordered filed.

The report of the committee on award of Institute prizes, of the awards made by the committee for papers presented during 1936, was presented. (The report was published in the June issue of ELECTRICAL ENGINEERING, page 756.)

The annual report of the board of directors to the membership for the fiscal year which ended April 30, 1937, as prepared by the national secretary, was approved for presentation at the annual meeting of the Institute on June 21. This included reports in full or in abstract of general standing committees. The report appears elsewhere in this issue.

The annual report of the national treasurer was presented and approved.

In accordance with section 37 of the constitution, consideration was given to the appointment of a national secretary of the Institute for the administrative year beginning August 1, 1937; and National Secretary H. H. Henline was reappointed.

President A. M. MacCutcheon was appointed the official delegate of the Institute to the semicentennial of The Engineering Institute of Canada, June 15–18, 1937.

Other matters were discussed, reference to which may be found in this or future issues of ELECTRICAL ENGINEERING.

## Honorary Members Named at Summer Convention

Election of Bion J. Arnold and Alex Dow to honorary membership in the AIEE was formally announced at the opening session of the Institute's 1937 Summer Convention, which is being held in Milwaukee, Wis., as this issue goes to press. These 1937 elections are the first since 1933 when 6 prominent engineers and scientists were so honored. Doctor Arnold has been an independent consulting engineer since 1893 and has been active in Institute affairs, having served as the 16th president (1903–04). Doctor Dow is a pioneer in the electric utility field and was awarded the AIEE Edison medal for 1936 for outstanding leadership in that industry. Biographical sketches of both men are given in the "Personals" columns of this issue.

Neither Doctor Dow, who is in Europe, nor Doctor Arnold was present at the ceremony. Doctor Arnold was injured in an automobile accident on June 19, the Saturday before convention week, while on his way home from hospital confinement resulting from an earlier accident. Honorary Member certificates were sent to Doctor Dow by D. H. Baker, convention delegate from the Detroit-Ann Arbor Section, and to Doctor Arnold by his son.

As specified in sections 8 and 9 of the Institute's constitution,

**Honorary Members may be chosen from among those who have rendered acknowledged eminent service to electrical engineering or its allied sciences.**

**Honorary Members shall be proposed in writing by at least 10 members, and may be elected only by the unanimous vote of the board of directors, a ballot in writing to be forwarded by members absent from the directors' meeting. The election of an Honorary Member shall be deemed invalid if an acceptance is not received within 6 months after the date of his election.**

The grade of honorary member is the highest in the AIEE, and since the founding of the Institute in 1884 has been granted to only 33 men, including Doctors Arnold and Dow. Of those elected prior to this year, only the following are still living: Andrè E. Blondel, W. L. R. Emmet, Herbert Hoover, A. E. Kennelly, Guglielmo Marconi, R. A Millikan, Chas. F. Scott, and Motoji Shibusawa.

### NEW OFFICERS ELECTED

The report of the committee of tellers also was presented at the first session of the convention, and the following new officers were declared elected, each to take office August 1, 1937.

*President:*

**W. H. Harrison, assistant vice-president, department of operation and engineering, American Telephone and Telegraph Company, New York, N. Y.**

*Vice-Presidents:*

**I. Melville Stein, director of research, Leeds & Northrup Company, Philadelphia, Pa.**

**Edwin D. Wood, general superintendent, Louisville Gas & Electric Company, Louisville, Kentucky.**

**L. N. McClellan, chief electrical engineer, U.S. Bureau of Reclamation, Denver, Colo.**

**J. P. Jollyman, hydroelectric and transmission engineer, Pacific Gas & Electric Company, San Francisco, Calif.**

**M. J. McHenry, manager, Toronto district, Canadian General Electric Company, Ltd., Toronto, Ont.**

*Directors:*

**C. R. Beardsley, superintendent of distribution, Brooklyn Edison Company, Inc., Brooklyn, N. Y.**

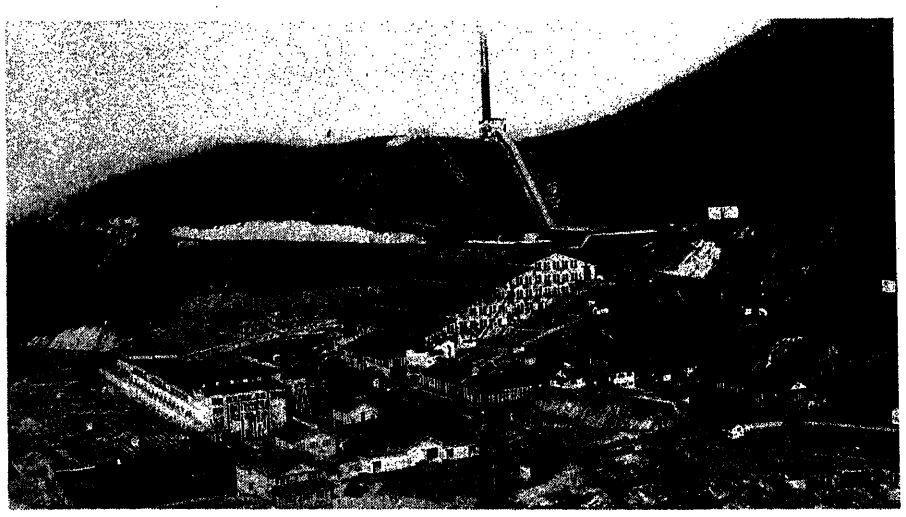
**Vannevar Bush, vice-president and dean of engineering, Massachusetts Institute of Technology, Cambridge.**

**F. H. Lane, manager, engineering division, Public Utility Engineering & Service Corporation, Chicago, Ill.**

*National Treasurer:*

**W. I. Slichter, professor of electrical engineering, Columbia University, New York, N. Y.**

The board of directors for the administrative year beginning August 1, 1937, consists of these newly elected officers, together with the following hold-over officers: A. M. MacCutcheon (retiring president), Cleveland, Ohio; J. B. Whitehead (junior past president), Baltimore, Md.; F. Malcolm Farmer, New York, N. Y.; N. E. Funk, Philadelphia, Pa.; H. B. Gear, Chicago, Ill.; F. Ellis Johnson, Columbia, Mo.; C. R. Jones, New York, N. Y.; W. B.



**The electrolytic zinc plant of the Sullivan Mining Company, a 2- or 3-hour drive from Spokane, will be an attraction to those attending the Institute's 1937 Pacific Coast convention who are interested in the application of electricity to ore mining and refining**

Kouwenhoven, Baltimore, Md.; K. B. McEachron, Pittsfield, Mass.; C. A. Powel, East Pittsburgh, Pa.; R. W. Sorensen, Pasadena, Calif.; A. C. Stevens, Schenectady, N. Y.; O. B. Blackwell, New York, N. Y.; C. F. Harding, Lafayette, Ind.; L. T. Blaisdell, Dallas, Tex.; C. E. Rogers, Seattle, Wash.

The first day's registration, which numbered 563 members and guests, presaged a highly successful convention. A detailed report of the various convention activities is scheduled for inclusion in the August issue.

## New Name for Electrophysics Committee

The name of the AIEE committee on electrophysics has been changed to "committee on basic sciences" by authorization of the AIEE board of directors, following the recommendation of the committee. The function of the committee remains unchanged.

The electrophysics committee was organized in 1911. Its scope, as defined at the present time, is: "Treatment of all matters in which the dominant factor is electrophysics, and which are of such novel character as to be unapplied in any apparatus or field of application within the scope of the other technical committees, or which are of such generality as to be significant within the scopes of several technical committees. Such subjects as general circuit theory, electrostatics, mathematical treatises, magnetics, general electrical units, and nomenclature are properly within the scope of this committee."

## Executive Committee of Pacific District Meets

A meeting of the executive committee of the AIEE Pacific District was held in the Engineers' Club at San Francisco, Calif., May 27, 1937. Members of the executive committee who attended were:

N. B. Hinson, vice-president, AIEE, Los Angeles
J. C. Gaylord, chairman, Los Angeles Section
E. F. Peterson, chairman, District committee on student activities, Santa Clara
H. S. Lane, chairman, San Francisco Section
F. S. Benson, secretary, San Francisco Section
Fred Garrison, secretary, AIEE Pacific District

Present by invitation:

R. F. Monges, executive committee, San Francisco Section
W. H. Evans, executive committee, San Francisco Section
C. V. Fowler, executive committee, San Francisco Section
E. M. Wright, executive committee, San Francisco Section
R. O. Brosemer, chairman-elect, San Francisco Section
J. P. Jollyman, nominee for vice-president AIEE
J. S. Carroll, member-elect of executive committee, San Francisco Section

Vice-President Hinson presided. As the first item of business, chairman Gaylord of the Los Angeles Section read the following letter which he had written to Chairman Lane of the San Francisco Section:

At a recent meeting of the executive committee of the Los Angeles Section, it was unanimously voted that we should pledge to the San Francisco Section our wholehearted support in its effort to have San Francisco chosen as the convention city for the national summer convention of the AIEE in the year 1939.

It was also voted that should you be successful in obtaining the convention that year, we would do everything in our power to help make the convention a success.

After the reading of this letter, the committee voted to go on record as being in favor of holding the Institute's 1939 summer convention in San Francisco.

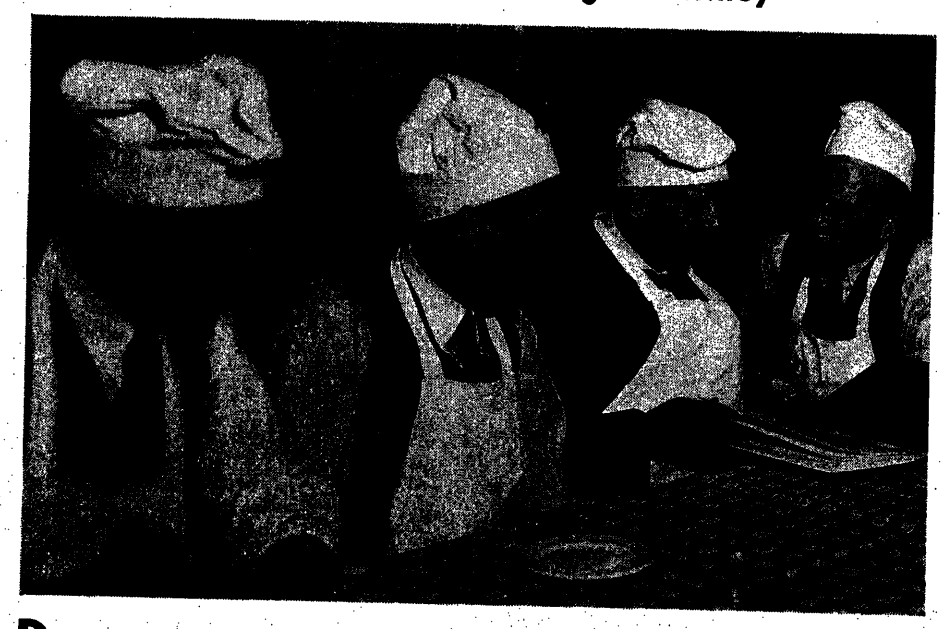
Promotion of greater interest on the part of students in preparing papers for District Branch paper competition was discussed. It was believed that the student counselors were in best position to encourage the preparation of such papers. It was thought also that the closer co-operation of student relations members on the executive committees of neighboring Sections with the students would encourage the students to prepare papers.

The proposed method of *inviting* Institute members to become Fellows, rather than leaving to the members themselves the initiation of applications for transfer to that grade, was discussed. It was the opinion of the committee that this plan should be adopted.

Much discussion centered about the proposed professional engineers licensing act, which was defeated in the California State Assembly at Sacramento this year. It was reported that a committee has been appointed from the San Francisco Engineering Council, which will co-operate with a similar committee from the Los Angeles Engineering Council, to frame a bill licensing professional engineers for possible introduction into the Assembly at their 1939 meeting.

After adjournment, those present attended the regular dinner and monthly meeting of the San Francisco Section.

## Electrical Industry Honors George Stickney



During a chef dinner given as part of the annual advanced lighting conference held recently at General Electric Institute, Nela Park, Cleveland, Ohio, tribute was paid by the electrical industry to G. H. Stickney (A'04, F'24) consulting engineer of the incandescent lamp department of the General Electric Company, Cleveland, in recognition of his numerous contributions to lighting progress during more than 40 years of service with the company. Formal presentation of an elaborate book in which the tribute was inscribed was made by E. E. Potter, eastern sales manager of the incandescent lamp department, in behalf of the hundreds of lighting men whose personal signatures the memento also contains. In the photograph reproduced above are shown John Arthur, Kansas City Power and Light Company; Ward Harrison (F'36) director of Nela Park engineering department; Mr. Stickney, examining his souvenir book; and Mr. Potter.

## Schenectady Section Sponsors Steinmetz Museum

The Schenectady Section of the AIEE, believing that the home of Dr. C. P. Steinmetz, including his library, laboratory, and personal effects, should be preserved to serve as an inspiration for the engineers of all time, is participating with other groups in a campaign to secure funds for its purchase. This property, when acquired, will be converted into a memorial museum to serve as a showplace for all the worthy Steinmetz mementos available, and will provide a point of great interest for all visitors, particularly to electrical engineers. An invitation to participate in the establishment of the museum has been extended to friends of Steinmetz throughout the United States.

## Membership—

Mr. Institute Member:

By bringing to the attention of your Section membership committee, the names of those who you feel are eligible for membership in the Institute, you help both the Institute and your fellow engineers.

Such co-operation on your part is very greatly appreciated by the Section membership committees.

John Banks

Vice-Chairman, District No. 9
National Membership Committee

This is the second activity to memorialize this noted electrical engineer to be engaged in by the Institute's Schenectady Section, the Steinmetz Memorial Lectures having been established by that Section in 1925. To date, 11 lectures in this series have been delivered, the last of which was published in the May 1937 issue of ELECTRICAL ENGINEERING, pages 510–17.

## Student Conference Held by North Central District

The tenth annual conference of Student Branches of the AIEE North Central District was held at the South Dakota State College, Brookings, April 23–24, 1937. The conference included 2 technical sessions at which 8 papers by student authors and a demonstration lecture were presented, a banquet, and 2 business sessions of the Student Branch counselors in the District. Although the official registration numbered only 68, it was estimated that more than 100 persons attended the technical sessions. All 9 Institute Branches within the District were represented.

President A. M. MacCutcheon of Cleveland, Ohio, was present for the entire conference and participated actively in all the technical and business meetings. His interest and advice was said to be very helpful in making this one of the most successful student conferences ever held in the District. He was the principal speaker at the banquet.

The meeting was opened by AIEE Vice-President R. H. Fair of Omaha, Neb., who introduced President MacCutcheon and Doctor H. M. Crothers, dean of engineering of the South Dakota State College, who made an appropriate address of welcome. After the opening address the first technical session began with T. J. Anderson, chairman of the University of Nebraska Branch, presiding. Lester C. Corrington of the South Dakota State School of Mines Branch presided at the second session. The following papers were presented at these sessions:

ARC WELDING AND ITS APPLICATION IN THE INDUSTRY, by James Landmesser, South Dakota School of Mines, Rapid City.

ELECTRON FOCUSING, by R. P. Buckingham and E. Pekhonen, University of North Dakota, Grand Forks.

THE DEVELOPMENT OF SOUND PICTURES, by John McKendry, University of Wyoming, Laramie.

X-RAYS AND THEIR APPLICATIONS, by Charles B. Minnich, University of Nebraska, Lincoln.

THE LIFE OF CHARLES PROTEUS STEINMETZ, by Everett H. Lee, South Dakota State College, Brookings.

SUN AND WIND AS POWER GENERATORS, by Howard McAllister, University of Colorado, Boulder.

SOME INVESTIGATIONS ON ELECTRETS, by John J. Shideler and Alfred R. Lee, University of Denver, Colo.

NEWTON'S DEVELOPMENT OF THE CALCULUS, by Kenneth Frolund, North Dakota State College, Fargo.

In addition to the foregoing papers, a demonstration relating to inductive co-ordination was given by S. B. Hughes and I. M. Ellestad (A'24) of the Northwestern Bell Telephone Company and A. A. Little of the Dakota Central Telephone Company. In this demonstration a miniature transmission line paralleled by a miniature telephone line was employed, and the effect of various conditions on the amount of noise induced on telephone circuits paralleled by power circuits was illustrated. The effectiveness of transpositions in mitigating interference effects was very clearly demonstrated.

Counselors present at the 2 business sessions were: W. H. Gamble, Branch counselor chairman, AIEE North Central District, South Dakota State College; H. S. Rush, North Dakota Agricultural College; H. F. Rice, University of North Dakota; J. O. Kammerman, South Dakota State School of Mines; L. A. Bingham, University of Nebraska; H. B. Palmer, University of Colorado; and G. H. Sechrist, University of Wyoming. President MacCutcheon and Vice-President Fair also attended. Chairman Gamble, who presided, first gave a report of the discussions at the conference of officers, delegates, and members held during the Institute's 1936 summer convention at Pasadena, Calif. Upon formal invitation of Professor Bingham, it was voted that next year's conference be held at the University of Nebraska, Lincoln. Following the usual custom, Professor Bingham then was elected District Branch counselor chairman for the coming term.

Concerning the conduct and scheduling of future student conferences, the following actions were taken:

1. Time allowed for delivering student papers is to be limited to 20 minutes each.
2. Each paper is to be discussed immediately following its presentation.
3. Discussions of student papers are to be limited to students, and the time allowed each discusser is to be limited to 10 minutes.

The proposition of obtaining an outside speaker for the annual conference was discussed and was viewed with favor. T. H. Granfield of Omaha, Neb., secretary of the AIEE North Central District, acted as secretary of the conference.

## Electrical Reports at NFPA Meeting

At the forty-first annual meeting of the National Fire Protection Association, held in Chicago, Ill., May 10–14, 1937, reports were presented by the electrical committee and by committees on static electricity and protection against lightning. H. S. Warren (A'03, F'13) attended the meeting as Institute representative on the electrical committee of the association, and the following information was received from him.

The report of the electrical committee, A. R. Small, chairman, was a summary report outlining the more important changes in the National Electrical Code which were adopted by the committee in March 1937. A minority report was submitted, but this did not prevent the acceptance of the electrical committee's report. The issue raised by the minority report was whether the use of a nontamperable type of plug fuse should be mandatory after July 1, 1937. The electrical committee's attitude was that such mandatory requirement would be premature because of the patent situation and because satisfactory types of nontamperable fuses embodying interchangeability have not yet been made available. Another item in the electrical committee's report which received extended discussion had reference to the classification of pyroxylin plastic manufacturing plants in respect to hazardous locations. The 1937 edition of the code will contain many changes, and will have an entirely new format and editorial arrangement.

The committee on static electricity, P. V. Tilden, chairman, presented a report consisting of 44 printed pages of text and diagrams. Sparks from static electricity constitute a very serious hazard where flammable liquids or gases are present. In many kinds of manufacturing establishments flammable or explosive materials are

involved, so careful safeguarding against sparks is essential. The report tells how accumulations of static electricity can be prevented most effectively by the interbonding and thorough grounding of all metal pipes, containers, and other equipment.

The report of the committee on protection against lightning, M. G. Lloyd (A'08, F'12) chairman, was devoted principally to an additional section covering the protection of reinforced concrete stacks. A similar addition was approved by the sectional committee on protection against lightning of the American Standards Association, which held a joint session with the NFPA on one of the days during the meeting. Doctor Lloyd is chairman of both committees, and Mr. Warren is a member of the ASA committee.

**National Adequate Wiring Program.** Appointments to a national adequate wiring committee have been completed, according to a recent issue of "Nema News," and the committee will now proceed to consider the details for the national adequate wiring program initiated by the National Electrical Manufacturers Association. The broad purpose of the program is to educate the householder to recognize and meet the need for adequate electrical wiring. Members of the committee are: M. E. Skinner and C. A. Eastman (A'35), Edison Electric Institute; E. G. May and S. J. O'Brien, National Electrical Contractors Association; W. E. Sprackling and G. C. Thomas, Jr., NEMA; and J. S. Bartlett and George R. Conover, International Association of Electrical Leagues.

# Current Items From American Engineering Council

## Engineers' Public-Employment Trends

Engineering employment by government agencies in Washington is somewhat disturbed by the threats of both Congress and the Administration actually to apply economy measures. The President has ordered all departments, administrations, and commissions including the Bureau of the Budget materially to reduce current expenditures and to limit future operations to be budgeted within the national income. Congress seems to have accepted the President's advice, and to have set itself to the task of reducing federal expenditures. Allowing for the application of political expediency in yielding to "certain pressures," a substantial reduction in the flow of public funds through the "emergency agencies" for "work relief" and "pump priming purposes" appears more like a certainty than ever before.

As evidence of the acceptance of the seriousness of these intentions, "administrative executives" are advising capable associates to transfer to other work within government service or seek opportunities in private enterprise. Rural electrification and the more permanent agencies are absorbing some of the engineers. Others will be re-employed by special activities similar to "the building materials study" scheduled to be started by the Bureau of Standards in July but a distressingly large number of competent engineers are leaving government work with its uncertainties and meagre compensation for the increasingly attractive private life. In recognition of operating difficulties likely to develop as more of the better engineers return to private employment and practice, the Civil Service Commission is planning to conduct an unassembled examination for engineers of the several grades of a dozen branches of engineering at an early date. Although civil service cannot be made more attractive in either classification or compensation until there is new legislation in that direction, an effort is being made to raise educational and experience standards for each grade, with the hope that engineers better fitted for public service may be induced to qualify for the design, construction, operation, and maintenance of public property, and for research, educational, or advisory and supervisory or inspection duty in the several lines of accepted public service.

Without becoming involved in anything leading toward the socialization of engineering or the standardization of either duties or salaries which might limit engineering initiative, Council through its staff and committees, is aiding the Commission and its "engineer examiners" in their efforts to improve the engineer personnel under civil service. This opportunity to forward engineering recognition and to act indirectly for the improvement of the economic status of the engineer in public service, comes to AEC as an invitation from the Civil Service Commission. Council is thus accepted as an instrumentality of organized engineering in position to express the united opinion of engineers regarding the qualifications for and conditions of the employment of engineers by those arms of the federal government of the United States whose employees are under civil service. In that position, Council may well be a stabilizing influence against unionization. Council is also given an opening to act for the engineering profession to further the use of the merit system in preference to patronage and in the public welfare.

## Government Reorganization

American Engineering Council has made its files available to both The President's Committee on Administrative Management and the Select Committee on the Investigation of Executive Agencies. Members of the staff have advised with both committees regarding the economies which might be attained by regrouping or reorganization of existing agencies. Council has also offered its services to the Joint Committee on Government Reorganization.

Each of the committees has studied Council's recommendation for the centralization of all public works under one qualified head and it is understood that ideas advanced by AEC have been incorporated in committee suggestions as representing the best thought on the subject available. None of the findings of the committees have been announced but all 3 committees are believed to have urged the creation of a public works department.

Four bills carrying the principal points in the President's reorganization program are scheduled for this session of Congress but it is doubted that any of them can pass under present circumstances. Even if departments of public work and social welfare should be established, Congress is not believed to be in a mood to delegate authority to the President over such important "arms" of government service as the comptroller general's office and Interstate Commerce, Federal Trade, Communications, and Power Commissions, or willing to relinquish control over the disposition of public works appropriations and authority. Feelings along these lines, in the Congress, are believed to be almost as deep seated as that involved in the present Supreme Court controversy.

## Rural Electrification Administration

The Rural Electrification Administration had its second birthday on May 11, 1937. As of that date REA had approved 310 projects involving $58,952,958. Of that amount, about $56,862,958 will be used for line construction; $1,980,000 for building generating plants; and $110,000 for financing wiring and plumbing installation. Loan contracts have been executed for more than $45,500,000 of the allotted funds. Projects totaling about $32,000,000 have reached some one of the several stages of construction and according to REA enough wire has been strung on projects which it has financed to reach twice around the earth at the equator.

Some of the new REA procedures will be of interest to engineers in contact with rural electrification: Rural electric co-operatives are now required to use consulting engineering services. The co-operatives may also employ skilled management even before the lines are built and charge such salaries against REA loans until the project is completed and in operation. Help in building load is being supplied by REA experts working in the field under the direction of a small headquarters staff in Washington.

Engineers interested in the production and distribution of electric energy may also be interested in knowing that Administrator John C. Carmody of the Rural Electrification Administration has just announced that a new order of the Kentucky Public Service Commission establishes a whole-

sale rate of about 11 mills per kilowatt-hour, to be made available to rural co-operative projects by 7 private utility companies operating in Kentucky. In a telegram to Governor Chandler, Administrator Carmody states that the Kentucky action "might well serve as a model for other state commissions."

## National Rivers and Harbors Congress

The outstanding feature of the April 1937 meeting of The National Rivers and Harbors Conference was the attention given to various features of water use and control in our river basins other than navigation. In past sessions of this congress, the emphasis has been placed upon navigation and water transportation. At this session, consideration was given to such factors as flood control, stream pollution, power development, water supply for municipal and industrial purposes, and biological and recreational uses.

After a series of addresses and discussions on each of these factors, the following resolution was unanimously adopted: "Ample funds should be provided at once to construct flood control projects already authorized by Congress—There should be no stint where human life and human misery are involved—Nothing substantial has been undertaken to prevent a recurrence of these catastrophies, largely through lack of appropriation—At this very moment another flood is generating at Johnstown, Pittsburgh, and the upper Ohio valley and still there is delay and lethargy."

Two diametrically opposite plans for water resources development received emphasis in this meeting. The first plan is exemplified by the Tennessee Valley Authority and the recent legislation proposed by Senators Barkley, Bulkley, and Norris providing for a series of similar projects throughout the country. The second plan contemplates the co-ordination of federal, state, and local agencies according to the recommendations of the National Resources Committee in the development of basin plans and programs for the various phases of water use and control including navigation, water power, municipal and industrial water supply, sanitation, irrigation, drainage, soil conservation, and the biological and recreational uses.

Council's present attitude favors the plan of co-ordination but the matter is before the AEC committee on the conservation and utilization of natural resources and its recommendation is yet to have consideration by the executive committee and the assembly. In the meantime Council shall be glad to have both opinions and suggestions from individual engineers and member engineering organizations on these questions of such vital social and economic implication.

# Letters to the Editor

CONTRIBUTIONS to these columns are invited from Institute members and subscribers. They should be concise and may deal with technical papers, articles published in previous issues, or other subjects of some general interest and professional importance. ELECTRICAL ENGINEERING will endeavor to publish as many letters as possible, but of necessity reserves the right to publish them in whole or in part, or reject them entirely.

ALL letters submitted for consideration should be the original typewritten copy, double spaced. Any illustrations submitted should be in duplicate, one copy, to be an inked drawing but without lettering, and other to be lettered. Captions should be furnished for all illustrations.

STATEMENTS in these letters are expressly understood to be made by the writers; publication here in no wise constitutes endorsement or recognition by the American Institute of Electrical Engineers.

## A Power Scale for the Instant Heavisidion

*To the Editor:*

At the AIEE winter convention in 1923 the writer demonstrated and described a computing kinematic device for long transmission lines which he named the "Heavisidion" ("The 'Heavisidion,' "AIEE TRANSACTIONS, volume 42, 1923, pages 42–53). With this device, the desired current and voltage having been set in their proper vectorial relationship at one end of the line, the corresponding quantities anywhere on the line, including the other end, could be obtained by a simple rotation of certain portions of the linkages. Moreover, the device was adjustable for any desired line constants and length of the line. Later, the author designed and built a simpler device, suitable only for a particular line and with the electrical quantities indicated only at the 2 ends of the line, but not at intermediate points ("The Instant Heavisidion," *General Electric Review*, volume 28, 1925, page 746). Both these devices indicate the current, the voltage, and the power factor, so that the power may be readily computed. However, it is convenient to have the real, reactive, and apparent power indicated directly on the device, in order to see at once their approximate magnitude and note the sense in which they vary as the load is varied. This is of particular importance in studies of static stability of a line, for which studies the device is particularly suited.

During the spring of 1937, a large heavisidion was built by 2 of the writer's students (figure 1) to illustrate the electrical relationships which may be expected on the 275-kv line between Boulder Dam and the city of Los Angeles. The device was quite carefully and accurately made out of steel bars and so proportioned that the electrical quantities could be scaled off from no load to short circuit within quite a wide range of operating voltages. The measured currents and voltages agreed with those analytically computed by means of hyperbolic functions of a complex variable to within better than one per cent. It was therefore deemed opportune to add a power scale to the device to enable true kilowatts, reactive kilovolt-amperes and apparent power to be read off directly.

The principle upon which the power scale is based is shown in figure 2. The line $CO$ is the same as that in figure 2 in the article in the *General Electric Review*, referred to above. The line $CD$ is drawn at an angle $\theta$ to it, $\theta$ being the same as in that article. $CB$ is the current vector whose correct phase angle $\phi$ is with respect to $CD$, and not $CO$. $CDFG$ is a piece of ruled paper (ordinary cross-section paper with decimal divisions will do). $HJ$ is a guide, and $CK$ is a straightedge whose lower side, $UMN$, passes through $C$ and is used in measuring power. The straightedge can be fastened at any point of the guide by means of the thumbscrew at $L$. $S$ and $T$ are 2 markers which can slide along $CG$ in grooves or along straight guides, to fix the values of the real and reactive power until the next reading. The kilovolt scale along the edge $FG$ is a nonuniform scale, computed as is explained below. The setting at $U$ must be the same as the value of the voltage $OC$. Thus, if $OC$ is 300 kv, the straightedge must be set for the division 300 at $U$. If, however, $OC$ is read in centimeters and not in kilovolts another scale along $FG$ must be used, also calibrated in centimeters, but in reality a nonuniform scale.

The use of this attachment is as follows: Having set the Heavisidion for some desired currents and voltages, read $OC$ (in centimeters or in kilovolts) and set the straightedge $CK$ accordingly. Follow the ruled line $BN$ to point $N$ and set the marker $S$, following the ruled line $NS$. $CS$ gives the real power, on the scale marked on $CG$, directly in kilowatts. With a pair of dividers transfer the reactive component of the current, $CR$, into the position $CR'$. Follow $R'M$ with the eye, and set the marker $T$ accordingly. $CT$ will give the reactive kilovolt-amperes, to the same scale as the real power. If the total kilovolt-amperes

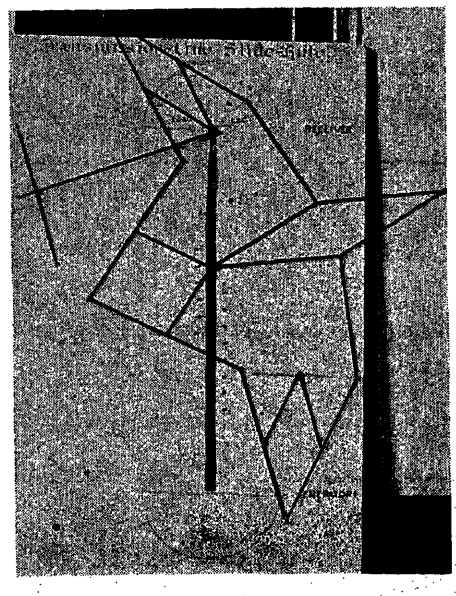


Figure 1

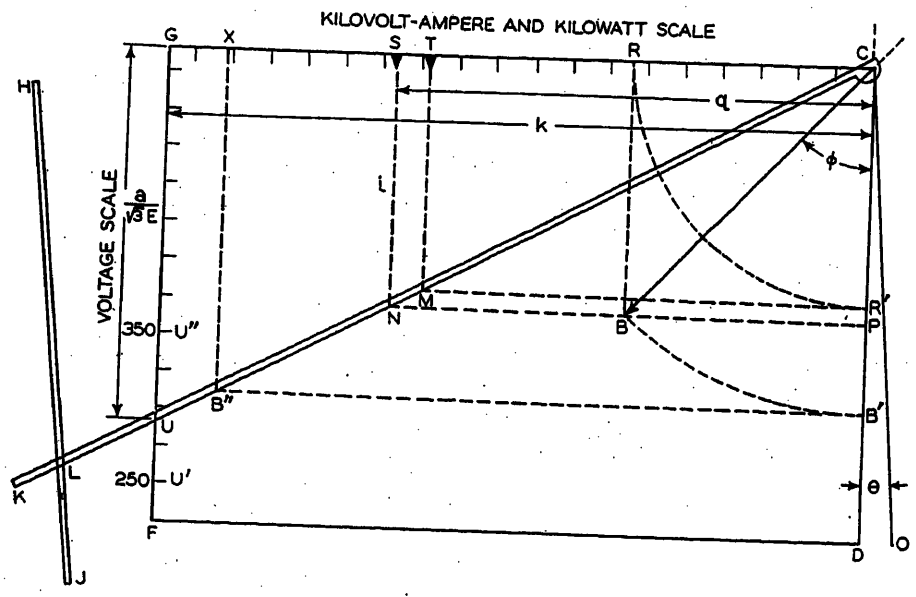



**Figure 2**

are desired, transfer $B$ to $B'$, follow $B'B''$ to its intersection with $KC$, and read $CX$ on the kilowatt scale, as before.

The foregoing arrangement is based on the similarity of the triangles $UGC$ and $NSC$. We have

$$UG/GC = NS/SC \qquad (1)$$

Make $UG = a/(E\sqrt{3})$, where $a$ is a convenient arbitrary constant, and $E$ is the line voltage $OC$. $GC$ is an arbitrary length denoted by $k$. $NS$ is the power component, $i$, of the line current. $SC$ must be the value of the real power, $iE\sqrt{3}$; let it be denoted by $q$. Equation 1 may therefore be rewritten in the following form:

$$a/(Ek\sqrt{3}) = i/q \qquad (2)$$

from which

$$q = Eik\sqrt{3}/a \qquad (3)$$

Since $a$ and $k$ are arbitrary constants, they can be so chosen that $q$ will give the 3-phase power, $Ei\sqrt{3}$.

The following example illustrates the choice of the scales. Let the range of operating voltages be from 250 to 350 kv. Choose arbitrarily $a = 25 \times 35 \times \sqrt{3}$. For $E = 250$ kv, the length $GU'$ will be 35 centimeters, but the division marked there will be 250 kv. For $GU''$ the length will be 25 centimeters, but the voltage marked there will be 350. Any number of intermediate divisions may be similarly computed, and a fairly detailed nonuniform scale drawn. Let the current scale be 1 centimeter = 50 amperes, and let us compute the conditions for an in-phase component $i = 400$ amperes, or 8 centimeters. Let the line voltage be 350 kv, so that the real power is 242,500 kw. To pick out a convenient value for $k = CG$, we reason as follows: $NS$ is 8 centimeters, and $GU$ is 25 centimeters (assuming $U$ to be at 350 kv). Hence, the division of the power scale at $G$ must be (25/8) 242,500 = 758,000 kw. It is therefore convenient to choose 1 centimeter = 20,000 kw, making the length $CG$ = 37.9 centimeters. The same power scale will be correct, by construction, for any other value of the line voltage.

One could establish theoretical equations for the interdependence of the scales, but it seems that a few trials, such as the foregoing example, will readily permit to choose the most convenient proportions within the available space on the board. The power scale is shown in the upper left corner in figure 1. The board on which the Heavisidion is mounted is 42 by 64 inches; this will give the idea about the size of the device.

The writer wishes to express his appreciation of the help rendered by his 2 former students, Robert R. Gay (Enrolled Student) and Paul H. Hunter, both Cornell '37, who computed the sizes of the linkages and actually built and assembled the device following the writer's instructions in the 2 abovementioned articles.

Very truly yours,

VLADIMIR KARAPETOFF
(A'03, F'12, Life Member)
Cornell University, Ithaca, N. Y.

## Articles on Radio in "Electrical Engineering"

*To the Editor:*

This is just a note to let you know how attractive the June issue of ELECTRICAL ENGINEERING is with its cover lettered in red. I am sure that the combination of color printing and the unique paper which is used makes this publication by all odds the most pleasing in appearance of the 20-odd periodicals which reach my desk every month.

I will also take this opportunity to tell you how pleased I was to find not just one but 2 articles on radio in the June issue. When it is remembered that the radio industry produced about 8-million receivers last year, the importance of this branch of electrical engineering stands out. I trust that this field will continue to receive the attention it so clearly deserves in ELECTRICAL ENGINEERING.

Very truly yours,

ALBERT R. HODGES (A'37)
Associate, Ralph H. Langley,
Consulting Engineer
165 Broadway, New York, N. Y.

## Induction Motors on Unbalanced Voltages

*To the Editor:*

I wish to point out some errors in my discussion which appeared in the May 1937 issue of ELECTRICAL ENGINEERING on page 621.

In the center column the equation appears,

$$I_c = I$$

This should be

$$I_c = -I$$

Lower down in the same column the equation

$$V_{bc} = j(\sqrt{3}\ V_{s1} - V_{s2})$$

is shown. This should be

$$V_{bc} = j\sqrt{3}\ (V_{s1} - V_{s2})$$

Equation 1 reads

$$I_{s1} = I_{s2}$$

This should be

$$I_{s1} = -I_{s2}$$

The second line of equation 4 appears as,

$$V_b = \alpha^2 I_1 Z_1 + \alpha I_2 V_2 - (I_1 + I_2)\ Z_0$$

This should be,

$$V_b = \alpha^2\ I_1 Z_1 + \alpha\ I_2 Z_2 - (I_1 + I_2)\ Z_0$$

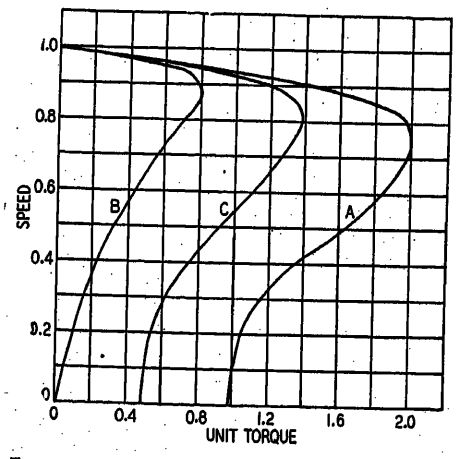



**Figure 4. Speed-torque characteristics of a 5-horsepower 220-volt 3-phase 60-cycle 6-pole induction motor**

*A*—Normal 3-phase operation
*B*—Single-phase operation, line-to-line voltage
*C*—Operation on 2 of the 3 phases
The motor constants in unit values are as follows:

$r_{s1} = 0.044$
$r_{r1} = 0.057$
$Z_0 = 0.044 + j\,0.140$
$Y_{m1} = 0.023 + j\,0.380$
$X_{s1} + 0.140$
$X_{r1} = 0.140$

The speed-torque curves of figure 4 were not published in the May issue and are therefore given here.

Very truly yours,

H. J. REEVES (A'30)
PAUL AND REEVES,
Spokane, Wash.

# Personal Items

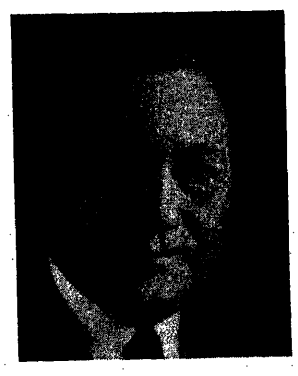
B. J. ARNOLD (A'92, F'12, past-president, member for life) consulting engineer, Chicago, Ill., has been elected an Honorary Member of the Institute. Colonel Arnold was born at Casnovia, Mich., in 1861, and received the degrees of bachelor of science (1884) and mechanical engineer (1887) at Hillsdale College; later, he took a graduate course in electrical engineering at Cornell University, in 1897 received the degree of electrical engineer from the University of Nebraska, and at various times has received several honorary degrees. One of Colonel Arnold's first important engineering projects was the design and construction of the Intramural Elevated Railway at the Columbian Exposition in Chicago, in 1893. This was the first commercial demonstration of the third rail on a large scale. Later he did pioneer work of construction for such railroads as the Chicago-Milwaukee Electric Railway and the Lansing, St. Johns, and St. Louis Railway in Michigan. For the latter company he devised, in 1900, a single-phase a-c system. Colonel Arnold electrified the Grand Trunk Railroad through the St. Clair Tunnel from Port Huron, Mich., to Sarnia, Ont., Canada, and used for the first time a single-phase high-voltage system for heavy electric railway work. Among his other important commissions were the electrification of the Grand Central Terminal, New York, N. Y., and the development of the subway system in New York. He has been a consultant on surface and underground traction problems for cities throughout the United States and consulting engineer for numerous railroad commissions. During the World War Colonel Arnold served in various capacities, being assigned as lieutenant colonel in the aviation section in 1917, to make a complete survey of aircraft supply and production facilities for the United States Army and Navy, and to take charge of the development and production of aerial torpedos. He has served the Institute as manager, 1895–98; vice-president, 1902–03; and president, 1903–04. In addition, he has served as a member of the committees on education, 1924–26; meetings and papers (now technical program), 1902–03 and 1908–09; executive, 1924–26. He was a member of the American Committee on Electrolysis (1914–21 and 1922–32) and of the John Fritz Medal board of award during 1905–08. Colonel Arnold received the Washington Award of the Western Society of Engineers in 1929, and is a member of many technical and engineering societies, including the American Society of Civil Engineers, The American Society of Mechanical Engineers, and the American Society for the Promotion of Engineering Education.

P. S. MILLAR (A'03, M'13) president, Electrical Testing Laboratories, Inc., New York, N. Y., has received the 1936 AIEE national prize award for best paper in engineering practice for his paper "The Qualities of Incandescent Lamps." Mr. Millar was born at Andover, N. J., in 1880, and obtained his formal technical education at Paterson Classical and Scientific School and through the International Correspondence Schools. In 1897 he entered the employ of the Lamp Testing Bureau (now Electrical Testing Laboratories, Inc.) and in 1899 became assistant manager of that organization. He became general manager in 1914, and has been president since 1930. Mr. Millar has done much original work in illumination research, being co-inventor of the Sharp-Millar photometer, and has contributed liberally to the technical press. He has been a member of the Institute's committees on electrophysics, 1917–18; meetings and papers (now technical program), 1925–28; and production and application of light (chairman, 1925–28) since 1924. Recently he was elected president of the United States National Committee of the International Commission on Illumination. Mr. Millar is a fellow of the American Physical Society, member of the council of the Association of Consulting Chemists and Chemical Engineers, secretary-treasurer of the Association of Edison Electric Illuminating Companies, member and past-president of the Illuminating Engineering Society, and a director of the Thomas Alva Edison Foundation.

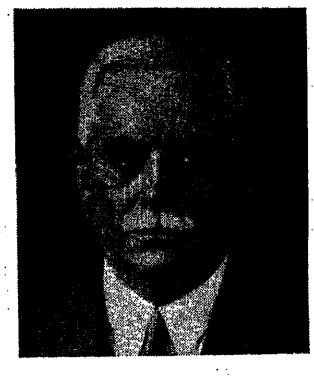
ALEX DOW (A'93, F'13, member for life) president, Detroit (Mich.) Edison Company has been elected an Honorary Member, the highest grade of membership in the Institute. The petition proposing his election as Honorary Member stated: "Doctor Dow's responsible guidance has developed one of the great utility companies, which has, throughout this long period [Doctor Dow has been President of the Detroit Edison Company for 24 years] been in the van of technical progress and which has maintained a high standard of service in the public interest." He has been a leading pioneer in the United States in the engineering, rate making, and general operation of the electric light and power utility, and is given credit for both the engineering and financial success of his enterprises. He is considered the father of the so-called "big" steam boiler in the United States and was the first to adopt the underfeed stoker for large installations. A more complete biographical sketch of Doctor Dow was published in the January 1937 issue of ELECTRICAL ENGINEERING (page 197) upon the occasion of the award to him of the AIEE Edison Medal for 1936 "for outstanding leadership in the development of the central station industry and its service to the public."

W. J. LYMAN (A'25) electrical planning engineer, Duquesne Light Company, Pittsburgh, Pa., has received honorable mention in the 1936 AIEE national prize awards for best paper in engineering practice for his paper "The Relation Between Load, Capacity, and Service Continuity on an Electric Power System." Mr. Lyman was born August 30, 1901, at Cambridge, Mass., and received the degree of bachelor of science in electrical engineering at Carnegie Institute of Technology in 1924. Prior to his enrollment at that school he was affiliated briefly with the Turners Falls Power and Electric Company, Greenfield, Mass., and the Automatic Transportation Company, Buffalo, N. Y. In 1924 he entered the employ of the Duquesne Light Company as an apprentice engineer, but in the following year was transferred to the planning division of that company, where his work has consisted of engineering and economy planning for the entire system. Mr. Lyman has been electrical planning engineer since 1929, in which capacity he has been in entire charge of the electrical planning section. From 1927 to 1932 he served as a member of the lightning arrester subcommittee of the AIEE protective devices committee, and was active in committee work of the former National Electric Light Association. In addition to his regular duties, Mr. Lyman has taught technical subjects in the night school at Carnegie Institute of Technology since 1924. He has written several technical papers and articles, including 2 papers presented before the Institute.

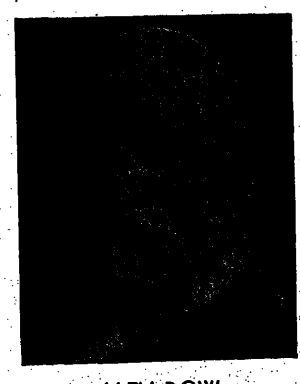
H. P. SEELYE (A'19, M'28) engineer for The Detroit (Mich.) Edison Company, has received honorable mention in the 1936 AIEE national prize awards for best paper in engineering practice for his paper "Modernization of Power Distribution Systems." Mr. Seelye was born June 27, 1890, and was graduated from the University of Michigan



P. S. MILLAR

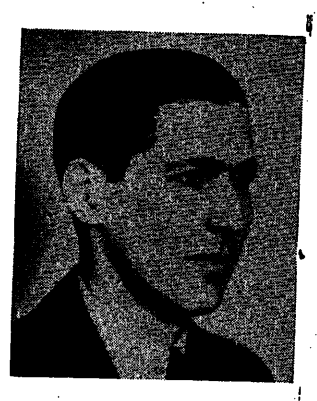


B. J. ARNOLD

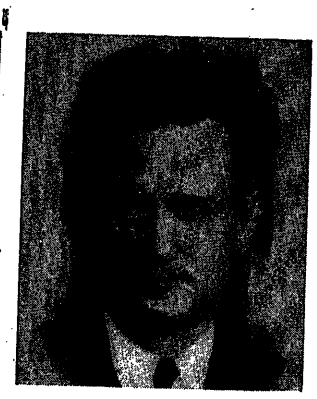


ALEX DOW

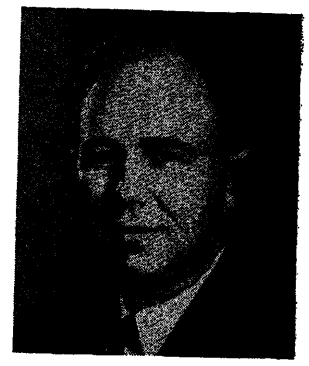
with a degree in civil engineering in 1912. After 4 years of varied engineering training, he entered the employ of The Detroit Edison Company in 1916, and since that time has been engaged in transmission and distribution engineering problems and design. Mr. Seelye now is in active charge of the transmission and distribution section of the Company. He was chairman of the AIEE Detroit-Ann Arbor Section during 1935–36, and is a member of the distribution subcommittee of the AIEE committee on power transmission and distribution and the electrical standards committee of the American Standards Association. In addition, he is a sponsor of the group on standards and specifications of the transmission and distribution committee of the Edison Electric Institute. Mr. Seelye is the author of 2 books: "Electrical Distribution Engineering" and "Economics of Electrical Distribution."



D. H. ROWLAND



H. R. WOODROW



H. E. EDGERTON

H. R. WOODROW (A'12, F'23) vice-president, Brooklyn (N. Y.) Edison Company, Inc., has been elected vice-president of the Consolidated Edison Company of New York, Inc., New York, N. Y. Mr. Woodrow was born April 15, 1887, at Luverne, Minn., and received the degrees of bachelor of science (1909) and master of science (1911) at Drake University and University of Illinois, respectively. Following his graduation in 1911 he joined the engineering staff of The New York Edison Company, Inc., as assistant to the chief electrical engineer, and held that position until he was appointed assistant chief electrical engineer in 1917. In 1920 he became affiliated with Stone and Webster, Inc., as an electrical engineer, but remained with that company for only one year before transferring to the Westinghouse Electric & Manufacturing Company, East Pittsburgh, Pa., as a general engineer. Mr. Woodrow entered the employ of the Brooklyn Edison Company in 1922 as an assistant electrical engineer. Four years later he was promoted to electrical engineer, and since 1932 he has been vice-president. He served the Institute as a director from 1931 to 1935, and is at present serving as its representative to the United Engineering Trustees for the term 1934–37, just ending. He has also served as a member of many of the Institute's technical committees.

H. E. EDGERTON (A'27, M'32) assistant professor of electrical engineering, Massachusetts Institute of Technology, Cambridge, has received the 1936 AIEE national prize award for best paper in theory and research for his paper "High Speed Motion Pictures." Doctor Edgerton was born April 6, 1906, at Fremont, Nebr., and was graduated in electrical engineering from the University of Nebraska in 1925, following which he entered the test course of the General Electric Company, Schenectady, N. Y. In 1926 he enrolled in the graduate school of Massachusetts Institute of Technology and received from that institution the degrees of master of science (1927) and doctor of science (1931). During 1927–28 Doctor Edgerton served as a research assistant, and in the following year was appointed to the faculty of MIT as an instructor in electrical engineering. He became assistant professor in 1932. His graduate work for his doctor's degree consisted of research on synchronous machines and stroboscopes, and much of his subsequent research has been of a similar nature. He has become widely recognized for his accomplishments in studying motions of machines and moving parts by means of high-speed motion pictures. Doctor Edgerton served as a member of the Institute's committee on electrical machinery from 1931 to 1935.

D. H. ROWLAND (A'26) research engineer, Locke Insulator Corporation, Baltimore, Md., has received the 1936 AIEE national prize award for initial paper for his paper "Porcelain for High Voltage Insulators." Mr. Rowland was born December 25, 1898, at Baltimore, and received the degree of bachelor of science in electrical engineering at The Johns Hopkins University in 1922; however, his college training was interrupted by his service in the United States Army during the World War, and at the conclusion of the war Mr. Rowland went to Paris, France, to study physics and mathematics at the Sorbonne University before returning to the United States. Following his graduation he was employed in the statistical department of Stone and Webster, Boston, Mass., but shortly thereafter he entered the lightning protection department of the Western Union Company, New York, N. Y. In 1922 Mr. Rowland became affiliated with the Locke Insulator Corporation and in various capacities has since served that company continuously. He is the author of several technical articles on ceramics as related to insulators. He is a member of Tau Beta Pi and Omega Delta Kappa honorary fraternities.

W. L. SMITH (M'22) professor and head of the department of electrical engineering, Northeastern University, Boston, Mass., recently retired from active duty, after more than 40 years of service. Professor Smith was born September 6, 1867, at Concord, Mass., and was graduated in electrical engineering from Massachusetts Institute of Technology in 1890. Following his graduation he was appointed to the faculty of the same institution as an assistant in physics; later, he became an assistant in electrical engineering and an instructor in electrical engineering, but resigned in 1902 to pursue experimental and consulting-engineering work. Professor Smith has been head of the department of electrical engineering since the incorporation of Northeastern University in 1916.

A. A. LOW (M'37) executive vice-president, Brooklyn (N. Y.) Edison Company, Inc., has been elected vice-president of the Consolidated Edison Company of New York, Inc., New York, N. Y. Mr. Low was born August 1, 1889, at Saratoga Springs, N. Y., and received the degree of bachelor of arts at Yale University in 1911. He entered the public utility field in 1928 as organizer and president of the Old Forge (N. Y.) Electric Company. In 1931 he became affiliated with the Utica (N. Y.) Gas and Electric Company as executive vice-president, which position he held for 3 years before being elected president of that company in 1934. Mr. Low became identified with the Brooklyn Edison Company in 1936 as executive vice-president in responsible charge of operations.

W. R. HARRY (A'37) Bell Telephone Laboratories, Incorporated, New York, N. Y. has received honorable mention in the 1936 AIEE national prize awards for Branch paper for his paper "A High-Speed Vibration Analyzer." Mr. Harry is a native (1912) of Detroit, Mich., and an electrical engineering graduate of Cornell University. Prior to graduation, he was employed during summer vacations by The Detroit Edison Company and radio station CKLW, Windsor, Ont., Canada. Since the beginning of his association with the Bell Telephone Laboratories, in 1936, he has been engaged in the derivation of a new microphone for broadcast use.

W. P. GRAHAM (A'02, F'23) acting chancellor, Syracuse University, Syracuse, N. Y., has been appointed chancellor. As stated in a biographical sketch of Doctor Graham published in the December 1936 issue of ELECTRICAL ENGINEERING (page 1404) he has been affiliated with the university for almost 40 years, and was vice-chancellor for 15 years prior to his appointment as acting chancellor in 1936.

W. J. WALSH (Enrolled Student) graduate student in electrical engineering at Oregon State College, Corvallis, has been awarded the 1936 AIEE national prize award for

Branch paper for his paper "Heat Transfer Efficiency of Electric Range Surface Units." Mr. Walsh was born February 7, 1915, at Portland, Me., and received the degree of bachelor of science in electrical engineering at Oregon State College in 1936. In addition to his regular scholastic work, Mr. Walsh serves as a research assistant in the Oregon State College Engineering Experiment Station. He is a member of Tau Beta Pi, Eta Kappa Nu, Phi Kappa Phi, and Sigma Xi.

G. H. JONES (A'02, F'12) for many years power engineer for the Commonwealth Edison Company, Chicago, Ill., recently was appointed manager of power sales. Mr. Jones was born at Fond du Lac, Wis., in 1874, and received the degree of bachelor of science in electrical engineering at the University of Wisconsin in 1897. He became affiliated with the Commonwealth Edison Company in 1909.

E. S. SIEVERS (A'34) who has been a sales engineer in the New York (N. Y.) offices of the Weston Electrical Instrument Corporation, has been transferred to Los Angeles, Calif., as assistant to the Weston company's representative in that area. Mr. Sievers has been associated with the Weston organization continuously since his graduation from Purdue University in 1934.

T. H. HAINES (A'23, M'31) superintendent, distribution department, Edison Electric Illuminating Company of Boston, Mass., has been appointed a representative of the AIEE on the Sectional Committee on National Electrical Safety Code.

W. C. GOODWIN (M'33) air conditioning department, Westinghouse Electric & Manufacturing Company, Mansfield, Ohio, has been appointed a representative of the AIEE on the Sectional Committee of Safety Code for Mechanical Refrigeration.

H. B. GEAR (A'01, F'20, director) vice president in charge of operating and engineering, Commonwealth Edison Company, Chicago, Ill., has been appointed a representative of the AIEE on the Commission of Washington Award for the 2-year term beginning August 1, 1937.

J. F. LAMBIAS, JR. (A'36) formerly a distribution draftsman for the Brooklyn (N. Y.) Edison Company, now is a junior engineer in the evaluation bureau of the New York and Queens Electric Light and Power Company, Long Island City, N. Y.

S. P. SAWYER (A'30) formerly assistant district engineer, New England Power Service Corporation, Northampton, Mass., now is assistant superintendent of distribution, Central Massachusetts Electric Company, Palmer, Mass.

L. L. ROBINSON (A'31) who has been employed by the Kinnear Manufacturing Company, Columbus, Ohio, now is associated with the production division of the Marion Steam Shovel Company, Marion, Ohio.

S. A. SMITH, JR. (A'24, M'31) resigned recently from the Public Service Electric and Gas Company, Newark, N. J., to become affiliated with the engineering department of the General Cable Corporation, New York, N. Y.

F. W. MEYEREND (A'34) electrical engineer, John A. Roebling's Sons Company, San Francisco, Calif., has been transferred to the Trenton, N. J., offices of that Company.

FRANK MANSUR (A'35) local agent for the Southern California Edison Company, Placentia, Calif., has been appointed commercial and industrial lighting specialist for that company, with offices at Santa Ana.

M. M. DE LASCURAIN (A'36) recently resigned his position in the engineering department of the General Electric Company, Mexico City, Mexico, to become sales manager of Cía Comercial Ericsson, Mexico City.

K. C. HOLLISTER (A'35) assistant sales engineer, Westinghouse Electric & Manufacturing Company, East Pittsburgh, Pa., has been transferred to the New York (N. Y.) offices of that company.

JOSEPH GLADIS (A'27) who has been employed by the Board of Transportation, City of New York, N. Y., now is affiliated with the switchgear engineering department of the Westinghouse Electric & Manufacturing Company, East Pittsburgh, Pa.

C. H. ANDERSON (M'34) formerly general superintendent of the Ontario division of the Niagara, Lockport, and Ontario Power Company, Medina, N. Y., now is general superintendent of the Niagara Falls division of the Buffalo and Niagara Electric Corporation, Niagara Falls, N. Y.

NATHAN FRIEDLAND (A'36) formerly production manager of Belmet Products, Inc., Brooklyn, N. Y., now is employed in the office of the signal engineer of the Interborough Rapid Transit Company, New York, N. Y.

W. C. STEWART (A'28) formerly an engineer in the data division of the General Electric Company, Schenectady, N. Y. has become technical adviser to the American Institute of Bolt, Nut, and Rivet Manufacturers, Cleveland, Ohio.

PAUL SHAAD (A'34) student engineer, General Electric Company, Schenectady, N. Y., has been transferred to the San Francisco, Calif., offices of that company.

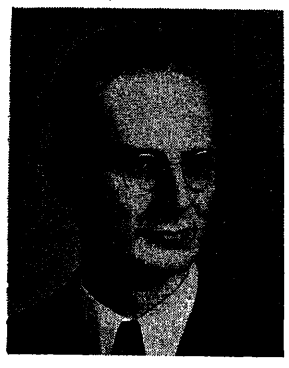
H. W. GIESECKE (A'35) formerly employed in the electrical department of the Federal Shipbuilding & Dry Dock Company, New York, N. Y., now is an engineer in the general engineering department of the Standard Oil Development Company, Elizabeth, N. J.

B. V. HOARD (M'36) who has been an engineering assistant in the plant bureau of the Consolidated Edison Company of New York, Inc., New York, N. Y., now is with the Westinghouse Electric & Manufacturing Company, Newark, N. J.

TALIAFERRO MILTON (A'11, F'20) has been appointed special representative of the K. W. Battery Company, with headquarters at Chicago, Ill.

## Obituary

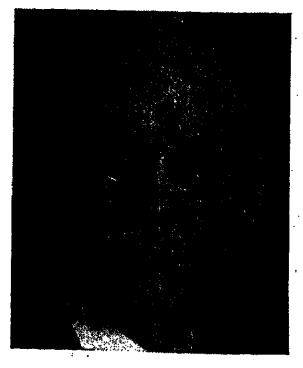
AMBROSE SWASEY (HM'28) chairman of the board, The Warner and Swasey Company, Cleveland, Ohio, died at his summer home in Exeter, N. H., June 15, 1937, in his 91st year. Doctor Swasey was born at Exeter, N. H., December 19, 1846. During the period 1869–80 he was with the Pratt and Whitney Company, Hartford, Conn., where he gave special attention to problems of gearing. In 1880 he formed a partnership with W. R. Warner, the firm being incorporated in 1900 as The Warner and Swasey Company. The company engaged in the manufacture of machine tools and astronomical instruments at Chicago, Ill., moving later to Cleveland, Ohio. Doctor Swasey has been chairman of the board since the death of Mr. Warner. In 1914, he established the Engineering Foundation, research agency of the 4 national societies of civil, mining and metallurgical, mechanical, and electrical engineers. He has contributed gifts totaling more than $750,000 to the Foundation. Doctor Swasey's many



W. J. WALSH



A. A. LOW



W. P. GRAHAM

honors include: The John Fritz Gold Medal, 1924; Franklin Medal, highest award of the Franklin Institute; Washington Award, 1935; The Second Hoover Gold Medal, 1936; and the Medal of Honor of the Verein Deutscher Ingenieure, 1936. In addition to honorary membership in the AIEE, which was awarded him June 27, 1928, he is an honorary member of The American Society of Mechanical Engineers (president 1904), American Society of Civil Engineers, Institution of Mechanical Engineers (Great Britain), Institution of Mining Engineers (Great Britain), and the Society of Civil Engineers. He is a chevalier and officer of the French Legion of Honor, and has received several honorary degrees in the United States.

ARTHUR LANGLEY MUDGE (A'01, M'12, F'12) consulting electrical engineer, Toronto, Ont., Canada, died April 29, 1937. Mr. Mudge was born October 17, 1873, at Montreal, Que., Canada, and was graduated in mechanical engineering at McGill University in 1894; in 1895 he received a degree in electrical engineering at the same institution and almost at once joined the Canadian General Electric Company, Peterborough, Ont., as an instructor in the student training course. In 1897 Mr. Mudge became affiliated with the Royal Electric Company, Montreal, where he remained for 2 years as a test engineer before being appointed electrical engineer for the Grand Trunk Railway Company. In 1901 Mr. Mudge became engaged as a test engineer for the Stanley Electric Manufacturing Company, Pittsfield, Mass., but in 1904 he began a series of brief associations with the Allis-Chalmers Manufacturing Company in the United States and the Allis-Chalmers-Bullock Company and the Crocker-Wheeler Company, Ltd., in Canada, which lasted until 1908. At that time he joined the consulting engineering firm of Smith, Kerry, and Chace, Toronto, and was placed in charge of the electrical department. He remained with that company until 1925, when he was appointed senior electrical engineer with the joint board of engineers in the Canadian section of the St. Lawrence waterways project. In 1927 Mr. Mudge was appointed senior electrical engineer of the Welland Ship Canal and remained in charge until construction was completed. He was chairman of the AIEE Toronto Section during 1911–12, was a past-vice-president of the Canadian Electrical Association, and a member of the Association of Professional Engineers of Ontario.

HARRY MILTON DEARMIN (A'22, M'28) supervising draftsman, Pacific Gas and Electric Company, San Francisco, Calif., died recently. Mr. Dearmin was born September 16, 1895, at Hillsboro, Texas, and received the degree of associate in electrical engineering at the Polytechnic College of Engineering. Following brief periods of association with the Pacific Gas and Electric Company, the Marconi Wireless Telegraph Company of America, and the Western Electric Company, he entered the employ of the United Electric Vehicle Company, Oakland, Calif., and was placed in charge of plant maintenance. He was affiliated with that company for only one year, however, before enlisting in the United States Navy, in 1917, as an electrician. Later he was promoted to the rank of ensign, and was made an inspector of machinery at the Union Iron Works, San Francisco. At the end of the World War Mr. Dearmin joined the engineering staff of the Pacific Gas and Electric Company as a designer, and had been a supervising draftsman since 1924.

ELDEN S. CODE (A'11, M'20) electrical engineer, Westinghouse Electric & Manufacturing Company, Seattle, Wash,. died January 1, 1937, according to word just received at Institute headquarters. Mr. Code was born January 15, 1883, at Carleton Place, Ont., Canada, and received the degree of bachelor of science in electrical engineering at Queens University in 1907. Following his graduation, he entered the electrical engineering apprenticeship course of the Westinghouse Electric & Manufacturing Company, East Pittsburgh, Pa., and upon completion of the course was transferred to the switchboard engineering department of that company. In 1910 he was sent to the Seattle offices of the Westinghouse company. His work there comprised sales and design work for industrial, power, railway, and lighting projects, and his service extended over more than 25 years.

MICHAEL ROMANO (A'20) manager and treasurer, Hackett Products Company, Inc., Providence, R. I., died March 21, 1937. Mr. Romano was born in Italy, February 15, 1886, and attended Lowell Institute and Massachusetts Institute of Technology. From 1908 to 1914 he served the General Fire Extinguisher Company, Providence, first as an electrician and later as maintenance engineer. In 1914 he entered the employ of the General Electric Company, Schenectady, N. Y., as a test engineer and remained there for 4 years before becoming an inspector for the United States Navy. He became associated with the Hackett Products Company, Inc., in 1925.

ZELLA A. MCBERTY (A'24) secretary and treasurer of The Federal Machine and Welder Company, Warren, Ohio, and one of the few women members of the Institute, died May 24, 1937. Mrs. McBerty was born August 27, 1878, at Mineral Ridge, Ohio, and received her formal technical training through private instruction. In 1913 she became interested in electric welding, and began to design low-voltage transformers and electric welding machines. In the following year she became affiliated with the National Electric Welder Company, Warren, and her service with that company and its successor, The Federal Machine and Welder Company, was continuous for more than 22 years. Mrs. McBerty had retired from active service on the day of her death.

EMIL M. KAEGI (M'36) electrical engineer for the Allis-Chalmers Manufacturing Company, Milwaukee, Wis., died recently. Mr. Kaegi was born June 21, 1900, at Zurich, Switzerland, and received his technical education by serving an apprenticeship with the Trueb Tauber Company, Zurich, from 1915 to 1919. In 1919 he became a designer of d-c control apparatus for the Brown Boveri Company, at Baden, Switzerland, but in the following year came to the United States, where he secured a position with the Hoskins Manufacturing Company, Detroit, Mich., and remained 2 years. After a brief association with the F. B. Electrical Company and the Premier Radio Corporation, Detroit, Mich., he joined the Brown Boveri Company, Camden, N. J., and was placed in charge of the drafting department for rectifiers and auxiliary equipment. In that capacity Mr. Kaegi supervised the design of several large substations in the United States and Canada, and when the Brown Boveri Company was purchased by the Allis-Chalmers Manufacturing Company in 1931, he was retained in the same position, but with the title of electrical engineer.

THOMAS HOSKINS KETTIG (A'34) construction superintendent, Southern Bell Telephone and Telegraph Company, Louisville, Ky., died February 12, 1937. Mr. Kettig was born at Louisville, August 2, 1889, and received his education in the public schools there. He served the Southern Bell Telephone and Telegraph Company in various capacities for 31 years, and was superintendent of construction in the Kentucky division for more than 12 years.

# Membership

## Recommended for Transfer

The board of examiners, at its meeting on June 16, 1937, recommended the following members for transfer to the grade of membership indicated. Any objection to these transfers should be filed at once with the national secretary.

**To Grade of Fellow**

Bailey, R. Cooper, system control engineer, Virginia Electric and Power Company, Richmond.
Spurck, R. M., manager, circuit breaker sales, General Electric Company, Philadelphia, Pa.

2 to Grade of Fellow

**To Grade of Member**

Blevins, Edward, assistant superintendent, Tampa Electric Company, Plant City, Fla.
Burroway, A. C., division plant superintendent, Cincinnati and Suburban Bell Telephone Company, Cincinnati, Ohio.
Carlin, P. J., superintendent of distribution, Florida Power and Light Company, Miami.
Concordia, C., engineer, General Electric Company, Schenectady, N. Y.
Coursey, R. W., underground engineer, Oklahoma Gas and Electric Company, Oklahoma City.
Crary, S. B., member central station department, General Electric Company, Schenectady, N. Y.
Dean, C. E., radio engineer, Hazeltine Service Corporation, New York, N. Y.
Fife, S. T., professor of electrical engineering, and head of department, University of Louisville, Louisville, Ky.
Holton, J. L., assistant distribution engineer, New York and Queens Electric Light and Power Company, Flushing, N. Y.
Houchens, J. M., co-ordinator (assistant professor), University of Louisville, Louisville, Ky.
Howes, J. C., electrical engineer, General Electric Company, Pittsfield, Mass.
Jones, J. Coleman, superintendent of transmission, Florida Power and Light Company, Fort Pierce.
Lea, R. A., distribution engineer, Union Electric Light and Power Company, St. Louis, Mo.
Loeffler, B. T., division equipment engineer, Indiana Bell Telephone Company, Indianapolis, Ind.
Macalpine, William W., communication engineer, Federal Telegraph Company, Newark, N. J.
McMorris, William A., electrical engineer, General Electric Company, Pittsfield, Mass.

Miller, C. W., sales engineer, Westinghouse Electric & Manufacturing Company, New York, N. Y.
Mulligan, J. F., superintendent, transmission division, Consolidated Edison Company of New York, Inc., New York, N. Y.
Parker, William W., technician, switchgear engineering department, Westinghouse Electric & Manufacturing Company, East Pittsburgh, Pa.
Skone, R. C., resident engineer, Diablo Project, Rockport, Wash.
Southworth, H., assistant manager, Lawrence Gas and Electric Company, Lawrence, Mass.
Tadlock, W. L., supervising engineer, Commonwealth and Southern Corporation, Birmingham, Ala.
Town, G. R., research engineer, Stromberg-Carlson Telephone Manufacturing Company, Rochester, N. Y.

23 to Grade of Member

## Applications for Election

Applications have been received at headquarters from the following candidates for election to membership in the Institute. If the applicant has applied for direct admission to a grade higher than Associate, the grade follows immediately after the name. Any member objecting to the election of any of these candidates should so inform the national secretary before July 31, 1937, or Sept. 30, 1937, if the applicant resides outside of the United States or Canada.

Ashbaugh, E. G., Westinghouse Electric & Manufacturing Company, Sharon, Pa.
Byers, J. F., Libbey-Owens-Ford Glass Company, Charleston, W. Va.
Caldwell, C. A., Houston Lighting and Power Company, Houston, Texas.
Carter, R. C., Jr., Company 1843, Camp *NP-5-C*, Mesa Verde, Colo.
Coates, R. E., General Electric Company, Pittsfield, Mass.
Cooley, M. C. (Member), W. N. Matthews Corporation, St. Louis, Mo.
Corves, G. S., Southern New England Telephone Company, West Haven, Conn.
Dimmitt, E. H., Federal Power Commission, Washington, D. C.
Elmer, E. R., Jr., Underwriters' Laboratories, Inc., Chicago, Ill.
Fetherolf, J. M., in care of Edward J. Cheney, New York, N. Y.
Fox, C. E. (Member), 806 North Fifth Avenue, Knoxville, Tenn.
Goodburn, R. A., Florida Power and Light Company, Miami.
Harmon, L. B., Westinghouse Electric & Manufacturing Company, Los Angeles, Calif.
Hubbard, R. R., J. A. Adams Company, Indianapolis, Ind.
Jabour, E., Department of Light, Los Angeles, Calif.
Kearns, J. J., Crucible Steel Company of America, Harrison, N. J.
Kimball, A. L. (Member), Otis Elevator Company, Buffalo, N. Y.
Klumb, R. K., Southern California Edison Company, Ltd., Chino, Calif.
Lickey, H. F., State College of Washington, Pullman.
Madsen, R. V., Southern Pacific Golden Gate Ferries, San Francisco, Calif.
Mathes, R. E., RCA Communications, Inc., New York, N. Y.
McCormick, F. J. (Member), Wisconsin Telephone Company, Milwaukee, Wis.
Mellor, A. G., Buffalo, Niagara and Eastern Power Company, Buffalo, N. Y.
Miller, M. I., Carolina Power and Light Company, Raleigh, N. C.
O'Neal, F. C., Jr., Texas Electric Service Company, Eastland, Texas.
Parsons, C. W., Johnson Electric Supply Company, Cincinnati, Ohio.
Power, R. B., Jr., Kennecott Wire and Cable Company, Phillipsdale, R. I.
Ramsay, H. B., New Orleans Public Service, Inc., New Orleans, La.
Rogers, H., Jr., Western Electric Company, San Francisco, Calif.
Rossrucker, E. A., Ohio Bell Telephone Company, Cleveland, Ohio.
Scheer, G. B., San Francisco-Oakland Bay Bridge, San Francisco, Calif.
Selman, M. H., housing division, Public Works Administration, Washington, D. C.
Shannon, S. R., Jr., General Electric Company, Erie, Pa.
Sheblak, V. B., Bureau of Power and Light, Los Angeles, Calif.
Simmons, E. E., Jr., California Institute of Technology, Pasadena.
Sinnott, J. F., San Diego Consolidated Gas and Electric Company, San Diego, Calif.
Smith, C. J., Charles H. Smith and Company, Engineers, Inc., New York, N. Y.
Soares, Glen J., 5482 Kales Avenue, Oakland, Calif.
Stafford, D. E., National Electric Coil Company, Columbus, Ohio
Stahler, L. L., Florida Power and Light Company, Miami.
Taylor, W. F. (Member), New England Allis-Chalmers Manufacturing Company, Boston, Mass.
Tellez, J. S., Pipe Trades Service Company, Toledo, Ohio.
Thomson, W. T., 1224 Park Avenue, Alameda, Calif.
Vesely, S. M., Chicago Electric Company, Chicago, Ill.
Waidhas, G., Allis-Chalmers Manufacturing Company, West Allis, Wis.
Ward, S. J., Houston Light and Power Company, Houston, Texas.
White, E. L. (Member), Federal Communications Commission, Washington, D. C.
Willis, J. D., Canadian General Electric Company, Ltd., Toronto, Ont., Canada.
Witzke, R. L., Westinghouse Electric & Manufacturing Company, East Pittsburgh, Pa.
Woolley, H. P., Woolley Welding and Machine, Houston, Texas.

50 Domestic

**Foreign**

Apte, S. V. (Member), College of Engineering, Poona, India.
Geltz, F., South American Development Company, Guayaquil, Ecuador.
Gordon, F., Cerro de Pasco Copper Corporation, La Oroya, Peru.
Madahar, G. D., Modern Electric Works, Lahore, Punjab, India.
Page, F. W., British Electrical and Allied Industries Research Association, London, England.
Shivapuri, P. R. N., Punjab Electric Power Company, Ltd., Gujrat, Punjab, India.

6 Foreign

# Engineering Literature

## New Books in the Societies Library

Among the new books received at the Engineering Societies Library, New York, recently are the following which have been selected because of their possible interest to the electrical engineer. Unless otherwise specified, books listed have been presented gratis by the publishers. The Institute assumes no responsibility for statements made in the following outlines, information for which is taken from the preface of the book in question.

CONTRIBUTIONS from the PHYSICAL LABORATORIES of HARVARD UNIVERSITY for the Years 1933, 1934, and 1935. Series II, 2 volumes. Cambridge, Mass., Harvard University Press, 1936–1937. Illustrated, 11x8 inches, volume 1, 628 pages; volume 2, 469 pages, leather, $2.50 each. Collections of 65 and 57 papers, respectively, on work done in the physics laboratories of Harvard University.

First Course in STATISTICAL METHOD. By G. I. Gavett. 2 edition. New York and London, McGraw-Hill Book Company, 1937. 400 pages, illustrated, 9x6 inches, cloth, $3.50. A textbook for use as a foundation course in "statistical method" for all fields in which the mathematical representation of facts is desirable.

ZERO to EIGHTY, being My Lifetime Doings, Reflections and Inventions, also My Journey around the Moon. By E. F. Northrup. Princeton, N. J., Scientific Publishing Company, 1937. 280 pages, illustrated, 10x6 inches, cloth, $3.00; foreign countries $3.50. Devoted to a presentation of the possibilities in the production of high linear velocities by the use of traveling waves of electric force. Cast in the form of the autobiography of a scientist living from 1920 to 2000 A.D.

(The) WORLD of ATOMS. By A. Haas. 2 edition, translated by G. B. Welch and H. S. Uhler. New York, D. Van Nostrand Company, 1937. 183 pages, illustrated, 9x6 inches, cloth, $3.00. A translation of the revision of a series of lectures intended to present to a lay public the achievements of modern atomic physics in as brief and yet thorough a manner as possible.

VALUATION of PROPERTY. 2 volumes. By J. C. Bonbright. New York and London, McGraw-Hill Book Company, 1937. 1271 pages, 9x6 inches cloth, $12.00. A presentation of the results of a research in legal and economic theories of property valuation. Volume 1 covers concepts of value, methods of valuation, and valuation for specific legal purposes. Volume 2 covers specific cases of valuation under certain rules, tax restrictions, and other legal considerations.

TECHNIQUE of MARKETING RESEARCH. Prepared by the Committee on Marketing Research Technique of the American Marketing Society. New York, McGraw-Hill Book Company, 1937. 432 pages, illustrated, 9x6 inches, cloth, $4.00. A review of methods for investigating problems in marketing policies, salability of products, markets, and selling.

SAE HANDBOOK, 1937 edition. New York, Society of Automotive Engineers. 774 pages, illustrated, 9x6 inches, cloth, $5.00 to SAE nonmembers ($2.50 to members). Contains specifications covering parts and fittings, materials, and small hardware in the automotive field. Also covers standard tests, ratings, and codes.

RELATIVITY THEORY of PROTONS and ELECTRONS. By Sir A. S. Eddington. New York, Macmillan Company; Cambridge (England) University Press, 1936. 336 pages, tables, 11x7 inches, cloth, $5.50. A companion volume to "Mathematical Theory of Relativity." The central problem is concerned with the conditions which fix the amount of mass and electric charge carried by protons and electrons.

PASCAL, the Life of Genius. By M. Bishop. New York, Reynal and Hitchcock, 1936. 398 pages, illustrated, 10x6 inches, cloth, $3.50. Biography of a man whose life had many interests and contacts.

NATIONAL PHYSICAL LABORATORY REPORT for the YEAR 1936. Great Britian, Department of Scientific and Industrial Research. London, His Majesty's Stationery Office, 1937. 144 pages, tables, 10x6 inches, paper. (Obtainable from British Library of Information, 270 Madison Avenue, New York, $0.80.) Contains a résumé of the research work done in 1936 in the departments of physics, electricity, radio, and engineering.

MOTOR and CONTROL APPLICATIONS. By G. H. Hall. New York, McGraw-Hill Book Company, 1937. 259 pages, illustrated, charts, tables, 9x6 inches, cloth, $3.00. Contains information for the machine designer; also presents data and dimensions of motors as standardized by the National Electrical Manufacturers Association.

MARCONI, the Man and His Wireless. By O. E. Dunlap, Jr. New York, Macmillan Company, 1937. 360 pages, illustrated, 9x6 inches, cloth, $3.50. A "biography" of wireless telegraphy, from infancy to maturity, combined with personal information concerning Marconi.

FUNDAMENTALS of VACUUM TUBES. By A. V. Eastman. New York and London, McGraw-Hill Book Company, 1937. 438 pages, illustrated, 9x6 inches,, cloth, $4.00. Discusses the basic theory underlying the operation of all types of modern vacuum tubes. Discusses at length high-vacuum tubes, mercury-vapor tubes, and several special varieties, with engineering analyses of their more important applications.

ELECTRIC POWER DEVELOPMENT in the U.S.S.R., edited by U.S.S.R. Committee for International Scientific and Technical Conferences, Krzizhanovsky Power Institute of the Academy of Sciences of the U.S.S.R. London, Lawrence and Wishart, Ltd., 1936. 496 pages, illustrated, 9x6 inches, cloth, $3.00. An exposition of the principal technical and economic problems of electrical development in the Soviet Union, and of the plans for meeting them.


**Engineering Societies Library**
29 West 39th Street, New York, N. Y.

MAINTAINED as a public reference library of engineering and the allied sciences, this library is a co-operative activity of the national societies of civil, electrical, mechanical, and mining engineers.

Resources of the library are available also to those unable to visit it in person. Lists of references, copies or translation of articles, and similar assistance may be obtained upon written application, subject only to charges sufficient to cover the cost of the work required.

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Many other services are obtainable and an inquiry to the director of the library will bring information concerning them.




# Industrial Notes

**New Rod Mills in Operation.**—The two parallel continuous rod mills of the American Steel & Wire Co. at Joliet, Ill., have been completed and were formally dedicated on June 23. These mills, designed by the wire company's own engineers, embody all modern improvements and a number of new developments never before used in such mills. Every 40 seconds a No. 5 rod, nearly a mile long, comes off the final pass at a speed of 3428 ft. per minute, as compared with 1500 ft. per minute in the old Joliet mills. Speed practically eliminates temperature drop in the rod during rolling and assures greater accuracy as to contour, and physical properties which improve wire quality. The new project is part of a $5,000,000 development which includes improvements in the South Chicago and Gary billet mills, as well as the wire mills in Illinois. Local power companies supply power at 6600 volts for the new mill. Direct current is supplied by a 4 unit motor-generator set, one generator supplying direct current for general use, the other two generators providing power to the reel motors which must be run in step with the mill at the final pass. One 4500-hp motor drives all the rolls on one mill.

**New High Speed Electric Locomotives.**—Six new streamlined electric locomotives, more powerful than any of the 53 already in operation between New York and New Haven, have been ordered by the New Haven Railroad and will be built in the General Electric plant at Erie, Pa. Each 3600-hp unit will weigh approximately 130,000 pounds, capable of a speed of over 80 miles an hour. Power will be supplied by six motors on as many driving axles, with each motor having two armatures geared to the one axle.

**Cutler-Hammer Appointment.**—E. J. Gove has been placed in charge of a new Cutler-Hammer office recently opened in Youngstown, O., at 1106 Central Tower. The new office is a branch of the company's Pittsburgh office.

**Ohio Brass Appointment.**—E. C. Thompson, formerly supervisor of transmission for the Alabama Power Co., has joined the Ohio Brass Co., Mansfield, O., as sales engineer in the power utilities department. He will spend considerable time in the field contacting utility engineers in connection with transmission problems.

**New Resistors.**—Electrical resistors of an improved type have been developed by the Ohmite Manufacturing Co., 4835 W. Flournoy St., Chicago. Among the features emphasized are evenness of windings and special vitreous enameled covering.

**New Oil Filter Press**—A new line of oil filter presses for cleaning and drying insulating oils has been announced by the Westinghouse Elec. & Mfg. Co. These presses are light in weight, have low power consumption and are quiet in operation. Their features include a pump bypass through a $^1/_4$-inch needle valve to test the suction line for leaks; a small tank providing a primary gas trap; a discharge flow taken from the bottom of the filter sections providing a secondary gas trap. Standard outfits are rated 5, 10 and 30 gallons per minute for 60 cycle, 220 volt supply.

**New Cable Insulation.**—A new synthetic cable compound has been introduced by the General Electric Co. under the trade name of "Flamenol." While similar to rubber in its characteristics, it contains no rubber and will not support combustion. It is also highly resistant to moisture and acids, alkalies and oils, and has excellent aging qualities. The properties of the new material are such that it can be made a very soft and flexible compound, or one with celluloid-like rigidity. Flamenol-insulated cable is recommended by the manufacturer for power and control circuits at 600 volts and less, and is well adapted to machine tool wiring, switchboard wiring, and battery and coil leads.

# Trade Literature

**Lighting Equipment.**—Bulletin, 112 pp. Describes lighting equipment for theatrical, architectural, photographic and special purposes. Prices are listed. Century Lighting, Inc., 419 W. 55th St., New York City.

**Residential Wiring.**—Bulletin, 12 pp. Describes "Durax" non-metallic sheathed cable for residential and similar circuits and interprets its use according to the National Electric Code. Anaconda Wire & Cable Co., 25 Broadway, New York City.

**Bus Supports.**—Bulletin 34B, 32 pp. Describes outdoor bus supports and fittings. With the parts listed, approximately 50,000 bus support combinations are available. Delta-Star Electric Co., 2400 Block, Fulton St., Chicago, Ill.

**Instruments.**—Bulletin. Describes instruments for measuring coils, condensers, dielectrics and insulators at radio frequencies; covers the Q-Meter, QX-Checker, the new dielectric unit, the converter test oscillator, Hi-Q parts and inductors. Boonton Radio Corporation, Boonton, N. J.

**Motors.**—Bulletin. Describes manufacturer's method of integrally-casting end rings, fans and rotor bars of a-c squirrel-cage induction motors, whereby all possibility of bad contacts or loose connections is eliminated, and uniformly high performance is assured. The Reliance Electric & Engg. Co., 1086 Ivanhoe Rd., Cleveland, O.

**Detachable Instruments.**—Cat. Sec. 43-600, 10 pp. A description of these detachable instruments includes outline dimensions; application data; economic advantages; construction details of the socket and the instrument; accuracy and permanence of calibration; performance characteristics; multiple installations, etc. Westinghouse Elec. & Mfg. Co., East Pittsburgh, Pa.

**Insulating Paper Sample.**—A novel figure cut from "Manning 300" insulating paper,—a high quality, high density paper for slot insulation and other uses, characterized by extreme toughness, heat aging qualities and extreme dielectric strength. The purpose of the paper character, trade-named "Tuffy," is to illustrate the toughness of the product and unusual resistance to tearing. Insulation Manufacturers Corp., 565 W. Washington Blvd., Chicago, Ill.

**Motors.**—Bulletin 1032, 8 pp. Describes slip ring motors, 1 to 350 hp., designed for continuous duty, open and enclosed ratings, or for intermittent reversing application, short-time duty rating. Available in open, drip proof, splash proof, fully enclosed and gear head types for horizontal and vertical operation. Century Electric Co., 1806 Pine St., St. Louis, Mo.

**Lightning Arresters.**—Catalog 390, 116 pp. A comprehensive volume aiming to provide essential data on lightning protection for distribution systems and on Crystal Valve lightning arresters. Much new and up-to-date information has been included in the engineering section. Chapters are devoted to lightning protection for distribution systems, for rural distribution lines, performance characteristics of arresters, and theory of operation of CV lightning arresters and complete descriptions of the various types. Electric Service Supplies Co., 17th and Cambria Sts., Philadelphia, Pa.

**Electrical Steel Sheets.**—Bulletin, 32 pp. Describes development of electrical steel sheets and modern mill technique in producing this material. Ten grades of USS electrical steel sheets are discussed and many applications are detailed. Conversion tables are included as well as a new table on guaranteed maximum core losses and information on magnet wire and varnished cambric insulated cables made by the American Steel & Wire Co. Terms commonly used, including normal magnetism, hysteresis loss, etc., are treated and explained. The uses of electrical sheets in different types of electrical apparatus are illustrated. United States Steel Corp. Subsidiaries, P. O. Box 176, Pittsburgh, Pa.

**Arc Welding Design Chart.**—A newly-revised engineering drafting room chart to provide, in concise ready reference form, data necessary for producing arc welded designs. The chart includes the latest weld symbols adopted by the AWS in May. Additional data covers particulars regarding the 16 types of joints for arc welding; illustrated suggestions for better arc welded design; sketches explaining the nomenclature of welds; and a comparison of welded and riveted drawings. Tables are included giving properties of base metals, weld metals, electrode metals, etc. The Lincoln Electric Co., Cleveland, Ohio.

# Electrical Engineering

Registered U. S. Patent Office

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W. H. Harrison, President

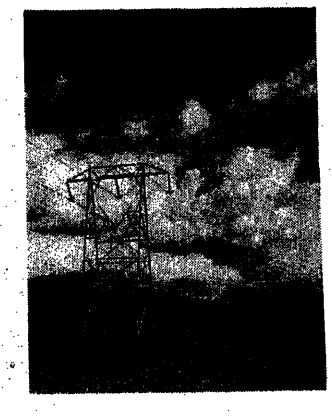
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### The Cover

A 220-kv line of the Southern California Edison Company



# High Lights

**The Engineer and Society.** Two stimulating addresses on the general subject of the engineer and his relation to society were delivered at the Institute's 1937 summer convention in Milwaukee, Wis.; both of these addresses are published in this issue. The first address, on the subject of "The Engineer and His Relation to Government," stresses the need for a more effective expression of the engineer's viewpoint on important public questions (*pages 928–36*). The second address discusses the position and duties of "The Engineer in a Changing World" and emphasizes the necessity for engineers to exercise their responsibilities more for the sake of society as a whole than for the sake of themselves or the private interests of the businesses with which they may be connected (*pages 937–41*). In a third article on this same general subject, an electrical-engineering student urges engineers to "interest themselves in something outside their narrow technical field . . . and become human and humanitarian" (*pages 943–4*).

**Circuit Breakers.** Simply dividing a circuit breaker into several units will not raise its interrupting capacity as a multiple of the number of breaks, because the voltage distribution across the breaks is not uniform. Capacitance shields will give a satisfactory distribution of duty in multibreak circuit breakers (*pages 1018–24*). Ultrahigh-speed reclosing of oil circuit breakers is said to provide an effective and economical solution to the problem of reducing transmission-line outages and thereby improving continuity of service (*pages 968–70*).

**Federal Power in the Northwest.** The federal administration of a public utility is a new idea in the United States; consequently, the formulation of some ultimate plan of administration has become a problem of major importance. The Tennessee Valley Authority and the plans proposed for the public administration of power from the Bonneville and Grand Coulee projects have been compared with the Ontario Hydro-Electric Commission and the British Grid (*pages 964–7*).

**Summer Convention Reports.** Reports covering the various activities of the Institute's 1937 summer convention held in Milwaukee, Wis., June 21–25, are published in the news section of this issue. Included are reports of the annual business meeting, the presentation of the Lamme Medal, conference of officers, delegates, and members, 2 technical conferences, prepared discussions on Institute activities, board of directors meeting, and other features (*pages 1042–52*).

**Radiotelephone Noise Reduction.** Several conventional methods, such as the use of higher power, directive antennas, and selective filters, may be used to increase the intensity of the signal with respect to the noise level in transmitting speech over radiotelephone circuits. Another method, somewhat unconventional in character, consists of diminishing the noise during the intervals of no speech (*pages 971–4*).

**Resonant Lines.** Transmission lines, composed of either parallel or concentric wires, provide a stable means of frequency control for ultrahigh radio frequencies of 30 megacycles or more. Radiation resistance has been found of dominant importance in determining the selectivity factor and input impedance, and therefore materially changes the optimum design of the line (*pages 1002–11*).

**Electricity on Aircraft.** Applications of electricity in modern aircraft construction are manifold, because electrical operation is convenient and the equipment required is relatively light in weight. The electrical system of a modern transport ship is described in a paper in this issue (*pages 959–63*).

**Power Inrushes Under Load.** "Starting" currents in transformers have been studied by several investigators, but most of such tests have been conducted under the special condition of no load. A paper in this issue presents the results of a study of starting currents in transformers connected to loads having various power factors (*pages 989–94*).

**Electric Range Units.** Several types of surface heating units are used in electric ranges, the heat being transferred by radiation, conduction, or both. The efficiency of heat transfer varies with the type of unit, and may be improved, particularly for radiation, by the use of black-bottom utensils (*pages 953–8*).

**Eta Kappa Nu Recognition.** An honorary electrical-engineering society has established awards to recognize outstanding young electrical engineers; statistics for the nominees for the 1936 awards reveal significant information concerning the leading American engineers under 35 years of age (*pages 945–9*).

**Cooling Transformers.** Units composed of a radiator and fan, commonly used for heating industrial buildings, have been found suitable by an eastern power company for cooling transformers by circulating oil from the transformer through the unit. A water spray further increases its effectiveness (*pages 950–2*).

**Pacific Coast Convention.** Plans are nearing completion for the AIEE 1937 Pacific Coast convention to be held in Spokane, Wash., August 30–September 3. The Pacific Northwest offers splendid opportunities for combined vacation-convention trips (*page 1053*).

**Harmonic Generation.** A harmonic generator circuit, suitable for the supply of carrier currents to multichannel telephone systems, for synchronization of carrier frequencies in radio transmission, and for frequency comparison, has been developed (*pages 995–1001*).

**Series Capacitors.** Improved voltage regulation in power circuits may be obtained by the insertion of capacitors in series with the line. Sometimes, however, difficulties such as hunting of synchronous machines and self-excitation of induction motors arise which require investigation (*pages 975–88*).

**The Vodas.** Suppression of feedback and singing in the interconnection of ordinary telephone systems by means of radiotelephone links requires a special type of apparatus known as the "vodas" (*pages 1012–17*).

**The Engineer of Tomorrow.** Some thought-provoking questions were propounded by President MacCutcheon concerning the engineer of tomorrow, in his 1937 summer-convention address (*pages 941–3*).

**New AIEE Officers.** Nine officers were newly elected at the recent AIEE summer convention to serve the Institute during the ensuing year (*page 1049*).

# DISCUSSIONS

Appearing in this issue are discussions of the following papers:

## Electrical Machinery


A Suggested Rotor Flux Locus Concept of Single-Phase Induction Motor Operation—Button 1028
Operational Solution of A-C Machines—Miller and Weil 1028


## Protective Devices


A New Service Restorer—Sixtus and Nodder . . . 1033
A New Thermal Fuse for Network Protectors—Nettleton 1031
A Single-Element Polyphase Directional Relay—McConnell 1025
The Control Gap for Lightning Protection—Higgens and Rorden 1036
Ultrahigh-Speed Reclosing of High-Voltage Transmission Lines—Sporn and Prince 1033


## Tensor Analysis


Complex Vectors in 3-Phase Circuits—Sah . . . 1030
Dyadic Algebra Applied to 3-Phase Circuits—Sah 1030



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# Electrical Engineering

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# A Message From the President

**Fellow Members of the Institute:**

I SHOULD LIKE to take this opportunity to say to all of you what I had the privilege of saying to those at the summer convention in Milwaukee in response to notification of election as president:

"Instinctively I feel sure you understand how wholly inadequate words of mine are to express appreciation of the great honor the membership of the Institute has conferred upon me.

"I am mindful of the responsibility that goes with the high and cherished office of president, and with humility I confidently look forward to this distinguished opportunity further to serve the profession in which we are spending our lives.

"It has been my privilege for many years to participate in the affairs of the Institute, and I am familiar with its high ideals, its traditions—its responsibilities to the profession at large.

"No period has ever afforded our organization a greater opportunity to be of service.

"One need but recall the many new developments looming on the horizon in almost every phase of the industry to visualize the important part the Institute will play in the period ahead. Perhaps even more immediate and bearing on the profession as a whole is the situation presented by the changing social and economic order of the world in which we live. In this we as engineers face a stiff challenge—a broadened horizon. The engineering societies can do much to point the way.

"The joy and satisfaction one gets in service to the Institute is the opportunity afforded for associations and acquaintanceships with the membership, and I am eagerly looking forward to this through the coming year.

"The life of the Institute is in the Districts, Sections, Student Branches, and committee activities. No organization, year in and year out, has ever had a more enthusiastic, loyal, and effective group of workers. Then there is an equally able headquarters staff, headed by our effective national secretary, Mr. Henline.

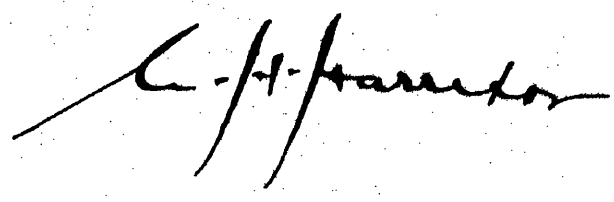
"As I think of all of these I look forward to the year with confidence.

"Last year District 2 of which I was then a member was accorded great distinction by having elected from its ranks our president, Mr. MacCutcheon. You need no reminder as to how faithfully he has carried out his responsibilities. Under the impetus of the enthusiasm he has generated I am sure we will continue to go forward. I want to take this opportunity to express great admiration for him, and for the work he has done in the past year.

"Again my deep thanks for the great honor you have conferred upon me. Milwaukee, 1937, is a milepost in my life."

The summer convention is over. Those of us who were fortunate enough to be there will long carry in mind the interesting, instructive sessions, the inspiring talks by Doctor Bush and Doctor Flanders, the inspection trips, the courtesy of those who made the trips possible, the entertainment, and in particular the consideration shown our families.

The Institute has gained new honors from the really superb manner in which the Milwaukee convention program was carried out. As host the Milwaukee Section earned high praise. It is a privilege to express appreciation.



# The Engineer and His Relation to Government

By VANNEVAR BUSH
FELLOW AIEE

**Whether democracy in America can endure depends in no small measure upon the attitude of the great professional classes in general, and in particular upon the attitude and effectiveness of the engineer in his relation to government, says this well-known engineer and educator, who states further that although there is an enormously complex system of organizations of scientists and engineers in the United States, this mechanism is not utilized to the full in expressing the viewpoints of engineers generally upon important public questions. To meet this need, Doctor Bush suggests that the organization of engineers should be integrated, simplified, and strengthened.**

WHATEVER one may conceive to be the future of civilization, whether one is pessimistic or optimistic in regard to the long pull, one thing stands out—we are certainly on our way. The world is full of change. Our systems of government, not only in Europe, but here in America, are in a state of flux. We live faster, occasionally longer, and always in a new pattern of relationships between man and man. We are headed somewhere in a hurry, whether that somewhere be a grand crash, a reversion to a long sleep, or a more abundant life.

The scientist and the engineer started us on this path. They wakened us from the semipeaceful somnolence of a century ago, shrunk the world to a fraction of its former size, and placed the well-oiled wheels of the scientific method under us; and we roar forward in a crescendo of tumult toward the unknown. Now it is suggested that some attention should be paid to the steering gear.

Much attention has been paid to equipping and speeding up the conveyance in which civilization rides, and comparatively little devoted to safety devices. The medical profession has conquered one plague after another, engineers and health officers have extended sanitary measures, and the mentally defective benefit along with everyone else, breed rapidly, and may inherit the earth. Bringing science to agriculture makes possible the production of food by fewer men on less acreage, and our farmers have no place to go. Individual transportation is cheapened, and automobile accidents kill 30,000 people a year. The airplane applies a multiplying factor to the useful lives of busy and creative men, and brings hostile nations within grasp of one another's throats.

Since the dawn of history the acquisition of skill and knowledge has rendered more complex the relationships between man and man. It is the function of government to control these relationships. Today the burdens and responsibility thrown upon government are increasing by leaps and bounds, and government everywhere is staggering under the load. The kaleidoscopic changes we have witnessed in governments of the nations are a direct result of the growing technical complexity of our lives. Every advance increases the rate of advance, in accordance with the law of acceleration of Henry Adams.* Whether democracy in America can successfully carry the modern burden and the burden to come, and endure, remains to be demonstrated. Certainly this depends in no small measure upon the attitude of the great professional class in general, and in particular upon the attitude and effectiveness of the engineer in his relation to government. It is this relationship that is examined in this address.

First, what really is this government of ours? I am not going to review the history of our democratic system, or the details of its organization. Certainly I am not interested at the moment in the affairs of individuals or parties. The important point is that we have a government which is responsive to public opinion. Sometimes, it is true, this is only haltingly effective; but by and large the course of our affairs is determined by what the great bulk of the public thinks and feels. As we all know, small minorities, through effective organization and pressure, can dictate the course of events in limited areas; but not the major trends. We have had striking illustrations of this power of public opinion in recent times. It first, in a reflection of the war enthusiasm, placed prohibition in the Constitution; and then, in a revulsion of sentiment, forced it out again, in spite of a complex legal situation and the strong resistance of well-knit groups. There is no doubt that, in 1936, public sentiment generally desired a continuance of federal social activity, and obtained what it wanted. More recently public sentiment has turned a tide that was running strongly against the power of the judiciary. The final outcome of the present labor movement similarly will depend upon what all the people think.

This is the essence of democracy, and of a government responsive to the will of the people. This we have and this we hope long to maintain. It is the most beneficent type of government that has yet been created by the mind of man. Yet it has its disadvantages and dangers in a complex modern world; and there is serious question as to whether it can be maintained indefinitely under modern conditions. I make this statement with no implications

* "The Education of Henry Adams," Houghton Mifflin Company.

An address delivered at an evening session of the AIEE summer convention, Milwaukee, Wis., June 22, 1937.

VANNEVAR BUSH is vice-president of the Massachusetts Institute of Technology, Cambridge, and dean of the school of engineering. He was graduated from Tufts College in 1913; in 1916 he received the degree of doctor of engineering from MIT and Harvard University, and in 1932 the honorary degree of doctor of science from Tufts. He is known for both his achievements in research and his contributions to engineering education. He has long been interested in the design of analyzing instruments, and for his work in this field he was awarded the Levy Medal of the Franklin Institute in 1928 and the AIEE Lamme Medal for 1935. Doctor Bush is one of the newly elected directors of the AIEE and has served on many AIEE committees. He is the author of many technical articles, and of "Operational Circuit Analysis" and, jointly with W. H. Timbie (A'10, F'24), of "Principles of Electrical Engineering."

whatever in regard to any individuals or isms. We have proceeded far in this country along the road of democracy. This republic started its career with great detail in its representative form, expressly designed so that the primary opportunity of the electorate would be to select trusted representatives who would then be somewhat removed from immediate pressure. The loss of real significance of the electoral college, the direct election of senators, the introduction of the referendum, have been some of the steps toward that complete democracy in which the people themselves decide on the important questions of the moment. This trend began with the election of Jefferson and has continued ever since.

Yet this enormous country, with its heterogeneous population and interests, is one of few remaining democracies. We witness a movement in the world at large toward absolutism. It has made little difference in the end result whether this has come about by reason of a first move toward the left or the right. We see many nations turning toward the placing of absolute power in the hands of one man, with consequent suppression of individual freedom. Democracies elsewhere have proved unstable. No small factor in this situation is to be found in the fact that the questions of the day are too complex for the people truly to grasp in time.



Doctor Bush

There is a pessimistic philosophy of government which holds that the trend of democracy toward breakdown and succeeding absolutism by an individual or a class is inevitable. According to this theory, democracies tend to become increasingly more direct, checks and balances gradually are thrown aside, the dependence of the governing group on public whim leads to weakness in law enforcement, respect for law decreases, and finally chaos ensues, to be followed by seizure of arbitrary power by a closely organized minority. Shall this be true of America? Not necessarily. All these dire results were predicted to follow promptly upon Jefferson's accession; and in fact many seriously expected that the Reign of Terror of France would be repeated here. But it was not, and over a century has passed while this republic has gone through stress of the most intense form. There is a counter influence which has saved us from catastrophe. This is the gradual increase in the standard of living, and the intelligent grasp of large affairs on the part of the people. We have also developed in this country a resistance to the forces of propaganda which occasionally manifests itself. So we may yet go on.

For present purposes, it is sufficient to note that our government is now of rather extreme democratic form, and that public opinion controls its trends in large affairs. Its governing bodies and executives, therefore, are bound to be men who are sensitive to, and able to cope successfully with, this opinion of the public.

In this form, our government is called upon to decide momentous technical matters, most of which are so complex that they can be fully understood, if at all, only by experts. Such questions involve finance, sociology, economics, engineering. They cannot be grasped completely and intelligently by the general public. They cannot be grasped by the elected representatives of that public, who must in the nature of things, be specialists principally in the political art. How then are they to be decided wisely in a democracy?

Much depends upon the answer to this question. We are in competition with nations in which absolutism and intense nationalism control. The maintenance of our position, our relative standard of living, depends upon the skill with which our affairs are handled. Under an absolute ruler all specialists of every sort become government specialists. A dictator can make final, binding, prompt decisions upon weighing their recommendations. Will we, with our exceedingly loose system, be similarly able to bring to bear the best of intelligent judgment upon the technical problems of the day? We must do so, if we are to hold our place. Our frontiers have vanished; the surge of a pioneering people cannot indefinitely carry us forward; we are making rapid inroads upon our unique national resources. The day is coming when our progress will lean heavily on the intelligence with which we treat our public questions.

The age-old struggle between those who have and those who have not is distinctly modified by advancing standards of living. A greater proportion of the people become property holders, and this tends toward stability and orderly processes. Yet the trend proceeds slowly, and the struggle is far from termination. We still face a clash of interests which is as old as history, between those who control our social and industrial systems, and the great mass of people who labor. Whatever the political system, whatever changes in the character of our institutions may come, this situation will always be with us, for someone must always control; there must always be those who issue orders, benignly or harshly, if the industrial mechanism is to function. It is the proper sphere of government to control and regulate; to set up and enforce the rules that will insure efficiency and equity, to protect minorities, and to deal with other nations. For government to step in and itself become the manager of industry is a mistake. There is no longer an umpire in the field. The lines become drawn between the people and government itself, and this is the beginning of disaster. We cannot afford, in this country of ours, to have an umpire who also plays on one of the teams.

## What Distinguishes a Professional Man?

Standing aside from the industrial system, and yet intimately connected with it, are the great professional classes, of which the engineer forms a part. What renders a man a member of this professional group? It is much more than the possession of special knowledge, although this is a necessary attribute. The skilled machinist possesses special knowledge, as does indeed the man who owns and manages a machine shop; yet neither thereby is constituted a professional man. It is more than the nature of the source of income. True, many professional men, physicians and lawyers especially, derive their income from fees from clients. Yet a clergyman is usually on a salary. The majority of scientists are similarly paid by universities and scientific institutions. The great proportion of engineers are employed regularly by industry on a salary basis. Definite association with a specific organization on a salary basis does not bar a man from rightful membership in the professional class. The distinguishing characteristic is the possesssion of a philosophy and a point of view. The true criterion lies in the basis of motivation of the individual.

In any society there are 4 primary classifications of individuals. First is the great body of artisans who carry on the work of the world. Second are those who manage and direct, deriving their power rather directly from the possession of the facilities for production, or indirectly by delegation from the actual owners. Third stand those who govern. Finally come those whose primary mission in life is to acquire learning and render it usefully available to those in every classification. These last form the professional group.

It is possible for an individual to belong simultaneously to several groups. The farmer is often a worker and a manager. The owner, to whom management is at least formally responsible, may comprise hundreds of thousands of stockholders in all walks of life. He who governs may derive from any group. Similarly, the professional man may adhere also to other classifications. But if he loses his philosophy, if he ceases to regard the acquisition of knowledge for the public welfare and rendering it available to all groups as his primary mission in life, he no longer is truly a professional man.

The late Arthur D. Little in an essay* delivered before the Franklin Institute, defined the "fifth estate" as: "those having the simplicity to wonder, the ability to question, the power to generalize, the capacity to apply. It is, in short, the company of thinkers, workers, expounders, and practitioners upon which the world is absolutely dependent for the preservation and advancement of that organized knowledge which we call science. It is their seeing eye that discloses, as Carlyle said, 'the inner harmony of things; what Nature meant.' It is they who bring the power and the fruits of knowledge to the multitude who are content to go through life without thinking and without questioning, who accept fire and the hatching of an egg, the attraction of a feather by a bit of amber, and the stars in their courses as a fish accepts the ocean."

It is the high privilege of the engineer to aspire to genuine membership in this distinguished category. The possession of an academic degree is not sufficient to admit him. Success, as measured by his income, does not admit him either. The humble Jesuit parching amid the sands of the desert that he may bring light to the lowly, and the country physician struggling through the storm to relieve suffering, need no decoration of material success to mark them as honorable members of the group. Recognition by colleagues, based upon true scholarship, untainted by self-advertising—this is the reward. Completely free from prejudice as to class or race, laboring for the ultimate good of society at large as he envisages it, above passion, secure in the possession of special knowledge which the world needs and hence independent of the whims of individuals and groups, the true professional man is and should be a figure apart, wherever he may be placed. It is his duty to merit that confidence which alone will permit him to operate with effectiveness.

## Government Needs Influence of Engineer

There is all too little respect for law in this country. There is also all too little respect for genuine scholarship. Fundamentally the influence of the professional group depends upon the development of this respect. Only thus can its influence be effective. The trend of affairs can be molded by those who have seen the light only in so far as they are welcomed into the counsels of the groups of the population. The influence of the professional man is sorely needed in these times. Managers of industry have been keen to grasp its peculiar advantages, and there is no lack of contact at this point; but unfortunately it often arises under conditions that render difficult the maintenance of true professional status by the professional man. But government most needs the influence. At this point in this country we proceed haltingly. The influence of the engineer upon the processes of government is especially necessary if there is to be sanity in public affairs. How then may it be enhanced?

The professions of law and medicine exert strong and generally beneficial group influence through their national professional organizations. The profession of engineering does not. No great legal change occurs without scrutiny and pressure from the American Bar Association. No move for the regulation of medical practice proceeds without the prompt, effective participation of the American Medical Association. Great engineering works are constructed in this country, and the group opinion of the body of engineers thereon is not even expressed, with results that are sometimes ludicrous. We have no reason to be proud of the influence of engineers on the course of government as it affects engineering. By and large our efforts have been pitiful.

There is a striking difference in the relationships of these 3 great professional groups to government. Many members of the legal profession are essentially part of government itself, since they fill our legislatures, sit on the judicial bench, and practice as elements of the court. At

* Centenary celebration of the founding of the Franklin Institute, September 17, 1924.

the opposite extreme is the medical profession, most of whose members shudder at the thought of governmental medicine and have their heels dug into the ground to resist the present tug in that direction. In between are the engineers, who are more and more becoming closely allied with government as the technical aspects of government activity intensify. We do not know whether, as a group, they resist this trend or not. Apparently they haven't even begun to think about it.

## Organization of the Engineering Profession Is Highly Complex

It is said that, where 3 Americans foregather, there soon will emerge a president, a treasurer, and a secretary. One might add to this that often when learned men associate themselves there will be found an intangible complex organization beyond the mind of man to fathom. There seems to be direct correlation between the scholarly attainments of individuals, and the looseness and ineffectiveness for action of the associations they create. The greater the grasp by a group of the intricacies of a social problem, the less likely is it to present a united front on anything whatever. The rate of progress of a group toward a single objective varies inversely with the number of members thereof, and inversely as the square of their special knowledge. The scheme of organization of the professional groups in this country is a marvel to behold. Those of the lawyers and the physicians have effective elements which have been noted. That of the scientists and engineers is a tangled maze in which most of the participants become lost. I think I can fathom something of the way in which our complex political system operates. I have been a member of many professional organizations for many years, and I have yet to form a rational picture of their activities. Their journals get a quick glance as they zip across my desk toward the sagging shelves. They collect dues with growing persistency. Yet the government digs a hole in the sands of Florida to no proved good purpose, and I hear no voice raised to say that we, the engineers of this country, insist that we be told authoritatively what the economic and engineering complexion of that particular hole really is. Much less do I gather that the hole will not be dug except when it has the blessing of the organized engineers of the country. The trouble is they are not really organized for this effective purpose.

In 1933, the *Technology Review** attempted to sort out the 900 scientific and technical societies listed in a handbook of the National Research Council, and to present something of an organization chart and family tree of the engineering societies included. The tree developed into something of a forest. True, one might construct an imposing list of medical or legal societies devoted to special interests. The difficulty is that the engineering group of societies does not head up anywhere. We are especially interested in the way in which this situation influences the relationship between engineers and government, so it will be examined somewhat in detail.

* *Technology Review*, July 1933, page 330, "Engineering Societies, their Multiplicity, their Relatives, their Duplication."

It is right and proper that there should be many organizations devoted primarily to special technical interests, and the increase of these is inevitable as the interests of engineers fan out. Yet it is far better that this development should occur by subdivision of large national societies, rather than by the creation of new groups with consequent increase in overhead costs, and lack of coordination of interests. The American Institute of Electrical Engineers, last of the 4 Founder Societies,† was founded in 1884. Since then have appeared the American Electrochemical Society, the Illuminating Engineering Society, the Institute of Radio Engineers, and others representing special interests within this general field. A similar disintegrating tendency appeared in the group of societies dealing with all aspects of physics, but in 1931 the creation of the American Institute of Physics regrouped these to secure closer interrelation, and economies in publication. No comparable integrating tendency among the Founder Societies has yet appeared. The most important question however, is that of attempts to integrate engineering societies as a whole.

The 4 Founder Societies are associated, through the United Engineering Trustees, Inc., for the purpose of managing a building used in common, for the maintenance of a library, and to sustain the Engineering Foundation "for the furtherance of research in science and engineering, and for the advancement in any other manner of the profession of engineering and the good of mankind." Excellent as is this joint effort, it is directed in practice primarily toward the attainment of technical objectives, and does not properly touch the relationships of engineers generally to government.

The Founder Societies, together with the American Institute of Chemical Engineers, the Society for the Promotion of Engineering Education, and the National Council of State Boards of Engineering Examiners, joined in 1932 to create the Engineers' Council for Professional Development. This "aims to co-ordinate and promote efforts and aspirations directed toward higher professional standards of education and practice, greater solidarity of the profession, and greater effectiveness in dealing with technical, social, and economic problems." Its activities have been pointed primarily toward young engineers, through the certification of engineering schools in connection with state licensing programs, and the postacademic education of engineers. It is doing excellent work in these fields, but does not aim to ascertain and impress group opinion of engineers on governmental or social problems.

## Central Engineering Organizations Already Exist

The nearest approach to a mouthpiece for engineers generally on important matters is the American Engineering Council founded in 1920 "to further the public welfare wherever technical and engineering knowledge and experience are involved, and to consider and act upon

† The others are:. American Society of Civil Engineers; American Institute of Mining and Metallurgical Engineers; and The American Society of Mechanical Engineers.

matters of common concern to the engineering and allied professions." This is exactly what we have in mind. Yet the engineer, with all his supposed genius for organization, has not rendered this the effective instrument that is sorely needed. Every country doctor knows of the American Medical Association. He may quarrel with its dicta; but he knows that with a host of others he influences its pronouncements, and he is proud that it represents him. I would be willing to wager that a survey would show that a large fraction of engineers in this country do not even know of the existence of the AEC. Certainly the average engineer has no feeling that his influence is brought to bear even indirectly upon their considerations of important public questions. It has not the intense interest and support of the profession generally, and its expressed opinions are to this extent ineffective. A devoted group of engineers deals meticulously with the affairs of AEC, and undoubtedly the situation is not their fault. It is none the less regrettable. There are some evident contributing factors to the situation: The average engineer pays no dues to AEC, sees no direct publication of AEC, and takes no direct part in the selection of this body of men who convene to decide upon the problems of the day. Pronouncements have not been strikingly timely. The engineering profession has held important group opinions, but has not seen them forcibly enumerated and spread on the front pages of the newspapers.

If the engineers of this country do not recognize and support their spokesman in the AEC, still less do they recognize that they have a duality of spokesmen. The American Association of Engineers was founded in 1915 "to accomplish for the unity, welfare, standards, and public recognition of the engineering profession what such organizations as the American Bar Association and the American Medical Association have accomplished for their respective professions." It has the slogan "proper recognition to the engineer and the engineering profession," awards a medal, provides group insurance for its members, and has been active in vocational guidance.

There are 3 laudable ideas involved in this matter of a central engineering organization. First is the furtherance of the interests of the profession. Second is the bringing to bear of the influence of the profession upon public matters. There should be no confusion between these. While it is highly fitting and proper that engineers should be active to guard their own interests, such activity is apart from the higher mission of influencing public trends for the benefit of the entire public. These are combined in the same organization only at the risk of weakening the latter. The attention of the AAE is primarily devoted to the former. The third laudable idea is that of direct advice to government departments or agencies on their specific problems.

## National Academy of Sciences Was Founded to Advise Government

On this third aspect the engineering societies function primarily only through a more general organization of scientists. The National Academy of Sciences was founded in 1863, by act of Congress, approved by President Lincoln "to advance science and especially to investigate, examine, experiment, and report on any subject of science or art whenever called upon by any department of the Government of the United States." It is a limited-membership self-perpetuating body, similar to the scientific academies of the old world. One of its many sections is composed of engineers. In 1916 its activities were implemented when it formed, at the request of President Wilson, the National Research Council for "the promotion of research in the physical and biological sciences, and the encouragement of the application and dissemination of scientific knowledge for the benefit of the nation." After the war the NRC was perpetuated by an executive order of May 11, 1918. Still later, and again in time of emergency, this organization was extended by the creation, under the Academy, of the Science Advisory Board, which reported on many important matters referred to it by government departments. The term of this board now has expired, and it has been superseded by a committee of the Academy. This whole organization is itself extremely complex.

By the very nature of this organization, it does not function to bring to bear upon great public questions the opinions of scientists, except when called upon and then in connection with definite scientific problems. In such matters it has rendered important aid and advice. One important aspect of its affairs has been to set up advisory committees for scientific bureaus of the government. Its active arm in research, the NRC, administers research funds for government and large groups, and correlates and promotes scientific research generally.

This is the official established mechanism by which government may call for the opinion of scientists generally, and engineers in particular, upon technical problems, for it was created by government for this specific purpose. Government does so call, and does thus receive advice and counsel. Questions involving important engineering matters, such as recently the problems of ship stabilization, and of lighter-than-air craft, thus are given the benefit of review by distinguished men. Such a controversial matter as the economic and engineering justification of building a tide-power plant on the coast of Maine, however, does not travel by this route. If government asked the question, it would obtain an answer; but it does not ask the question. The mechanism is available, but the pressure necessary to ensure that it will be used is absent. True, engineers are here joined with all types of scientists, but nevertheless the query would result in the gathering of a distinguished group of engineers and economists to deliver the answer. Later, I will discuss the function of the independent consulting engineer in this connection, but at this point I merely note that his services, under proper fee, are not at all inconsistent with the presence of distinguished voluntary committees of review.

One more organization remains to be mentioned. The American Association for the Advancement of Science, founded in 1848, is the great democracy of science in this country. This loosely knit organization comprises about 150 member societies, with half a million members. One

section with many member societies, is devoted to engineering, but engineers generally take no part in its activities. It serves the very useful purpose of bringing together diverse scientific groups for great annual meetings at a common point. Its council occasionally adopts resolutions on public questions, but legislators do not hang on its words. Its membership is too casually affiliated to render it a powerful voice in national affairs.

The engineer, who applies science in an economic manner for the benefit of mankind, certainly has as close common interests with the social scientist as with the physical scientist. Yet the organizations of the social scientists are not greatly participated in by engineers.

Since the beginning the engineer has co-operated closely with the physical scientist; and in fact many engineers are themselves physical scientists of no mean accomplishment. We have reached the point where engineers are learning to work in similar co-operation with social scientists, but the relationship must proceed much further than this. It is necessary, in connection with many of the problems that come to him, that the engineer be himself a social scientist —not a dilettante but a deep student and scholar in his own right in various branches of the social sciences. Only thus may he be properly cognizant of the source from which his activity derives, and also properly cognizant of the social conditions under which it becomes applied. Long familiar with applied economics, he now finds pressing upon him other branches of the broad science of human relationships. The colleges have a duty to perform here, and so have the professional engineering societies. Certainly their meetings and publications should generously reflect this growing need and interest.

## Integration, Not Another Society, Needed

To summarize this matter of organization: Real attention is being given to the professional advancement and the technical interests of the profession. We have an enormously complex system of organization of scientists and engineers in this country, and yet no effective single central organization representing *all* engineers and expressing their viewpoint on public questions. We have an elaborate mechanism for bringing advice to bear on scientific and engineering problems as they arise in government, and this mechanism is not utilized to the full.

What is to be done about it? Certainly no solution lies in forming one more society to join the throng. Integration is indicated; and since societies now exist for all the express purposes we have considered, a duplication of effort by a newcomer would simply complicate matters. Rather, the existing mechanism should be simplified and strengthened.

Would it be of aid if the great national organizations, such as the AIEE, were to take official and definite positions on public questions involving engineering? I do not think this is their proper function, for reasons I will discuss. This is being done in some such organizations, and the effect so far has not been especially helpful. It is another thing entirely for the AIEE to provide a forum for the frank discussion of important questions by men of all shades of opinion. In this I believe it has a duty to perform. So far it has not been done, and the reason seems to be that those in control have not had the courage to take a step which they fear would split the society. Perhaps a frank and fearless discussion on the floor of an AIEE convention of such a problem as that of the proper sphere of activity of government in the generation and distribution of electric power would split the society. I do not think it would. This is certainly a matter of present interest to electrical engineers. If those who are best able to approach it dispassionately and intelligently fear to open the question at all, how is public opinion to be influenced? In the membership of the Institute are men who hold all sorts of opinions on this subject, many of them violently. Many will not express their honest opinions because of their affiliations with government or with public utilities. But there are many more who can and will bring light upon the subject, and, like all subjects of great controversy, it has at least 2 sides. When I speak of a free forum in this connection I do not mean one where the floor is open to the public. I have in mind one where the participants are carefully chosen for their ability to present their views clearly and calmly, and carefully chosen to bring out all shades of opinion. Such an airing of views on this and many other matters would do a great deal of good. A similar benefit will result when professional publications carry powerful expositions and arguments on the live issues of the day, again with an opportunity for accomplished representatives of all sides to be heard. But the Institute itself should express no opinion on this or any other controversial question where its membership holds diverse views. It cannot at once be the guardian of a free forum and an advocate. Still it should certainly not be an ostrich.

This taking of stands should be left to a body having that as its primary function. That body should be made up of men of great distinction in the profession, chosen for the purpose by the membership of the profession directly. It should use every legitimate means to be well known to the membership, by questionnaires, publications, and by reasonable publicity in regard to its deliberations and findings. It should be absolutely without fear and without prejudice. Its pronouncements should be front-page news in every corner of the land. It should enter into any public question involving engineering as a right and without invitation. It should not hesitate to swing public opinion by rousing the profession when such action is indicated. In order that it may speak with a single voice it should represent engineers only, with deference, of course, to the opinions of other professional groups. We do not have this situation today. The metamorphosis of existing organizations, under the guidance of public-spirited engineers, may bring it to pass. As it proceeds it should have the aggressive support of every engineer who has the good of his country at heart, whether or not he agrees with its findings in every respect.

The technique of applying the pressure of engineering opinion on great public questions is only one aspect of our problem. Another aspect involves the advice by engineers to government on specific technical problems. This is a

large question and one that involves many of us in one way or another, as citizens and taxpayers as well as engineers.

## Government Needs Independent Consulting Engineers

That there is an elaborate mechanism by which government departments may secure the advice of scientists and engineers, has been shown. For several reasons, this is not sufficient for the purpose. First, the way is indirect, through an organization that is preponderantly scientific. With the best intentions in the world such an organization cannot function precisely and promptly to bring to bear on a great national engineering problem the best engineering brains to be had anywhere; only a few of the great engineers of the country are directly affiliated with it; and the indirect path is cumbersome. The complexities and inertia of this situation were overcome in time of war and in time of great depression, but during normal times the mechanism works feebly. Second, to wait to be called upon in a busy world is not enough, and the present organization has a natural and proper hesitancy to press itself into controversies. Third, the setting up of distinguished boards of review on a voluntary basis is not enough.

One cannot give sound advice on important engineering matters without spending considerable time and money. This is the function of the independent consulting engineer. We will not be on sound ground in this country until government, on a basis of adequate and dignified fees, calls for the opinions of independent consulting engineers whenever it has an important engineering problem. This it does not do at the present time to any determining extent. If, when the subject has been deeply studied and reports have been presented, the government wishes review by distinguished boards, it always will find men ready to give their services as a matter of public duty. The main reliance, however, must be upon independent consulting engineers, and I wish to make a plea on their behalf.

There are many engineers—many able engineers—in government itself, and these are utilized by government when it has an engineering project to carry out. Army engineers have carried forward on a high plane many outstanding engineering works. The Reclamation Service conducts a research laboratory that is second to none. But the government engineer is not an independent engineer and the latter is sorely needed. Given a definite project the government engineer can carry it forward; but he cannot at the same time say that it is a foolish thing to carry out at all, even if his engineering studies convince him that it is. Here is a point at which a democracy is at an advantage compared with an absolute government. The dictator has *only* government engineers—units in a rigid machine. Independence of thought and speech there cannot be tolerated. Yet, having the advantage as a democracy of the presence of engineers of real independence, we do not make use of them. This is partly because truly independent engineers are becoming rare; partly because unfortunately government is sometimes not anxious that the full truth be known; partly the fault of the engineers themselves. This matter is worth discussing briefly, for it is truly unfortunate if one of assets of a democracy is being thrown away.

The rise of great industries in this country, own engineering organizations, has restricted operation of independent consultants. The extend free engineering services as part of the grams of large companies similarly has encroached tunately, industry by and large cannot maintain neering departments capable of coping with the and these peaks are surmounted by calling in porary services of independent engineering organ Yet the way of the consultant has not been easy number of men who are truly independent, seasoned opinions based upon wide experience fields, is not large. This is distinctly the fault ment. There should be more utilization of the type of John F. Stevens called for service at the Canal. If it were our practice in this country ment to employ independent engineers frequently number of such engineers would be greater. When ment calls on the engineer at all, it usually does so on a niggardly basis. It appears to starve out a group upon which it distinctly needs

But part of the fault lies with engineers themselves. While we deplore any reluctance on the part of ment to let the full light of reason play on its engineering works, we must admit at the same the approach of engineers often has not been based sufficiently broad consideration of these very To show that a government engineering work will an adequate financial return on the original investment not necessarily sufficient to condemn it; yet engineers prone to limit their considerations to a strict cost basis. The building of a battleship cannot be justified this basis. The setting aside of a national forest not be thus approached with limited logic.

Do not think that I advocate letting down the strict reasoning to which all engineering works subjected. I have no sympathy with any waste money. To build a great dam to supply electric a region already amply supplied with power, to land in a region of no inhabitants while farm lands idle close by, to render navigable a stream that into a wilderness, are fool pieces of work in any Yet I would have the engineer join with the the sociologist, the student of government, that grasp problems in their entirety.

Is it foolish to clear slums, and to cause living to be built by subsidy from public monies, for previous slum dwellers on a rental basis that returns a portion of the direct investment? It may or may be, and the answer can come only when the works with the sociologist. It may be a decided investment on the part of government from a financial point of view, if the decrease in costs of health hazards, hospitalization, and social decay follow slum clearance, offsets the direct cost of But merely because the problem involves more matter of direct costs and direct revenues, does the government for proceeding without independent

it merely emphasizes the need for analysis by professional men of diverse types.

## Consulting Engineers in Educational Institutions

Both government and industry should support the independent consultant in this country, that he may be available in time of need. A duty also rests upon our educational system in this same connection. This duty may rest lightly, for the consultant with university affiliations can bring strength to the educational system itself. Much has been said on this subject, and some would block consultation by members of college faculties. This always would be a catastrophe, but especially so at present when the consulting engineering profession needs to be enlarged and supported. Moreover engineering education must be real, conducted in an atmosphere of success, and in close contact with industrial and governmental advance; and the consultant on the faculty can aid greatly in this regard. There are dangers in the relationship, of course, but they can be avoided and the benefits secured. The use of the name of university affiliation, without the substance of educational duties and responsibilities on the part of the consultant, is a perversion. Encouragement of consulting by university administrations should be accompanied by insistence that such contacts be on a high plane and such as to advance the professional standing of both the individual and his institution. The fees charged should be on a dignified basis and such that there is no unfair competition with consultants who do not combine educational activities. There should be no use of university laboratories in consulting connections except where the institution is fully reimbursed for all costs of having the facilities present, and then only when there is no interference with the use of these facilities for their primary purposes. Educational institutions that have unique research facilities not available elsewhere, should make them available as far as possible without impeding educational use, either directly or through those commercial organizations which perform research services for industry. This certainly does not mean, however, that an educational institution should do routine testing for industry where there is a commercial organization capable of performing the work. Industrial research within an educational institution may be a fine thing, when it carries its full costs, when its results become published, and when its presence adds to the educational process of training men capable of coping with industrial research problems after graduation. But neither the educational institution itself, nor the consultant who is a member of its faculty, should carry on activities that tend to lower the plane of independent consultants or independent commercial research laboratories. When these matters are realized, the presence of a consultant on a faculty may be of benefit to the institution and render available one more independent engineer for advice to government and industry.

There are many ways in which the individual engineer makes contact with government, and several in which a more intimate contact would be of benefit. One important way lies in the growth of the commission form of activity. These commissions usually, as in the case of the Federal Communications Commission, the United States Shipping Board, and the Tariff Commission, are essentially groups of experts within the frame of government itself. So also are such units as port authorities, irrigation district authorities and the like, set up within our still flexible frame of government to unite the administration of regions having common technical character. These and similar units offer one promising mechanism by which to implement the specific actions of government in technical affairs. The engineer is an important member of all such bodies. By and large they have been decidedly effective. An important element, however, appears to be generally lacking in the movement. Usually such boards depend upon the technical knowledge of their own membership, supplemented only by the examination of witnesses who come before them. They are not amply enabled, by the act which establishes them, to increase their grasp and power by temporarily joining to their membership outstanding consultants with special knowledge of the particular problems before them. The independent engineer would find in such association many opportunities to be of genuine service.

## Engineers and the Legal System

Another important way in which the engineer makes contact with government is in connection with the legal system, both in law enforcement and in the administration of justice in the courts. This is too large a matter to be treated adequately in an address having a broader subject, yet the point comes up inevitably. There is a real need for close association of scientists and engineers with the legal system at many points, especially in the patent system. The reason is clear. The determination of any legal question depends jointly upon the law and the facts. In a modern technical world the facts are beyond the comprehension of the layman. When dealing with a scientific or engineering subject, the most eminent jurist or attorney is usually decidedly a layman. The result is often sad. Decisions are rendered by judges to whom the facts of a case are in essence imcomprehensible. Present procedure is expensive, indeterminate, and sometimes ludicrous. Details of procedure aside for the moment, the real reason for this situation is the unwillingness of the legal profession to admit to a basis of partnership the scientist who understands the technical facts of modern civilization, with the attorney who understands the law. We have the spectacle of opposing experts, cross-examined by lawyers who have a week's cramming as a background in the subject under consideration, for the benefit of a judge whose scientific training ended at "Physics I." The childlike faith of most attorneys in this process of elucidating technical facts is beyond comprehension. To the technical man on the sidelines it is often evident that the discussion proceeds to about page 20 of an elementary text, when the true answer lies on page 500 of an advanced treatise. The general atmosphere, charged with suspicion, progressing at a snail's pace, is such that the majority of scientific men engage in legal matters just as little as

possible. To expect men of great scientific attainment generally to be willing to take part in this procedure is expecting a great deal from the human race. Yet the members of the legal profession generally regard the presence of a technical adviser to the court, not subject to cross-examination, as an anachronism, and they are perfectly sincere and honest in the opinion. The dilemma is clear. The legal profession, which controls the system, cannot itself or through its artifices deal justly in the type of world in which we now live. It will not have the true co-operation of the best scientific and engineering minds in expeditiously arriving at justice until it welcomes them to something besides a subordinate status. In some of its phases, the legal system has been dangerously close to breakdown, and no small portion of this situation is the extent to which it is bogged down in a scientific morass. If breakdown comes, it will be the fault of the profession that molds its affairs and determines its form. Scientists and engineers stand always ready to aid in a matter of public concern and on a basis of professional partnership. In this connection the independent consulting engineer can be of real service in many ways, but space does not permit a detailed examination of them.

Throughout this address I have emphasized the value of independence. So long as this is maintained and there is the effective guidance of affairs by an independent professional class, I have no fear for the future. A true democracy, given this support, can compete with dictatorship and prevail.

## Frontiers of Science Still Remain

It was independence of thought, freedom of action, the opportunity of a vast untamed domain that built this country and gave it the highest standard of living in the world. The geographical frontiers have disappeared, but the frontiers of science and technology still remain. Those qualities which built a trail into the wilderness can still build trails in the technological advance. The same qualities of courage, resourcefulness, and independence which opened the nation, are as necessary today as ever.

The growing complexity of life tends to make men cogs. The world is growing smaller, and it is becoming crowded. We "rub elbows" and find increasing dependence upon the activities of our fellow men. The race for economic domination becomes a race, from which we only partially are separated, for military supremacy. The burden on government increases, and the problems arising are more and more beyond the true comprehension of the proletariat. Intense nationalism is in the saddle, and everything, including freedom itself, toward which the human race always has aspired, is being sacrificed for a momentary advantage in the struggle. Nations are turning toward absolutism as a refuge.

Gladstone predicted the decay of democracy if the indigent voter found the power of his vote sufficient to seize arbitrarily and unreasonably the fruits of production. Jefferson himself, the father of American democracy, postulated as a necessary feature of a democratic régime that the bulk of the voters must be tillers of their own land. Whatever we may wish to modify in these opinions, one thing should be added in view of modern conditions. As the social machine becomes more complex and interdependent, it becomes increasingly easy for an aggressive group to disrupt it. The need for discipline is greater, the necessity for restraint of the asocial individual or group is more pressing. Individual freedom, always circumscribed, from the clan up, by the necessity of consideration of the rights of others, becomes inherently narrowed. The right to do this or that ceases to be a right when its performance injures a neighbor; and the ways in which each individual's acts reflect upon the security of his fellows are constantly multiplied. The democratic form of government is adapted to the maintenance of discipline only to the extent that great groups of varied peoples are ready and willing to discipline themselves. The failure to do so in other countries is the primary reason that the people have reverted to absolutism in the hope that it would prove benign. The immediate result of course, has been to impose discipline, often harshly and in the extreme, to curtail radically individual freedom, and thus to create a state in which efficiency is secured at the sacrifice of much that makes life worth living. The plunge into absolutism is abrupt. The winning of individual liberty is a slow and painful process. Must all democracies go through this cyclic process? Can the great populace, which is governed by its intuitions, its emotions, its mass psychology, grasp this trend and preserve its stability? Moved by the persuasion of those with ulterior interests, who play upon their emotions, can they yet understand the voice of reason? It depends upon whether those who would bring to the people the accumulated wisdom of the ages speak in words that are powerful, genuine, and capable of being truly understood; and then it depends only upon whether the people listen and are willing to be guided by reason.

## Professional Man Should Make Himself Heard

The free operation of professional classes, motivated by public zeal and altruism, is an anchor upon which our democracy depends to hold it through the storm. There is a great obligation upon the professional man to speak clearly, to insist upon being heard, to maintain his independence. This obligation rests heavily upon engineers.

To be a professional engineer in the true sense, does not require that we have some special set of relationships to society and to the organizations of which it is made up. It does require that the primary motivation be the acquisition of scholarship and its generous application to the needs of man.

To be an engineer in these days is to bear a proud title. To be able and willing to speak true opinions on the complex technical affairs of the day, without prejudice and free from control, is a privilege that is becoming rare in the world. Insistent upon his prerogatives, kowtowing to no man, respected because he speaks a truth the country needs to know, the independent engineer stands as an important member of the professional class—a strong bulwark against disaster, which can guide our steps into the ways of pleasantness and into the paths of peace.

# The Engineer in a Changing World

By RALPH E. FLANDERS

**What can and should engineers do about the social and economic problems that beset the modern world? In answering this question, Doctor Flanders says: "We must exercise our responsibility more for the sake of society as a whole than for the sake of ourselves as individual engineers or for the private interests of the businesses with which we may be connected." He states further that: "It is an inescapable duty that we each make of ourselves centers of education and influence, to the end that our useful offices may continue, and our civilization fulfill its destiny of an ever-growing service to the needs of mankind."**

THE WORLD in which we are living is changing in many ways, and those changes are rapid. The physical frontier has disappeared from this continent and, except for the antarctic regions, it has practically disappeared from the earth as a whole. With the occupation of the frontier has gone one of the powerful automatic stimuli to private enterprise and material progress.

Much of the progress we are making is so based upon elaborate research and requires such extensive and expensive provision of facilities that it is best carried out by large corporations or well-financed research groups, rather than by individual scientists, engineers, and inventors of the old type. This is another influence that tends to restrict the expansion of individual initiative and tends to throw the burden of further social progress onto aggregations of capital and of men.

A further element in our increasing socialization is the recent rapid sensitizing of the social conscience and a resulting expansion of social activity into fields of action which in past generations had been considered reserved for the individual or for small social groups. The severity of the depression was so great and the social responsibility for it seemed to be so definite that both our relief measures and our recovery measures have tended to be social and political, rather than individual and philanthropic.

Finally, though without exhausting the list of recent developments, we have become aware of the fact that in our banking, credit money, and general aggregate of financial institutions, we have a useful but delicately balanced, and at times unbalanced, mechanism difficult to control and tending on the whole greatly to increase the violence of business fluctuations and economic distress, rather than to provide a dampening effect on them. All these phenomena and others not mentioned pose a new set of problems to the engineer and to the engineering societies in which they are organized.

In their beginnings and until recent times, engineering societies had the purely technical purposes of bringing to the attention of their members all the latest technical developments in their fields and offering a forum for criticizing them, advancing them, and disseminating knowledge about them.

Even while this type of activity remained almost the sole object of society action, the problem nevertheless began to be complicated by the numerous divisions into which engineering work began to elaborate itself. Engineers were no longer simple engineers. Some were in control of their own businesses as consultants or manufacturers of engineering apparatus; others were employees of various grades. Some were engaged in teaching; others in research, design, construction, sales, operation, and administration. This multiplication of function brought a host of new problems to the engineering societies, on the one hand opening new opportunities to usefulness, and on the other tending so to elaborate engineering activities as to lose much of the harmonious directness and strength of the earlier days.

As a result of the tendency for engineering advance to be focused in and to be carried out by large aggregations of men and of money, the problem of the engineering society has been complicated further by widespread sentiment in favor of entering employer-employee relations, so that in the extremes of such policies the societies might be tending to take on some of the aspects of trade-union organizations.

This continuous elaboration of function is here described and emphasized so that we may realize that the problems facing us are no longer simple, and that any endeavor forcibly to keep them within too simple lines may result in giving to the societies a cloistered and sterile outlook, devoid of vital function and social usefulness. We are in fact faced with the problem of maintaining our social usefulness and finding out just what are the spheres in which it most clearly may be demonstrated and exercised.

## World of Today a Product of the Engineer

The world we know has been made by the engineer so far as its physical aspects are concerned, and his influence has had no small part in determining its spiritual environment.

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An address delivered at the general session on the economic aspects of engineering and Institute activities held during the AIEE summer convention, Milwaukee, Wis., June 23, 1937.

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Perhaps some remember the epitaph of Sir Christopher Wren, the architect, engraved on the walls of his masterpiece—St. Paul's Cathedral in London. It reads: "Si monumentum requiris, circumspice," or, in English, "If you seek his monument, look about you." In like manner, if we wish to inquire as to the material influences of the engineer, we have but to look about us. We will see thousands of daily reminders of the fact that our material civilization has at the bottom an engineering foundation.

Its useful services are many. Our profession has filled the world with a profusion of comforts and luxuries which were denied to kings a short century ago, but are now enjoyed by the average citizen. Flowing water in the kitchen and bathroom, brightly lighted streets, and the radio, are all ordinary conveniences for the ordinary citizen. They were nonexistent when Queen Victoria began her reign.

There is no need to multiply instances. The tale has been told and retold; but told and retold, as well, has been the story of the problems an engineering civilization has posed for the solution of its citizens. The perils of drought and pestilence have been exchanged for the mischances of technological unemployment. That unemployment may be transitory and a part of a process which history shows to be benevolent in its total results, but it is as yet a serious and sometimes insoluble personal problem.

Worst of all, our engineering civilization proves to be less stable than the older forms based upon subsistence agriculture. It gives us more, but its gifts are more irregular. There are seasons of outpouring and seasons of withholding. Boom follows depression, and depression follows boom, and this relentless alternation leaves much human wreckage in its wake. What can and should we engineers do about the evil features of this world we have made?

## Engineers Should Not Intrude Into Alien Fields

It is not my intention to go into the details of this problem. I believe that the engineer's work has been healthy and constructive. I believe that the maladjustments have come from our narrow and selfish activities as industrialists, workers, farmers, and financiers, and from the imbecilities of our politics. In particular, I do not believe, as so many have urged, that the remedy lies in the intrusion of engineers with engineering methods into the alien fields of politics, economics, and finance. This subject will be discussed briefly, because in popular opinion our profession alternately has been damned for causing all the ills of our era on the one hand, and on the other for not curing them by still more radical engineering activity.

This question was raised some months ago in an address by Walter Lippmann, and I take the liberty of quoting here in part from his criticisms and in part from a reply to them:

> There were several years, I should say roughly from the crash of 1929 to the end of 1933, from the breakdown of prosperity to the beginning of recovery, when the ideal of an engineered and planned economy had almost completely captured the imagination of the Western World. Every one who raised his voice—the Chamber of Commerce, the heads of big corporations as well as the New Dealers and the Progressives—talked about planning something. No doubt they had different ideas of how to plan and what to plan for, but the underlying image dominated most minds. The notion finally reached its grand climax, and its *reductio ad absurdum*, in the vogue of technocracy.
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> The point I wish to make is that the conception of government as a problem in engineering is a false and misleading conception, that the image of the engineer is not a true image of a statesman, and that society cannot be planned and engineered as if it were a building, a machine, or a ship. The reason why the engineering image is a bad image in politics, a bad working model for political thought, a bad pattern to have in mind when dealing with political issues, is a very simple one. The engineer deals with inanimate materials. The statesman deals with the behavior of persons.
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> The notion that society can be engineered, planned, fabricated, as if men were inanimate materials, becomes in its extremist manifestations a monstrous blasphemy against life itself.

These statements are a challenge to the engineer's training, his state of mind, and his usefulness to society. That challenge should be accepted and an answer given.

## Engineer Can Contribute to Government

Engineers never have been convinced, in great numbers or for long, of the effectiveness of their technique as a main reliance of government. In fact, the clearest, most reasoned, most convincing demonstration of its inapplicability is the work of an engineer. Those interested will find it in an article by David Cushman Coyle entitled "The Twilight of National Planning," published in *Harper's Magazine* for October 1935. In all this we are at one with Mr. Lippmann.

But it will not do to leave the matter in this negative state. The engineer has positive contributions to make to the processes of effective government. He cannot make them unless certain misconceptions expressed in Mr. Lippmann's address are removed and the real nature of his contribution is revealed. There are 2 primary misconceptions: (1) The engineer cannot "dictate to nature." He is the humble disciple of nature, serving society by virtue of that discipleship. (2) His undertakings grow ever farther removed from the completely material realm, and must perforce deal ever more and more with the realization of human ends, whereby the completed structure or mechanism is a joint product of material science on the one hand, and human desires, needs, and possibilities on the other. In no branch of engineering does this appear more clearly than in the modern forms of "scientific management," of which the foundation is a fundamental and sincere comprehension of the human and personal element. Engineering is science applied to human needs. It is both a science and an art. If it is not both, it is not engineering.

Another characteristic of engineering is derived from the fact that it is an applied science. It is science applied to definite purposes; and definition of the purpose becomes the ruling factor in engineering design. In government a similar definition of fundamental purpose is sadly needed. Our national policies are guided by such sec-

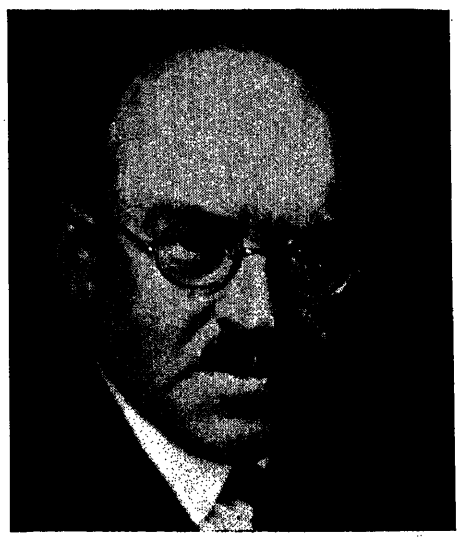
ondary and derivative purposes as raising the price level, restoring the freedom of international trade, raising wages, shortening hours, controlling production, restraining competition. Each of these confidently is put forward as a good in itself, with small pains taken to see that each is related to some larger, general set of purposes.

Good engineering is based upon a careful statement of the problem to be solved; and it happens that our profession has formulated such a statement of the economic problem and has publicly offered it for the consideration of government and governed. It is to be found in the first progress report of the committee on economic balance of American Engineering Council. It reads as follows:

> The problem is "the selection and recommendation of such governmental, financial, and business policies as will maintain in the United States a standard of living that is high, broadly distributed, and free from severe fluctuations."

At first sight such a statement appears trite and sterile; but when we take the trouble to examine the infinitude of partial and conflicting policies that go to make up our total program at this moment, the need becomes clear for some such statement of fundamental purposes, to which all policies must be referred.

A third contribution of our profession—and the last to be suggested in this connection—is a certain knowledge, and a particular faith. The knowledge is that the physical requirements are now at hand for a material standard of living far higher than the human race ever before has enjoyed. There are no physical obstacles. The engineer has removed them. He has played his part. If fault there be, it lies at some other door than this.



**Doctor Flanders**

With the knowledge goes a faith. He has faith that the complicated social and political problems involved in reaching our objective can be solved—not immediately nor completely, but in such wise and with such speed as may lead to a continuance of our old progress toward a higher and more widely distributed material prosperity. This knowledge and this faith we would share with others.

It is a privilege to belong to a profession that combines the practice of a science and an art. The combination is essential for leadership and achievement. For some time, it has seemed that at least 3 branches of education and professional practice are well fitted to prepare men for life in our present troubled world. They are the doctors, the engineers (to an extent and for reasons I have endeavored to explain), and the graduates of the first-rank schools of business administration, together with the practitioners of business who have attained professional first rank without grace of formal education.

Not only is each of these professions at once a science and an art, but they have another property in common. Each has to face the harsh judgment of ascertainable fact. For the doctor, the patient gets worse or better, lives or dies. For the engineer, the dam endures and serves its economic purposes, or it goes out under the pressure of the flood, scattering death and destruction. The business man faces the grim entries on the balance sheet. Each is in touch with reality. Society needs the touch of reality.

How should all this affect our lives and our actions? In many ways, but principally in 2 ways: We should derive from these considerations a deep and effective sense of the worth of our profession, and likewise of the responsibilities we bear as engineers.

## A Current Problem As the Engineer Sees It

It may be worth while to consider one of our current problems in the light of the engineer's knowledge and experience. We believe that the standard of living may be greatly raised for the mass of the population which is able and willing to work. We believe also that the increasing efficiency of machinery, processes, and management will permit the world's work to be done in shorter hours with more leisure for rational enjoyment. In a word we are sympathetic with and committed to the objectives of the present active labor movement in its endeavor to attain shorter hours and higher wages.

But the higher wages must be real wages, that is to say, they must be able to purchase more goods and services for the wage earner and his family. A mere increase in dollar wages will not do if there are no more goods and services to be bought and if prices advance as fast as or faster than wages do. When we see output restricted by shorter hours and the slowing up of the introduction of improved machinery, while wages are being raised, we are justified as engineers in applying elementary analysis to the problem. We must conclude on such analysis that it is hopeless to expect more goods for higher wages if less goods per worker are made. The hope for a better living under those circumstances is illusory and cruelly deceptive.

However, there is hope for a better living, and that better living can come only from better production as a preliminary to better distribution. For that better production—and particularly for better production in shorter hours—the world is now, and in the future will be, dependent on the engineer, as it has been in the past. If our hopes for better material conditions are to be realized, there will be work for the research engineer, for the process engineer, for the designing engineer, for the management engineer. And the sooner this is realized by the pro-

tagonists in our present social strife the better it will be for all concerned.

## A Major Threat to Social Progress

It is in our experience and our present method of meeting these current problems that we find the engineer's responsibilities of today. By the pressure of attractive but impossible doctrine, his usefulness to society is threatened; and with the limiting of his usefulness, there is arising a major threat to the social progress we have been making hitherto. We cannot ignore this situation. We must exercise our responsibility more for the sake of society as a whole than for the sake of ourselves as individual engineers or for the private interests of the businesses with which we may be connected.

There is indeed danger in the fact that the material progress with which we are concerned is so closely associated with business interests that they may seem to be one and the same thing. They are not completely so. There is a large area of business as it has been pursued in years past that has not been socially constructive, but socially dangerous instead. Perhaps the largest single area of this harmful business activity has been found in the realm of security speculation and its allied enterprises. Unfortunately for one area of our responsibility, this speculative activity has been so closely associated with the operation of utilities that it is difficult for the general public to distinguish between the useful and socially necessary on the one hand, and the destructive and damnable on the other. A part of our problem lies in making this distinction clear within our own minds and then in presenting the distinction so clearly that we can take the lead as individual engineers in directing public policy on this utilities question into channels more nearly serving the public interest than does the direction now being pursued.

Another danger that we must carefully avoid is that of running wild on the social and economic aspects of our profession and neglecting the technical foundation on which is built everything else that we say and do. The other serious danger, that we may be rash enough to carry our whole engineering point of view over into social planning, has already been discussed.

Whether or not as individuals or as a profession we attain to high reputation or only to humble usefulness, we know that our civilization depends on us. In the words of Spengler, though with more hopeful emphasis:

> The center of this artificial and complicated realm of the machine is the organizer and manager. The mind, not the hand, holds it together. But, for that very reason, to preserve the ever-endangered structure, one figure is even more important than all the energy of enterprising master-men that make cities to grow out of the ground and alter the picture of the landscape; it is a figure that is apt to be forgotten in this conflict of politics—the engineer, the priest of the machine, the man who knows it. Not merely the importance, but the very existence of the industry depends upon the existence of the hundred thousand talented, rigorously schooled brains that command the technique and develop it onward and onward. The quiet engineer it is who is the machine's master and destiny. His thought is as possibility what the machine is as actuality.

Those words are true! As individuals we may struggle, and succeed or fail; we may be rewarded beyond our deserts or miss a recognition that was richly our due. Whatever may happen, this at least we may hold to: that we lived in a glorious age, full of human possibilities; and that our daily work lay at the heart and center of that age.

As to our responsibilities, they are great. Perhaps the greatest of them lies in the understanding of the nature of the mechanisms and of the organizations on which depend the material interests of our generation. It is hard to say whether the greatest danger to them lies in their being perverted and frustrated by powerful selfish interests, or in being overthrown by the recklessness and ignorance of our fellow citizens—even by those moved by the best of intentions. Our material blessings do not come naturally, as fruit grows on a tree. They come because thousands of individuals, having engineering and organizing skill, devote themselves in large and small capacities to keeping the machinery of civilization in running order. It is an inescapable duty that we each make of ourselves centers of education and influence, to the end that our useful offices may continue, and our civilization fulfill its destiny of an ever-growing service to the needs of mankind.

## The Engineer's Responsibilities to the Public

Doctor Vannevar Bush has analyzed the social responsibility of the organized engineering profession with particular reference to its relations with government (see article elsewhere in this issue). I am going to suggest the nature of our responsibilities to the general public. We are now engaged in a strenuous race, a race between education and the breakdown of democratic government. As one of its major resulting catastrophies the breakdown of democratic government would destroy the engineer's usefulness to society and put an end to all reasonable hope for a continuation of our old progress toward a higher standard of living for the mass of our fellow citizens. To forestall this disaster, widespread education of the voting public is necessary. The first step in this process is our own self-education. Perhaps we never have stopped to think that we may be in need of that, that some of the ideas we have held since our youth may need revision.

We should examine our beliefs with all the critical capacity at our command. We should study and ponder with open minds proposals to which we have an instinctive aversion. Thomas Nixon Carver once wrote that the trouble with radicals is that they read only radical literature, and the trouble with conservatives is that they read nothing at all. We must erase this stigma from our record and approach these new problems from all directions, furnishing ourselves thereby with opinions perhaps somewhat changed but more solidly founded than before, for we do have new problems and they may require from us new attitudes. It is doubtless true that economic law does not change; neither does physical law. But we discover new physical laws and perhaps we may discover new economic ones. At any rate, we have behind us a marvelous record of new invention and enterprise operat-

ing under the ancient and immutable physical laws. Is it not possible that we may discover workable and useful social novelties operable under the ancient and immutable social laws?

As engineers, it is incumbent upon us to distinguish between the device that flies in the face of nature and the device that makes a new application of natural law. With our own beliefs fresh and clear and in order, we face the task of making them broadly useful. I wish to stress our responsibility as an educational force counteracting the forces of social dissolution. In our national meetings, in the meetings of our local sections, in our personal appearances before other bodies and groups, in our private conversations, in human contacts which we must learn to multiply and elaborate, in every way ingenuity can provide, with all the patience and wisdom at our command, we must speak and work for the continuance of an ordered society that moves forward to higher material possessions, more fruitful leisure, and deeper spiritual achievement.

Perhaps you will forgive me if I close with words that originally were addressed to a graduating class at commencement, for, in a sense, we too are facing a commencement.

In the Declaration of Independence our forefathers demanded for the individual the right to "life, liberty, and the pursuit of happiness." When those words were written it was a new idea in the world that happiness might be attained. The ancients and those of medieval times had other aspirations. They sought honor, liberty, and salvation, and were not sure that happiness was consistent with these or even possible on any terms. May I suggest that there is a deeper, richer word than "happiness," and that is the word, "satisfaction."

It is not too much to hope that we may attain satisfaction in the practice of our profession. In part it will come from the very fortunate fact that many of us as engineers see the idea in the mind finally embodied in the material machine, process, or structure, and actively serving the needs of mankind. But an even more powerful satisfaction will come to us if we see our profession in the aspects of history and of the evolving human drama. For those who see, and who act on the vision, the fullness of life is reserved. May that gift be ours!

# The Engineer of Tomorrow

## He should be guided, but not limited, by the record of the past

By A. M. MacCUTCHEON
PRESIDENT AIEE 1936-37

DURING this past year I have talked with and consulted many engineers. I have learned of their ideas and their ideals. They are men of purpose and conviction. The engineering record of the last 50 years is astounding; but these men are not satisfied. The typical engineer is more interested in the problems of the future than in the accomplishments of the past. The engineering profession demands that the engineer of tomorrow shall be broader and greater than the engineer of today or yesterday.

How can this be accomplished? None can deny that we are living in a changing world. History is the great teacher. We should be guided, but not limited, by the record of the past. The last hundred years has been a period of engineering invention and development, and invention will never cease. We should endeavor to decide whether the next 25 years is not to be more largely a period of adjustment—of consolidating, co-ordinating, perfecting, and best utilizing the inventions and developments of the past.

Much has been said of the "engineering method" of approach to, and solution of, a problem. Just what is this "engineering method," and has the engineering profession invariably used it in the consideration of its own problems? In an article published in the February 1937 issue of ELECTRICAL ENGINEERING (pages 206–07), Morris Leeds, a Fellow of the AIEE, defines the essentials as follows:

> A clear conception and precise statement of the objective to be achieved; a consideration, as thorough as practicable, of all the factors—be they physical, social, or psychological—which will influence or may be employed in getting the desired results; and, on the basis of this knowledge, the formulation of the most effective plan for achieving results that can be developed in the allowable time.

To this I suggest that the following be added:

1. An investigation to develop all facts pertinent to the problem.
2. Recognition of additional information which is necessary, and which may be secured by research and experimentation.
3. Correlation and evaluation of the information gathered. Conflicting evidence often develops, and each item should be weighted in reaching the final decision.
4. The decision shall be uninfluenced by ulterior considerations.

I have believed that engineering is an art almost as

The president's message presented at the opening session of the AIEE summer convention, Milwaukee, Wis., June 21, 1937.

much as it is a science. As an illustration, consider the design of a new electric motor. Assumptions are made as to the conditions to be met when the motor is applied, but exact information as to the operating conditions is seldom available. While the motor is designed for a specific horsepower, practically never is this the exact horsepower demanded of it in service. The proper weighting to be given to efficiency, cost, heating, and dimensions must be decided by the designer. A penalty in one direction is often an advantage in another. Materials are selected with a view to taking advantage of technical progress. Often these materials are yet unproved for the specific purpose. Innumerable decisions must be made, based upon past experience and probability. To be an engineering achievement, the finished motor must be as much a work of art as a painting by a master, and it cannot alone depend on the accurate solving of a number of formulas. The successful designer is guided by a trained instinct as much as by acquired knowledge. Of a hundred possible designs, he selects one in much the same way that the musician develops his creative theme. If this is a correct theory, its recognition is important. The future practice of engineering, the future training of engineers, the future relation of engineers to the rest of industry and society, should be influenced by this theory.

Many problems are referred to the engineer. Though the trained engineer is best qualified to make the decision, his recommendation often is questioned. He is expected, being an engineer, to demonstrate quickly and convincingly that no other solution was possible. Seldom is this true. While no engineer can always be right, this is the limit toward which he strives. The critics of engineers are asked to view the remarkable engineering progress of the last 50 years, and to value engineering opinion accordingly; but the engineers themselves should concentrate on what they have failed to accomplish, and by the application of the "engineering method" improve their engineering.

Applying self-analysis, what may be our faults of the past? Have we ourselves viewed engineering too much as a science and not enough as an art? Have we thought that engineering dealt only with inanimate things and natural forces, and failed to recognize that human reactions and the interests of humanity are essential factors to be considered and properly weighted in any engineering recommendation? Have we been too dictatorial and assumed that others should accept our decisions simply because we are engineers? Have we been too intolerant of criticism and failed to profit thereby? Have we had too great a tendency to refuse to recognize things as they are, and insist on how we think they should be? Have we given full value to the viewpoints of others? Have we always realized that while an exchange of views is desirable, a prolonged argument is seldom convincing? Have we been good students of human psychology and fully developed our ability to win confidence and influence others? Have we always recognized that the best speech is of no value unless it is heard; the best book of no value unless it is read; the best engineering plan of no value unless it is so convincingly presented that it is endorsed and adopted by others? Has the engineering profession always charted its course over a period of years, or has it planned from day to day and month to month?

In a recent talk, I presented this definition of an engineer: "one who through training, study, and practice adapts and controls the materials and forces of nature to the benefit of himself, his fellow engineers, and the rest of the human family." This definition implies the adapting and controlling of men, for they certainly can be classed as among the materials and forces of nature. I believe that society's past conception of engineering has been limited to invention, research, design, and education.

The following I list as the desirable qualities to be possessed by every engineer: integrity, dependability, enthusiasm, vision, determination, resourcefulness, forcefulness, adaptability, co-operation, diplomacy, friendliness, broadmindedness, training, experience, and engineering knowledge. Has every engineer of the past, and does every engineer of the present, meet this or a better definition, and possess all of these qualifications to a high degree? If not, is this possible for the engineer of tomorrow? Should the engineer of tomorrow be controlled by 4 fundamental ideals—co-operation, consideration of others, service, and accomplishment?

For more than 50 years, the American Institute of Electrical Engineers has represented professionally the electrical engineers of America, led by such distinguished engineers as Doctor Elihu Thomson, Doctor Edward Weston, and Doctor E. B. Meyer, all of whom have been lost to us during the past year. Their enthusiasm, their cheerful optimism, their breadth of vision, their indomitable spirit, their engineering ability, form a pattern which the engineer of tomorrow well may emulate. As the engineer of tomorrow learns from, and endeavors to improve upon, the engineer of yesterday, so should the Institute profit by the past and fully meet its opportunity and responsibility in representing the electrical profession in the future. To me it seems that our organization should not be static. As the profession grows and changes, it should grow and change, ever keeping in mind its fundamental purpose. Fine as the record has been in presenting, discussing, and recording technical progress; in developing standardization; in fostering and sponsoring engineering education in co-operation with all other agencies; in working with other engineering societies to develop professional ethics and a sense of professional responsibility; in encouraging acquaintance, and providing opportunity for developing the social instinct, is not still greater achievement possible?

Among the national societies and between the national and local societies, a still closer co-operation is needed. Many of their problems and interests are diverse. Many are closely allied. Their most fundamental purpose—service to the profession and to humanity—is identical. Their work should be further co-ordinated; duplication and conflict should be eliminated, each supplementing the others.

Is it not possible to make the Institute more representative of the whole profession? Cannot the organization develop a still finer program, interesting many who are

not now interested? For example, should there not be more papers and articles recording experience, which would appeal particularly to the many electrical engineers who use electric power and electrical equipment but are not connected with the manufacture of either—papers that would relate to electrical applications in the textile, the automobile, the oil, the chemical, the mining, and other industries? Might there not be an increased consideration of the problems of the profession, such as registration, and an endeavor even more actively to study and assist in their solution? Can there be a movement toward providing meetings and presenting information to those associated with the electrical industry but not eligible for membership in the Institute? Is all possible being done to encourage and develop the young men in the technical schools?

I suggest one additional committee, a committee to investigate, review, and plan for "the future of the AIEE." Their deliberations should consider the next 5, 10, and even 25 years. Would we, today, be satisfied with the Institute as it was in 1912? Will the members in 1962 be content with the 1937 model? Is it not in accordance with the "engineering method" not to accept things as they are if improvement is possible, but to make no change unless improvement is probable? I further suggest that this proposed committee particularly plan for activity in those fields where there is the greatest need, even though not the greatest interest.

# The Engineer's Responsibility to Society

## A student speaks his mind on a subject of importance to engineers

By CHAS. W. BLAKER
ENROLLED STUDENT AIEE

OF ALL the definitions of engineering that have been propounded, the one that seems to express most clearly and accurately the true function of the engineer is found in the preamble to the constitution of American Engineering Council. In that document engineering is defined as the "science of controlling the forces and utilizing the materials of nature for the benefit of man, and the art of organizing and directing human activities in connection therewith."

Engineering is, indeed, a science. Without the least fear of successful contradiction, engineering might be called the oldest of the sciences. Far back in the gray dawn of civilization were heard the first awakenings of the engineering consciousness. The savage who first learned to utilize the energy of a distorted elastic system in the contrivance of the bow and arrow was an engineer. The primordial man who recognized the power of fire as a protective agent against the prowling terrors of the night was an engineer as truly as any graduate of our foremost technical institutions of today. In the field of science, then, is to be found the generally accepted work of the engineer. Yet, in accord with the definition quoted, scientific application of the laws of nature covers only part of the field of engineering. Associated with the profession there is also the *art* of organizing and directing human activities. Any ordinary layman, if asked to give his interpretation of the term engineering, would no more think of social organization than he would of music. Many engineers even have no awareness of the art involved in their profession. Yet that engineering does involve, inherently, the art of directing human activities in connection with the scientific utilization of natural resources, is a fact that upon a little consideration must be accepted by even the most ardently technical man. That the duty of the engineer to society extends specifically into this field of organization must be apparent to all. The engineer can no more expect the products of his work to be used intelligently by uninitiated society than could a child be expected to use matches and debris for anything other than a harmful conflagration. Yet engineers, as a profession, have been consistently neglecting this most important side of their work, thus making possible the international conflagration of the years 1914 to 1918. This is discussed more in detail later in this article.

If the engineer is to concern himself with society, what is he to understand in the term? It has had many interpretations in the past, but the one that seems to explain it most clearly is the simple term humanity, or human activity, as mentioned in the AEC definition of engineering quoted previously. The engineer's responsibility to society is a humanistic one, involving the understanding of humanity and its individual personal problems as well as an understanding of the scientific problem and its stereotyped solution. It is necessary for the professional man to remember that, before any contemplation of engineering as a profession occupied his mind, he was an individual in a society of individuals; and that, as a matter of course, his duty is first to humanity and next to his

A paper presented at a conference of the AIEE Branches at the University of Pittsburgh, Carnegie Institute of Technology, and University of West Virginia, held at Pittsburgh, Pa., January 12, 1937.

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profession. One might say of engineering, as Lincoln said of government, that in order to survive it must be a profession for, by, and of the people; otherwise it must pass in the manner of governments and institutions from the beginning of time that have violated that simple code.

In a broad sense, the responsibility of the engineer to society may be divided into 3 major branches: (1) conservation, (2) production, and (3) distribution. In the last few years, there has been much publicity concerning the conservation problem. The public has been dosed quite efficiently with conservation propaganda; to such an extent has this been carried out that public sentiment has turned conservation conscious, with the result that much work that is good has been accomplished. Yet much of this fervor is but a transient emotion, engendered by a mild hysteria. Hence, it can but pass, leaving a most incomplete work in its wake, for pure sentiment, though a most potent force in mob psychology, is not sufficiently stable to form a basis upon which may be built the superstructure of any enduring principle. If conservation is a necessity, and in our present condition of envisaged power shortage it certainly is, the engineer should carry out a program of public education that will acquaint the public, in general, with the tremendous scope and importance of the problem.

In contrast to the problem of conservation, that formed by production is of a secondary type, being a problem not in the actual processes of production, but in the complications created by our system of mass production and intense specialization. The production lines in our large automobile factories are typical of the type of production wherein the individual consciousness is submerged in that of the entire group. The conditions of our mines and factories are all pregnant with social problems—with living-together implications, as one writer has called them. It is to the engineer that the people must look for the continuation of their individuality in the maze of industrial unification and the amalgamation of humanity.

Of the 3 problems, conservation, production, and distribution, the last is perhaps the most widely publicized, not only in the United States, but throughout the world. It has become an international problem, the solution of which will involve an eruption and disturbance of all existing principles. This disturbance will involve not a change or revolution in that sense, but an upheaval and purging of existing principles—this rather than radical change because there appears to be no other working economic system wherein the individual is permitted to retain his individuality and is as well rewarded, materially, for individual achievement as in the system under which we in the United States of America live. Every economic system has its faults; but the faults inherent in capitalism, in comparison with those of other working systems are small indeed from a humanistic viewpoint. By that I have no intention of implying that capitalism is nearly fault-free; it is far from that. However, in relation to other economic systems its defects are minor. In the purging mentioned, probably the evils that will be given the most careful attention are those accompanying idle and unmerited wealth. With the disappearance of that type of wealth-holder, and the removal of profit from war, the government will have made a definite advance toward the era of social readjustment and capitalism will be enabled to assume the position it merits. As a clear and analytic thinker is needed, who can be better qualified than the engineer to handle the remedial measures; who more naturally should handle them than the one whose works have created situations necessitating those remedies?

All the foregoing discussion might be condensed into a series of 4 "shifts in the social consciousness" for which the engineer might be proved responsible:

1. Shift from individualism to interdependence.
2. Shift from competition to co-operation.
3. Shift from scarcity to plenty with the accompanying living-together implications of industrialized society.
4. Shift from stressing rights to stressing duties.

A sincere consideration of these shifts will clarify the responsible position of the engineer in connection with the problems he has created.

Last of all to be discussed is that scourge of mankind—War. Not long ago a well-known speaker in Pittsburgh placed the responsibility for the Great War at the feet of the engineer. That is a most startling and grave accusation, the most appalling thing about it being its partial truth. None can deny that war would be impossible were all engineers to decree that it should be made so, for with the engineer lies the power to halt the advancing tide of destruction that threatens to tear apart the familiar structures of civilization. The insupportable horrors of warfare as it is made possible by engineering developments form one of the few immanent causes for the failure of engineering as mentioned earlier in this article. True, he who wages a battle against the protagonists of war fights no puny skirmish, for against his calculation and powers for analytic thinking lies the weight of money, that magic talisman used to open the doors to the material forces of the world. It will be a battle requiring men.

In closing, a few commonplace remedial measures are outlined, in a study of which the engineer might well profit:

1. Legislation for remedy of existing ills.
2. Thoughtful study of governmental alteration without disturbing the fundamentally sound principles of good government.
3. Profit removal from war.
4. Sensible and equitable distribution of national wealth.

Let engineers interest themselves in something outside their narrow technical field for a time—something outside the bounds of science—and become human and humanitarian, for it is only in such an interest that they can possibly find the solution to the myriad problems of adjustment and reparation awaiting them. In the words of Doctor W. F. Durand, president of the Third World Power Conference, held in Washington, D. C., last year: "What we are urging is a quickened sense, on the part of the engineer, of his responsibilities, not alone in a purely professional sense, but as a citizen of his community . . . of the world."

# An Experiment in the Recognition of Engineers

By ROGER I. WILKINSON
ASSOCIATE AIEE

**Recognition of outstanding young American electrical engineers by Eta Kappa Nu, honorary electrical engineering society, began with the presentation of awards for 1936. The society expects its plan of annual awards to incite a fuller and broader professional development of young electrical engineers. Statistics for the men nominated for the 1936 awards are presented and discussed in this article.**

IMPLICIT in American democracy is the idea that those who accept and discharge the greatest responsibilities, and those who contribute the most exceptional discoveries and inventions, shall be accorded the highest positions in the respect of their fellow citizens. Practically the only restriction placed on a man's activities is that his endeavors should be oriented in accord with mankind's persistent struggles to attain certain inalienable rights. The greatest of these is that he should one way or another forward the general opportunity for the pursuit of happiness. His own reward is presumed to follow axiomatically.

As with all pure theories, because of certain causes not being comprehended exactly, and of fortuitous circumstances, the practical application rarely works out precisely as predicted. Thus it was that the honorary electrical engineering society, Eta Kappa Nu, proposed to lend whatever weight it might to a more perfect operation of the American "democratic theory," at least as far as electrical engineers were concerned. In its establishment in 1936 of the Eta Kappa Nu Recognition of Outstanding Young Electrical Engineers, then, it is not surprising that the preamble to the conditions of award should state that, "As evidenced by their past records and future promise, this recognition shall be given annually to young electrical engineering graduates, for *meritorious service in the interests of their fellow men.*" In addition to more nearly assuring that due and appropriate recognitions accrue to outstanding young engineers, the award plan hoped to attain 2 other ends, scarcely less important: (1) to give to the engineering profession concrete examples of what young men under 35 years of age and not more than 10 years out of college can be expected to achieve, and (2) to inspire by these young men's careers, and to furnish guides for, undergraduates and new engineering graduates to take up their own professional development as soon as possible.

Very naturally, a broad range of accomplishments from scientific research to civic and political activity and artistic creation is recognized, so as to encourage young engineers to obtain a truly liberal and humanistic perspective at an early point in their careers. Figure 1 shows the contents of the questionnaire which each outstanding young electrical engineer nominated was asked to return. It will give an idea of the breadth of interests which Eta Kappa Nu feels that an engineer who takes full advantage of his academic and postacademic training might well acquire.

Nominations for the 1936 recognition to the number of 47 were received from all of the groups of persons eligible to propose candidates. The distribution of nominators is shown in table I. It is interesting to note that nominations came from 21 different states of the union, being as widely distributed as Vermont and New Hampshire, Florida, Texas, California, and Oregon, about half lying west of the Mississippi. Because of the preponderant number of nominations by heads of electrical engineering departments, there is a close correlation between the schools attended by the nominees and the states from which the nominations came. The present locations of these 47 accomplished young engineers are, of course, less widely distributed due to the concentration of electrical engineers in the areas of denser population. Quite naturally New Jersey, Pennsylvania, and New York each have over twice as many as any of the other 13 states of business, claiming 6, 9, and 10, respectively. The general types of work and industries in which they are engaged are shown in table II.

Table III gives the distribution of years by which the nominees received their baccalaureate degrees in electrical engineering, and their ages on April 1, 1936. Due to a possible misinterpretation of the wording of the 1936 regulations, the one case of a candidate being 35 years old, that is *over* 35, was not thrown out. In the future, however, only those *less* than 35 years of age will be considered to be eligible. The expected tendency for substantial achievement to be attained as an engineer grows more experienced is well borne out by the heavier concentration of nominees in the 1926 and 1927 graduation years and in the 30 to 34 age classifications.

**Table I. Distribution of Nominators**

| | |
|---|---|
| Members or Groups of Members of Eta Kappa Nu | |
| Individual members | 2 |
| Alumni chapters | 2 |
| Undergraduate chapters | 2 |
| Sections of the American Institute of Electrical Engineers | 6 |
| Heads of Electrical Engineering Departments of American Colleges | 37 |
| | 49 |
| Duplicates | 2 |
| Net | 47 |

Written especially for ELECTRICAL ENGINEERING.

ROGER I. WILKINSON is a member of the technical staff of Bell Telephone Laboratories, Inc., New York, N. Y., and is chairman of the award organization committee of Eta Kappa Nu Association.

## Record of Achievement

Date.....

To the Secretary, Jury of Award
Dear Sir:

The answers to the questions below give, to the best of my knowledge, a factual record of my work and activities since graduation from college.

### I. General Information

*a.* Name.....

*b.* Date of birth.....*c.* Place of birth.....

*d.* Home address.....

*e.* Business address.....

*f.* College granting your baccalaureate degree.....

*g.* Particular years attended and year graduated.....

*h.* Average grade attained in undergraduate work.....%.....

*i.* Social fraternity and honor societies of which you are a member.....

*j.* Married?.....Date.....Children and ages.....

*k.* Do you rent or own your own home?.....

*l.* Attach in the space below a small photograph or snapshot of yourself.

### II. "On the Job" Record

*a.* By what companies or institutions have you been employed and in what capacities since graduation? Salaries at start and finish of each?

*b.* What papers have you published as a result of your everyday work, or allied work? (Attach copies if possible.)

*c.* What new and important facts have you discovered?

*d.* What new machines, methods, theories have you devised? Patents?

*e.* What application of engineering principles have you made to industrial and business planning or organization?

*f.* What application of engineering principles have you made to civic problems?

*g.* What have you done in the instructional field?

*h.* Have you taken any advanced scientific or professional engineering degrees?

*i.* What other accomplishments in your job?

### III. Record of Activities in Behalf of the Community, State, and Nation

*a.* What philanthropic work have you actively engaged in?

*b.* What have you done for the church?

*c.* Have you led or assisted in boy scout, Y.M.C.A., or other young peoples' organizations?

*d.* What municipal, state, or other political or social volunteer boards have you served upon?

*e.* How have you helped further adult education in the community?

*f.* What have you done to make the depression less heavy for others?

*g.* Have you actively supported any candidates in political campaigns?

*h.* Have you ever run for political office yourself?

*i.* In what way do you think your work under II has added, or will add, to the comfort or happiness of mankind?

### IV. Cultural and Aesthetic Development

*a.* What general (nonengineering) articles or reviews have you written?

*b.* Since graduation have you attended courses in history, sociology, economics, psychology, to increase your understanding of the social order, and what can be done about it? Additional degrees received?

*c.* Have you studied one of the fine arts, or attended courses in art appreciation? Degrees or honors received?

*b.* Have you participated in literary, dramatic, musical, painting, or other fine arts creation? What evidences?

*e.* Have you made outstanding architectural contributions, or achieved noteworthy results in industrial design or decoration?

*f.* Have you assisted and encouraged others in developing their cultural potentialities?

*g.* What books have you read in the last 5 years?

### V. Other Accomplishments

*a.* Have you a hobby? What have you done with it?

*b.* Do you have any athletic distinctions?

*c.* What other advanced study have you taken up? Physics? Chemistry? Law? Philosophy? Astronomy? Religion?

*d.* What engineering societies do you belong to? Offices held?

*e.* What other organizations do you belong to? Offices held?

*f.* What else do you do in your spare time?

*g.* Describe any other accomplishments or honors received.

* * * * *

In addition I refer the jury of selection to the following persons (not less than 3 nor more than 5) who are intimately acquainted with my work and activities. (Please note affiliation, if any, with each person.)

Signed.....

**Figure 1. Questionnaire sent to nominees**

At the award dinner given in New York during the winter convention of the AIEE in January 1937, remark was made that the names of the men receiving the award and the 4 honorable mentions hardly sounded like the "Smiths and the Joneses" commonly associated with American progress. The future only can tell whether the ratio will be maintained which resulted in 1936, when of 4 foreign-born nominees 2 were chosen for honors, while only 3 were similarly selected from 43 American-born candidates! It should be stated here, perhaps, that of the remaining men (whose names have not been published) there was a quite sufficient number of "common" names to gratify even the most nationally minded critic.

Further consideration of vital statistics reveals that 70 per cent of the nominees were married, and of these 2 men out of 3 already have one or more children. Relatively few, however, have attained that state of financial security where they own their own home.

The salaries of these men have apparently been very markedly influenced by the depression. The median annual salary by number of years after graduation is shown in table IV. In figure 2 these salaries have been superposed on the curves determined in 4 salary surveys of electrical engineers made in the period from 1923 to 1930. Two were studies by Eta Kappa Nu on its own alumni,[1] the third by the Society for the Promotion of Engineering Education in 1924 on all electrical engineering graduates,[2] and the fourth from a survey in 1928 of graduates of land-grant colleges made by the United States Office of Education.[3]

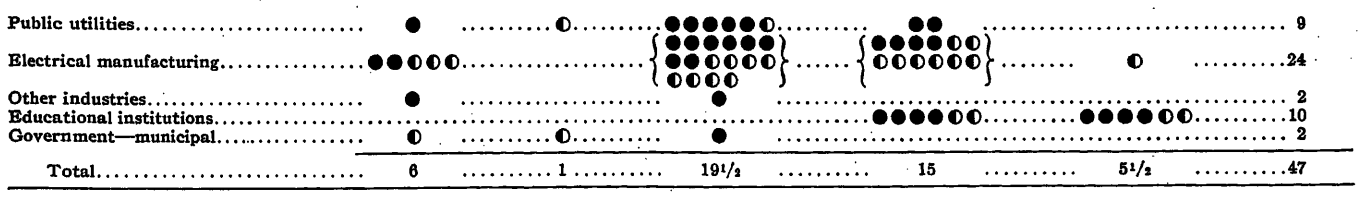
Other things being equal, one would feel justified in expecting that these exceptional young engineers would equal if not exceed the median salaries of the corresponding Eta Kappa Nu alumni. The recent financial unpleasant-

1. Results of the 1923 study appear in *The Bridge of Eta Kappa Nu* for November 1923, and January and May 1924. Note that averages, *not* medians, were used here. The 1930 study is summarized in "Comparison of Engineers' Salaries in 5 Major Industries," by M. S. Mason and J. A. Umhoefer, *The Bridge*, February 1931; a similar summary by the same authors appears in the *Proceedings* of SPEE, volume 39, 1931, pages 723–39.

2. The SPEE study on electrical engineers was published as Bulletin No. 8 of the Investigation of Engineering Education, volume I, pages 368–87. Also, in *The Bridge* for May 1926, H. P. Hammond compares the SPEE and the HKN 1923 salary results in "The Contributions of Eta Kappa Nu to the Investigation of Engineering Education."

3. "Engineering Graduates of Land Grant Colleges and Universities," by D. S. Bridgman, SPEE *Proceedings*, volume 39, 1931, pages 861–8, sets forth the data collected by the United States Office of Education in 1928 on electrical engineering graduates from 4 typical land-grant institutions.

## Table II. Distribution by Types of Work and Industries



| Type of Industry | Type of Work: Administration | Operating | Engineering Development | Research | Instructing | Total |
|---|---|---|---|---|---|---|
| Public utilities | ● | ◐ | ●●●●◐ | ●● | | 9 |
| Electrical manufacturing | ●●◐◐ | | ●●●●●●●●●●◐◐◐◐ | ●●●●◐◐◐◐◐◐ | ◐ | 24 |
| Other industries | ● | | ● | | | 2 |
| Educational institutions | | | | ●●●●◐◐ | ●●●●◐◐ | 10 |
| Government—municipal | ◐ | ◐ | ● | | | 2 |
| Total | 6 | 1 | 19½ | 15 | 5½ | 47 |

● Full time ◐ Part time (assumed half time)

ness, however, has seemingly delayed progress of these engineers, taken as a group, from 2 to 3 years. Somewhat more difficult to explain is the fact that the median of 32 of their starting salaries (nearly all prior to 1929) is only $1,287, lower indeed than those of any of the other studies on figure 2. A partial explanation may be found in the fact that such a preponderant number of the nominees went initially with large electrical manufacturing concerns (see table II). The 1930 Eta Kappa Nu salary study showed this group as receiving the lowest starting salaries, although 10 years later they had caught up with the general average, and thereafter exceeded it.

The problem of evaluating the achievements of so many engineers with such varied interests and activities caused the award organization committee much thought and reflection. The solution seemed to lie somewhere between a consideration of what engineers had probably done and what more they might be doing. After about a year was spent in discussing this basis with numerous leading educators and engineering executives who expressed a considerable interest in the idea, it was finally decided to inaugurate the plan giving a certain weight to nearly every activity a man might have engaged in under the following headings:

(*a*) His achievements of note in his chosen work.
(*b*) What he has done for his community, state or nation.
(*c*) How he has shown his cultural or aesthetic development.
(*d*) His activities in technical societies, and miscellaneous accomplishments, such as athletics, special honors, etc.

The exact weights which were placed on these categories were not decided upon until after reviewing a considerable number of nominees' records, because it was difficult to predict to what extent a group of young engineers might have participated in these various directions. The final weighting suggested by the award organization committee* and accepted for use by the final jury of award was

(*a*)—5 (*b*)—2 (*c*)—1 (*d*)—2

A very careful summary of each man's accomplishment was first made by 2 Eta Kappa Nu committees, and the engineers placed in 3 groups, called *A*, *B*, and *C*, in order to lighten the labor of the jury of award.** Each member of the jury reviewed carefully every one of the 25 nominees who had been placed in the *A* division, while at least one member reported on each of the nominees in the *B* and *C* divisions. Then a comparison of scores rather quickly brought the list down to a relatively small number of eligibles for the recognition honor. After considerable discussion and comparison, the jury selected Frank M. Starr (A'30, University of Colorado, '28) of the General Electric Company at Schenectady, N. Y., to be the first recipient of the Eta Kappa Nu Recognition for Outstanding Young Electrical Engineers. Awards of honorable mention also were given to P. L. Bellaschi (A'29, M'34), E. W. Boehne (A'29), A. C. Seletzky (A'29, M'35), and C. G. Veinott (A'28, M'34).†

Since not all nominees were rated by all members of the jury, it is not practicable to summarize statistically their conclusions—even were it desirable to do so. However, prior to the final jury selections, a fairly detailed analysis of all candidates was made by a committee of Eta Kappa Nu engineers actively interested in the recognition plan, the results of which later tallied very closely with the selections made by the jury of award. A portion of this study covering the 43 of the 47 who returned questionnaires and on whom sufficient information was known for forming relatively reliable ratings is shown in table V. These results, although perhaps not bearing too close analysis quantitatively, are nevertheless thought to be sufficiently revealing qualitatively to indicate quite clearly

## Table III. Age and Year of Graduation

| Age | Year of Graduation (Bachelor of Science Degree): 1926 | 1927 | 1928 | 1929 | 1930 | 1931 | 1934 | Total |
|---|---|---|---|---|---|---|---|---|
| 26 | | | | | 1 | | 1 | 2 |
| 27 | | | | | | 1 | | 1 |
| 28 | | | 1 | 1 | | | | 2 |
| 29 | 1* | | 3 | | 2 | | | 6 |
| 30 | 2 | 4 | 1 | 1 | | | | 8 |
| 31 | 4 | 1 | 1 | | | | | 6 |
| 32 | 4 | 2 | 1 | | 1 | | | 8 |
| 33 | 4 | 3 | | 1 | | | | 8 |
| 34 | 3 | 1 | | | | | | 4 |
| 35 | | 1 | | | | | | 1 |
| Unknown | | | | 1 | | | | 1 |
| Total | 18 | 12 | 7 | 4 | 4 | 1 | 1 | 47 |

* Class of 1926; did not graduate.

* The president of Eta Kappa Nu in the fall of 1935 appointed an award organization committee of R. I. Wilkinson (A'35), *chairman*, O. W. Eshbach (A'17, M'30), E. S. Lee (A'20, F'30, director), H. H. Henline (A'19, M'26, national secretary), and C. A. Faust (A'35) to put the recognition plan into effect.

** The jury of award is appointed annually by the president of Eta Kappa Nu and consists of 2 present or past national officers of Eta Kappa Nu, and 3 or more prominent American educators or industrialists. For 1936 L. W. W. Morrow (A'18, F'25, director), C. A. Butcher (M'22), the late General R. I. Rees, and the late E. B. Meyer (A'05, F'27, past-president) were appointed to serve on the jury; E. S. Lee and R. I. Wilkinson filled the 2 appointments from Eta Kappa Nu ranks.

† Of these 5 men, only one attended a college with a chapter of Eta Kappa Nu; later one other became an associate member of the society.

## Table IV. Annual Salaries

| Number of Years After Graduation | Number of Cases | Annual Salaries in 1936 | | |
|---|---|---|---|---|
| | | Median | Lowest | Highest |
| 0* | 32* | 1,287* | 938* | 2,600* |
| 5 | 1 | 2,400 | | |
| 6 | 2 | 2,704 | | |
| 7 | 2 | 2,880 | | |
| 8 | 7 | 3,300 | 1,900 | 4,800 |
| 9 | 10 | 3,210 | 2,400 | 8,200 |
| 10 | 15 | 3,450 | 2,250 | 5,600 |

* These are starting salaries at whatever year of graduation.

certain characteristics of the most exceptional young American electrical engineers who could be discovered in 1936. It is believed that this is the first of this type of comprehensive study of engineers attempted in this country.

In the first place, it is clear from table V that the nominators selected their candidates mainly by their technical accomplishments. Since this category is given the weight of "5," such a basis of selection would seem to have considerable justification. In several instances, however, those with records of the very highest quality of research work or other scientific contributions ranked near the bottom of one or more of the other classifications, thus drastically bringing down their over-all ratings. The fact that only 11 tallies out of 129 under headings *b*, *c*, and *d* exceeded a "50" rating might mean that either the method of appraisal was too severe, or that the engineers had not entered to any extended degree on pursuits outside of their chosen lifetime occupations. Even in the former event, the wide dispersion of the rankings would indicate that many of these technically proficient engineers had not paid very particular attention to their full professional development.

Correlation studies on the association between the various groups of activities showed positive results in every instance.* Only really significant, however, were the *ac*, *bc*, *bd*, and *cd* coefficients of correlation, ranging from $r = 0.34$ to 0.49. That is to say, although those engineers who participated most extensively in civic and social affairs were but little more distinguished technically than those who did not, their concurrent cultural and miscellaneous outside activities were very much greater. It is a little surprising that degree of technical accomplishment and cultural development (*ac*) should be found so strongly associated while no similar connection was noted between, for instance, technical accomplishment and civic and social work or miscellaneous activities. A most tentative hypothesis which might be advanced to comprehend these observed relationships is that a considerable block of the men with the highest technical achievement had concentrated on their personal advancement and development to the neglect of assuming group responsibilities.

Some have argued that in the early years of his professional career an engineer is, and ought to be, too busy on his technical development to devote much of his energ to other activities. The present study of exception young engineers disputes such a view, indicating instea a slight superiority of technical achievement by those wit considerable extracurricular activity. Partial-correlatic studies also show for those engineers in the upper half ( the rankings for social and civic activity, a marked ass( ciation between technical achievement and cultural de velopment. Thus, as far as these facts go, they woul seem to suggest that exceptional performance in scientifi pursuits need not at all preclude a paralleling develop ment along social and cultural lines.

Just such beliefs that an engineer's "service to mankin( is manifested not only by achievements in purely tech nical pursuits but in a variety of other ways," and tha "an education based upon the acquisition of technica knowledge and the development of logical methods o thinking should fit the engineer to achieve substantia success in many lines of endeavor," prompted Eta Kappa Nu to establish the recognition plan.

When it is considered, that, in the main, electrical engineers are working in large business organizations where their technical opportunities are largely prescribed by their immediate or distant superiors, the remaining activities in which a man engages, most of them voluntarily, are likely to be a considerably more accurate clue than his technical proficiency to his value as a citizen. Table V would seem to bolster the claim often heard these days that engineers have not yet gone very far as a professional group in engaging in more than their narrow technical pursuits.

For the purposes of the Eta Kappa Nu recognition, the rating plan was so devised that an engineer cannot be entirely one-sided and reach the top, nor hardly can he be a "jack of all trades and master of none." A study of the careers of the 5 men selected for honors in the first year of the award will quickly confirm the operation of this design. Biographies in some detail of these men appeared in the January 1937 issue of the Eta Kappa Nu *Bridge*, and somewhat briefer summaries covering their technical achievements were reported in the January 1937

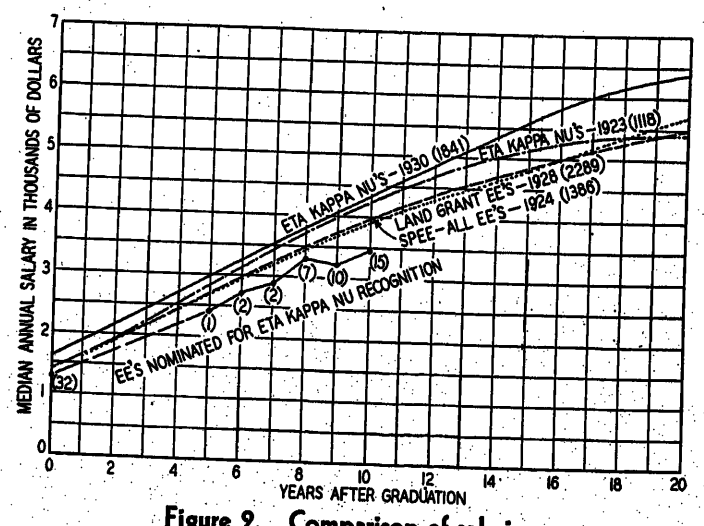



**Figure 2. Comparison of salaries**

Figures in parenthesis show number of returns

* Although the number of "observations" is only 43, still the fact that they are very homogeneous data seems to permit a certain amount of statistical analysis.

issue of ELECTRICAL ENGINEERING. The addresses made by these men at the award dinner, and which in the main gave their views on young engineers, their success and proper attitudes on life, appear in subsequent issues of the *Bridge*. The merest outline of the activities of Frank Starr, the 1936 recognition winner, will indicate the extent to which a young engineer may be expected to enter upon both technical and "extracurricular" work in his first 10 years after graduation:

(*a*) He is the author of 8 technical papers, several presented before AIEE conventions, principally on the theory and practice of electric power distribution. In 1932 he was awarded the Alfred Noble prize of the ASCE for his paper on "Equivalent Circuits." More recently he has been sent by the General Electric Company on a speaking tour of the country, touching practically every city of 100,000 population, discussing design problems with operating and engineering forces of power companies. His papers are used as texts in a number of engineering schools. He holds 2 patents on the control and protection of a-c network distribution systems, with others pending. He has been a lecturer in the advanced course of the General Electric Company for 6 years.

(*b*) He is a member of the Unitarian Church and the Schenectady Y.M.C.A., and has been active in boy-scout work.

(*c*) He has written a number of human interest articles and personal essays; since graduation he has attended classes in economics, psychology, sales analysis, and public speaking; he is an accomplished speaker; he has studied music and harmony, and is accumulating a sizable phonographic library of symphonic and operatic recordings. He is a member of the Schenectady Civic Players Association and has portrayed rôles in several of their amateur productions. He collects rare editions of books, and has read some 230 substantial books in the last 5 years. His main interest is in philosophy, and he follows a systematic reading plan.

(*d*) He is a member of the AIEE and Edison Golf Club, and is listed in "America's Young Men."

The winner of the Eta Kappa Nu recognition receives no monetary prize; presumably he has been successful

**Table V. Rating of Various Activities of 43 Young Engineers**

| | Type of Activity | | | |
|---|---|---|---|---|
| Ratings | (a) "On the Job" | (b) Civic and Social | (c) Cultural Development | (d) Technical Societies, Athletic, Miscellaneous |
| 100 (98) | 1 | | | |
| 95 | 4 | | | |
| 90 | 14 | | | |
| 85 | 8 | | | 1 |
| 80 | 4 | | | 1 |
| 75 | 4 | | | |
| 70 | 3 | | | |
| 65 | 3 | | | |
| 60 | | 2 | 1 | 4 |
| 55 | 1 | | 1 | 1 |
| 50 | 1 | 1 | 4 | 3 |
| 45 | | 4 | | 2 |
| 40 | | 3 | 1 | 3 |
| 35 | | 1 | 3 | 2 |
| 30 | | 4 | 5 | 1 |
| 25 | | 1 | 8 | 5 |
| 20 | | 2 | 2 | 7 |
| 15 | | 6 | 4 | 1 |
| 10 | | 7 | 6 | 7 |
| 5 | | 8 | 4 | 3 |
| 0 | | 4 | 4 | 2 |
| Total | 43 | 43 | 43 | 43 |

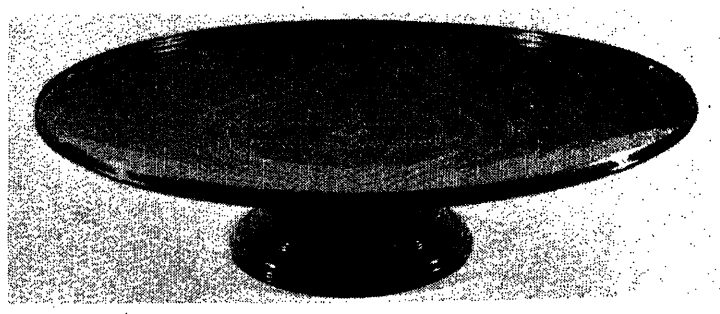


**Figure 3. The bowl for the recognition**

enough that he is hardly in any particular financial need. Rather it was believed that through the careful and scrupulous recognition of a closely limited number of candidates each year, the honor of being selected would be very great, and that as time proceeds its importance will be advanced by the illustrious records of past successful candidates. A large bronze bowl (figure 3) has been subscribed by some 30 Eta Kappa Nu alumni which will remain on permanent display in the AIEE headquarters in the Engineering Societies Building in New York, and each year will have added to its face the name of the recognition winner. The man, or men, so honored will also be presented with a smaller replica of the large bowl. Recipients of honorable mention are presented with a certificate appropriately naming their chief contributions to science and the humanities.

The future success of the Eta Kappa Nu recognition depends in no small measure on the continuing interest of engineering educators in nominating those young electrical engineers whom they believe to be outstanding. The possibility of doing some exceptionally talented young man a good turn, too, may conceivably persuade the faculties of some of our schools to follow more closely the progress of their graduates. It is apparent that in many instances this is being carefully done today; with the growing development of college personnel officers even closer contacts with the alumni may be expected to be maintained.

No less generous has been the response of the hundreds of business and engineering executives who were asked in the capacity of "references" to give their opinions of the qualifications of the nominees in the 4 major categories outlined hereinbefore. In numerous instances presidents and vice-presidents of the companies employing the nominees responded in considerable detail, often adding a personal word of recommendation. Whether or not he receives formal recognition from Eta Kappa Nu, any man nominated can hardly help but benefit from thus being advantageously called to the attention of those higher in his company or organization.

For 1937 the plan has been altered but very slightly. An interesting observation will be whether the scheme has to a detectable degree impelled any of the 1936 nominees who are still eligible for recognition (and are considered to be automatically renominated) to engage more widely in activities suggested by filling out the 1936 questionnaire. Such will be the severest test of the recognition plan.

# Industrial Unit Heaters Cool Transformers

By F. L. MOSER
MEMBER AIEE

H. B. WOLF
ASSOCIATE AIEE

**Unit heaters of the industrial type have been applied for external cooling of transformers and found to be especially useful as a substitute for the original water cooling system or as a supplement to the regular cooling system. Portable substations of smaller size and reduced weight were made possible by the use of these units.**

CHOICE of type of transformers, either self-cooled or water-cooled, in the design of a station is usually a matter of economics. In general, where transformers are small or where cooling water is not available, self-cooled transformers are used; where large transformers are required and water is available, water-cooled transformers are selected. Sometimes, however, conditions change through the years and it becomes desirable or necessary to change a water-cooled transformer to a self- or aircooled type.

Having in mind several stations on the Duke power system where cooling systems would soon require extensive replacement, company engineers made an effort in 1930 to apply external coolers to a transformer. A 1,000-kva 44-kv unit was selected and 2 automobile radiators were connected so that the oil would circulate through them from the top to the bottom of the transformer. Large fans forced air through the radiator fins. The results of this test were not encouraging; and from subsequent tests it was evident that the radiators were too small and that natural convection would not give rapid enough circulation through the radiators and piping.

In the latter part of 1933, the cooling coil in a 1,200-kw transformer at Gaston Shoals plant failed inside the tank. Ordinarily the repair or replacement of such a coil would be a minor job, but not so in this instance. This plant was erected about 1906, and was acquired by the Duke company in recent years. There were 9 1,200-kw transformers installed in a small room having thick stone walls and concrete roof. During the early existence of this plant, apprehension was felt that the transformers might be flooded during periods of high water, and therefore they were jacked up 8 feet and a concrete pier erected under each bank. This brought the tops of the transformers close to the 12-inch concrete roof. In these transformers the core and coil assembly and the cooling coils are suspended from the transformer covers. Therefore, to get at this particular cooling coil would require jacking 2 transformers off their piers and removing a portion of the station wall. It was decided to make an attempt to cool this transformer externally, this time using 2 industrial unit heaters as radiators. The particular units chosen were made of cast aluminum and had a fan mounted directly behind the radiating fins. The oil passed straight through the unit through rather large passages. A small pump circulated the oil from the top of the transformer through the coolers and into the bottom of the transformer tank, as shown in figure 1. Although these 2 units did not provide sufficient cooling to keep the temperature of the top oil within desired limits, the results were quite encouraging, so 2 additional unit heaters were obtained and installed, giving the desired results. This installation is shown in figure 2.

It was observed that with these 4 units in operation the fins of the radiators were cold; in other words, heat was not being transferred as rapidly from the oil to the metal of the radiator as from radiator to air. A study was then made of various types of available unit heaters, and one was found which had small copper tubes having a reverse bend. The intimate contact between oil and the walls of the small tubes, together with the comparatively long path obtained by means of the reverse bend, was believed to make a more efficient cooling unit for this application. One such unit was purchased and installed alongside the 4 cast-aluminum heaters, and on test it dissipated heat at approximately the same rate as the 4 cast-aluminum heaters combined. This test gave a

**Figure 1. Circulation of oil through cooler and direction of air flow**

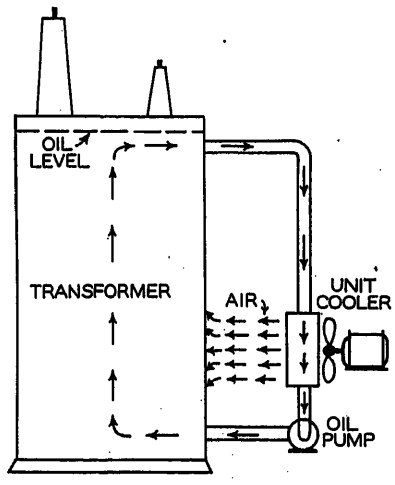
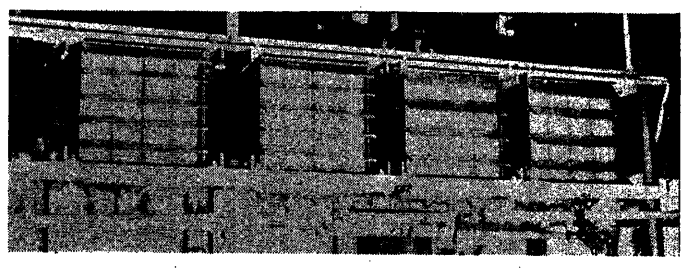



**Figure 2 (below). Cast-aluminum coolers at Gaston Shoals plant**



A paper presented before the AIEE North Carolina Section, February 18, 1937.

F. L. MOSER is superintendent of maintenance, and H. B. WOLF is maintenance foreman, for the Duke Power Company, Charlotte, N. C.

fairly accurate idea of the rate of heat dissipation for this unit. All 5 units have been in service since installation.

The next application of these external coolers was at the Greenville substation. Here, as the result of the combination of loss of efficiency of the cooling coils and severe operating conditions, 2 3,500-kva 100-kv transformers operated at unduly high temperatures. To supplement the existing cooling system, 2 coolers were installed on each transformer, together with a small oil-circulating pump for each pair of coolers. This installation gave entirely satisfactory results. A drop of approximately 15 degrees centigrade in the temperature of the top oil was obtained. On this installation a rate of oil circulation giving a drop of 5 degrees centigrade through the cooler with the top oil at 65 degrees and an ambient temperature of 30 degrees was determined upon. This gave good results and has been used on all subsequent installations.

At the Lakewood station, 12 4,000-kva 100-kv transformers are in service. These transformers, manufactured at the end of the World War when there was a shortage of copper, were equipped with iron cooling coils. That the cooling coils as well as other portions of the cooling system would soon have to be replaced was realized several years ago, and one suggestion was that the transformers be made self-cooled by the application of standard transformer radiators. However, when the manufacturers submitted a price of approximately $50,000, plus an estimated cost of $10,000 for installation expense, this idea was abandoned. In 1935, a test installation of unit coolers was made on 2 transformers, and complete and accurate data were obtained on cooling them without water in the cooling coils. These tests indicated that, with normal load, as shown by figure 6, 4 coolers per transformer would properly cool them; and it was further observed that spraying sufficient water on the radiator fins to keep them wet increased the rate of heat dissipation to such an extent that only 3 coolers per transformer would be required.

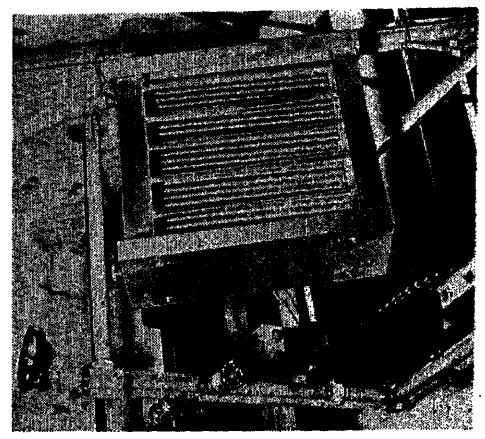


**Figure 5. Copper-tube cooler installed at Gaston Shoals for comparative test with cast - aluminum coolers**

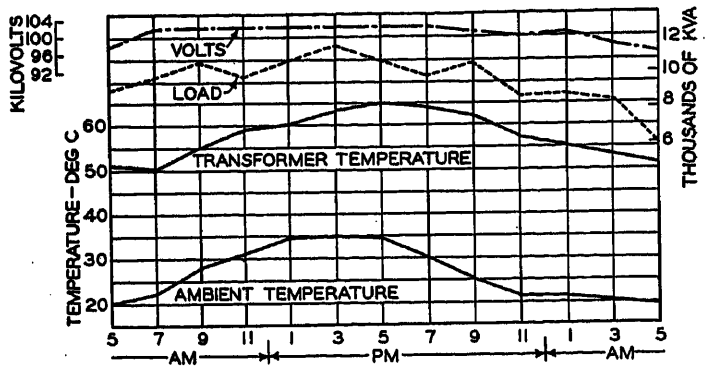



**Figure 6. Chart showing 24-hour test on 4,000-kva transformer, using 3 coolers and water spray**

Kilovolt-amperes in terms of load on bank of 3 transformers

Early in 1936, the cooling reservoir at this station was lost when the dam was washed away. The decision was then made that installing unit coolers on the transformers would cost less than rebuilding the dam. Three coolers per transformer were installed with provision for future installation of a fourth unit should it be found desirable. Two oil circulating pumps per transformer were used.

After the coolers were installed in 1936, various methods of spraying the cooling fins were tried and finally a hollow hub was installed on the fan shaft, which would throw the water radially between the fan and the radiator, and this was found to wet the radiator uniformly with a minimum wastage of water. These hubs were installed on all of the units and properly piped to the city water supply. This spray system gives a reserve to the cooling system which can be used in extremely hot weather or during periods of abnormal load on the transformers. The total cost of labor and material on this installation was under $10,000.

Recently, 3 transformers were moved from Lakewood and installed at China Grove. A fourth cooler was added on each transformer because no water is available at this station for spraying the fins.

Since the Lakewood installation was made, installations have been made on a 1,000-kva transformer to replace old radiators, on 3 1,000-kva transformers to replace

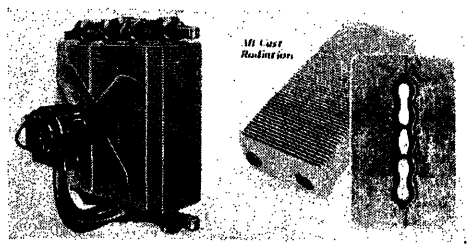



**Figure 3. Details of cast-aluminum coolers**

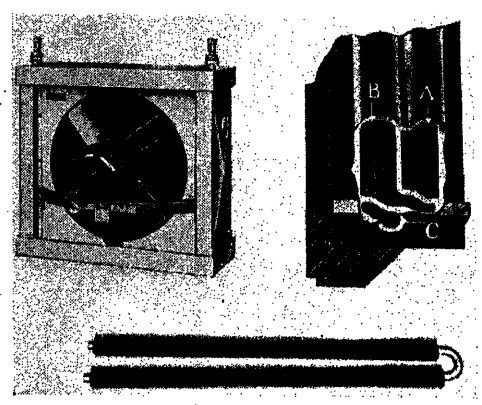



**Figure 4. Details of coolers having copper tubes with a reverse bend**



Figure 7. (left) Coolers at Lakewood station

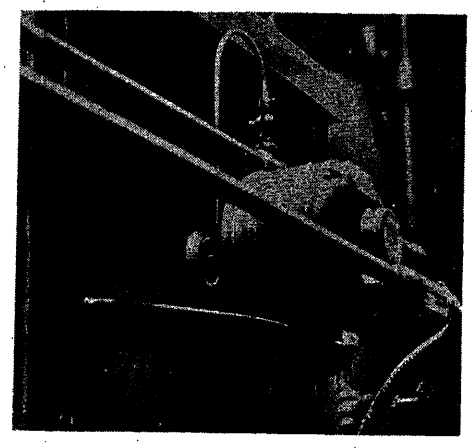


Figure 8. (right) Cooling unit equipped with spray hub

an old water cooling system, and on 3 more 3,500-kva transformers at Greenville to supplement the water cooling system.

A very interesting application is the recent furnishing of 2 1,320-kva portable substations, each equipped with 2 of these coolers by the transformer manufacturer. Not only are these transformer units more compact than those previously furnished, but they also weigh 2,000 pounds less, which is of considerable importance. The importance of keeping the weight of these portable transformers to a minimum can be appreciated when it is realized that these units, 6 in number, are used for backing over 380 banks of transformers having primary voltages of 44, 33, 22, or 13 kv, and secondary voltages of 13.2 kv, 6.6 kv, 2,400 volts, or 600 volts. Many of these are installed in substations located on very poor roads. It is interesting to note that a bank of 3 single-phase self-cooled 55-degree-centigrade transformers to give a capacity of 1,320 kva would weigh approximately 25,500 pounds. By the use of external fans, this weight might be reduced to approximately 21,100 pounds. A standard 3-phase transformer, complete with external fans, would weigh approximately 16,000 pounds. A special portable transformer with tubular radiators, built some time ago, weighs 15,000 pounds plus 6,400 pounds for the trailer, giving a total weight of 21,400 pounds.

The new portable transformer, shown in figure 10, equipped with unit coolers, weighs 13,000 pounds plus 3,000 pounds for the semitrailer, making a total weight of 16,000 pounds. This can be handled readily over almost any road.

The use of external coolers on transformers is not new, but the application of comparatively inexpensive commercial heating units as coolers seems to be an innovation. The principal use would appear to be the substitution in certain instances of this type of cooling for existing water cooling. It also provides a simple and inexpensive method of supplementing existing cooling systems. However, it would probably be wise to consult the transformer manufacturer before making a major change such as replacing an existing cooling system. On new transformers, the most obvious application is on those having space and weight limitations, and on those installed at points where water is not available.

The energy loss of this system is comparable to that of a water cooling system. It is evident that in many instances the first cost and maintenance will be less than with a water cooling system, particularly where reservoirs, cooling towers, or extensive piping systems would be required.

The authors have been informed that the manufacturer of this type of unit cooler, in co-operation with a large electrical manufacturer, has redesigned the unit, using nonrusting parts and improved joints, for this particular application.



Figure 9. Coolers installed on 3 1,000-kva transformers




Figure 10. Portable transformer equipped with 2 coolers

# Heat Transfer Efficiency of Range Units

By W. JAMES WALSH
ENROLLED STUDENT AIEE

**Surface units of electric ranges have various efficiencies of heat transfer according to the design of the unit. Results of a study made with bright- and black-bottomed utensils are reported in this prize-winning student paper.**

THE SUPERIORITY of electric cookery from the standpoint of cleanliness, convenience, and safety has been generally well established. However, the economy of using electricity for cooking depends usually upon 2 factors: (1) the cost of electrical energy, and (2) the efficiency of the equipment employed in utilizing the electrical energy. The results of efficiency tests performed on the surface units of several late-model electric ranges reported in this paper clearly show that there is need for material improvement in the heat transfer efficiency of these units. Since electrical energy can be converted to heat energy with an efficiency of 100 per cent, it is obvious that efficiencies ranging between 50 and 68 per cent, the values found for modern units, are far too low.

The methods employed in determining the heat transfer efficiency of the several units, the results obtained, and several suggestions for possible improvement are presented in this paper.

## Selection of Units for Test

Since it was desired to conduct the proposed tests on the selected surface units with the units mounted in the ranges for which they had been designed and as they would be used in actual practice, it was decided to obtain 3 complete, late-model, electric ranges for which the popular demand had been greatest. When the selected ranges were delivered, it was found that but 4 of the 12 surface units furnished with the ranges were of the same wattage. Fortunately, however, 4 different types of surface units were exemplified by the 4 units having the same rating of 1,200 watts. It was therefore decided to perform the proposed tests on these 4 units. The units selected for test are shown in figure 1. For purposes of identification, the units have been labeled, as indicated in figure 1, *A*, *B*, *C*, and *D*, and will be referred to by these symbols.

## Measurement of Energy Input to Test Units

In any efficiency test, it is necessary to determine the energy input to the energy-converting device, and the corresponding energy output. In this case, determination of the energy input to the surface units under test, because of the ease and accuracy with which electrical energy may be measured, presented little difficulty, it being merely necessary to select a suitable type of watt-hour meter. The meter selected for use in these tests was a standard instrument of the rotating type commonly used in the calibration of ordinary watt-hour meters. Prior to its use in the tests, the rotating standard was checked for accuracy against a laboratory standard watt-meter and stop watch.

The heat energy equivalent of the electrical input to the units, in calories, is, of course, simply the number of revolutions completed by the disk of the rotating standard multiplied by a suitable constant. However, the standard watt-hour meter was so connected that it not only measured the energy input to the unit under test, but also measured the energy consumed in its own potential circuit and that consumed in the voltmeter employed in measuring the constant alternating voltage applied to the terminals

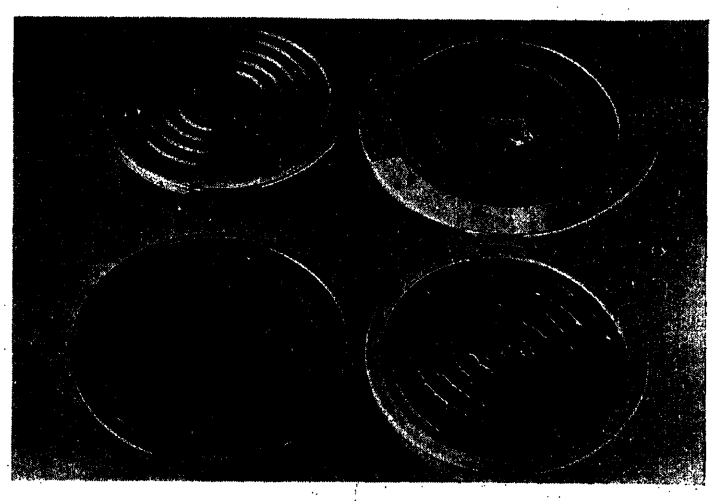


**Figure 1. Four types of 1,200-watt units tested**

Upper left—Unit *A* Upper right—Unit *B* Lower left—Unit *C* Lower right—Unit *D*

of the unit. The energy consumed in the potential circuit of the watt-hour meter was found to be negligible, but that consumed by the voltmeter was appreciable, so that a correction for it was deemed necessary. It may also be noted that the voltage applied to the units under test

A paper presented at a joint meeting of the Portland Section and the Oregon State College Branch, Corvallis, Ore., May 16, 1936, and subsequently awarded the Institute's 1936 Branch paper prize; recommended for publication by the AIEE committee on award of Institute prizes. Manuscript submitted February 15, 1937; released for publication June 10, 1937.

The author is indebted to the General Electric Company, the Westinghouse Electric & Manufacturing Company, and the Malleable Iron Range Company for the use of the electric ranges and elements studied in this investigation. Lee Bennett of the Mountain States Power Company was actively interested in the project and assisted in securing the equipment for test. The utensils used were furnished by the Aluminum Company of America. Much valuable assistance in conducting the tests was rendered by W. Arno Gish and Charles H. Butler. The author would also like to express his appreciation to Professor F. O. McMillan of the electrical engineering department of Oregon State College who suggested the subject and offered many valuable and helpful suggestions throughout the investigation.

was measured at the terminals of the units, so that no correction for losses occurring in the range wiring needed to be applied to the watt-hour meter reading.

The energy input to the unit under test at time $t$ seconds from the start of the test may then, taking into account the energy consumed by the voltmeter, be expressed as follows:

$$W_t = 860.4\left(K_h R - \frac{E^2 t}{3{,}600 r}\right) \qquad (1)$$

in which $W_t$ is the energy input to the unit in calories, $K_h$ is the disk constant of the watt-hour meter in watt-hours per revolution, $R$ is the number of revolutions completed by the disk of the watt-hour meter in the $t$ seconds which have elapsed since the start of the test, $E$ is the effective value of the alternating voltage maintained constantly at the terminals of the unit, $r$ is the resistance of the voltmeter in ohms, and $t$, as previously indicated, is the time in seconds which have elapsed since the test was started.

## Determination of Energy Transferred by Surface Units

While the determination of the energy input to the surface units was found to be a very simple matter, the measurement of the corresponding useful energy transferred by the unit was, in comparison at least, a much more difficult problem. Several methods of determining this essential quantity were considered. One of these entailed the use of a mass of some metal such as copper or iron with the use of thermocouples as the temperature-measuring device. It was decided, however, that the tests would be much more representative if a water-filled utensil of a type ordinarily used on the units in practice was employed. This further had the added value of presenting temperature differences between the unit and the substance being heated more commonly encountered in actual practice.

The suitability of several liquids other than water as the liquid to be heated was also investigated. The few



**Figure 2. Aluminum pans used in the tests**

liquids having suitable characteristics, however, either proved too costly, were not readily available, or information concerning the behavior of their specific heats over the temperature range to be covered was either very uncertain or apparently nonexistent.

Having decided that an ordinary kitchen utensil filled with water would be used as the receiver of the useful energy transferred by the units under test, there remained other items to be considered, such as the type of utensil to be used, and the means to be employed in measuring the temperature of the water. Since aluminum utensils have been widely used in recent years, 2 2-quart vessels of that material were selected. The 2 utensils selected were identical in size and shape, but the bottom of one had the usual bright finish, while that of the other was blackened with a lacquer-like material. The 2 pans are shown in figure 2 with handles removed as they were used in the tests. Another view of the same utensils showing the character of their bottoms is shown in figure 3.

Several factors other than their popularity were also instrumental in the selection of the aluminum utensils. In the first place, aluminum is a material of low specific heat and high heat conductivity, which means, as will develop later, a minimum of error in the computation of the energy transfer of the test units. In the second place, since the sides of the utensils are highly polished, radiation losses from the utensil will be a minimum, which also aids in reducing the error in the computation of the heat energy transferred by the units. Lastly, the aluminum utensils used were designed especially for electric range surface use.

One of the most important items in the determination of the heat transferred by the units is the method of measuring the temperature of the water contained in the aluminum vessels. Previous investigators have employed ordinary mercury-in-glass thermometers or thermocouples. Both of the latter methods give temperature indications at one or more points in the liquid dependent upon the number of



**Figure 3. Bottoms of pans, showing bright and black surfaces**

such instruments used. The temperature of the water in the vessel cannot be the same throughout its volume, because of the convection currents which are readily discernible in it. Therefore, a device capable of indicating an average of the temperatures existing throughout the volume of the water gives much more representative temperature values. It was therefore decided to construct a resistance thermometer with the resistance element spread out over a considerable cross section of the water volume. The resistance thermometer constructed is shown in figure 4. The light framework is of bakelite, and the resistance element is a number 40 American wire gauge nickel-alloy wire expressly made for the purpose. The fineness of the wire and its high resistance per unit length (16 ohms per foot) make it very sensitive to changes in temperature. Another desirable feature of the resistance thermometer is its extremely short time lag in comparison with the long time lag of a mercury-in-glass thermometer.

The resistance thermometer was calibrated with a mercury-in-glass thermometer by immersing both in a constantly stirred transil-oil bath, the temperature of which

was changed very slowly. Several points on the calibration curve obtained were checked by immersing the resistance thermometer in liquids, the boiling points of which were accurately known. It was found that the resistance of the thermometer was not a linear function of temperature, but followed a law of the form

$$\log r = a + bT$$

where $r$ is the resistance in ohms at the temperature $T$ degrees centigrade, and $a$ and $b$ are constants. In this case, $a$ had the value 2.162, and $b$ the value $9.92 \times 10^{-4}$.

By means of the resistance thermometer, it is possible to determine the temperature of the water at any time $t$ seconds from the start of the test, and, from the temperature measurements, the heat transferred from the unit to the utensil and water may be calculated by employing the following equation:

$$W_o = (w + c_{Al}w_{Al})(T_t - T_o) \qquad (2)$$

in which $W_o$ is the heat energy in calories transferred by the unit, $w$ is the weight of the water used in grams, $c_{Al}$ is the mean specific heat of aluminum in calories per gram per degree centigrade ($c_{Al} = 0.217$), $w_{Al}$ is the weight in grams of the aluminum pan used, $T_t$ is the temperature of the water in degrees centigrade at time $t$ seconds from the start of the test, and $T_o$ is the temperature of the water at the start of the test in degrees centigrade.

The specific heat of water departs so slightly from unity over the range from 20 to 100 degrees centigrade, the temperatures encountered in the tests, that it is impractical, in view of other limits of measurement, to consider it other than unity. The same statement may be applied to the specific heat of aluminum. It will further be noted from equation 2 that it is assumed that the aluminum pan experiences the same temperature change as the water. This, of course, is not strictly true, especially as regards the bottom of the pan. However, since the specific heat and weight of the aluminum pan are small compared to the corresponding values of the water used, and since the heat conductivity of aluminum is so very high, the error resulting from this assumption is negligibly small.

It will be noted further that equation 2 does not account for any heat transfer between unit and utensil represented by possible evaporation of water. This is permissible because special precautions were taken to greatly minimize evaporation. Normally, of course, the evaporation of water below the boiling point represents a heat transfer which is not negligible. The amount of heat transfer represented by evaporation at any particular temperature, however, is very difficult to determine because of the variation in the rate of evaporation and the heat of evaporation with temperature. It is, therefore, imperative that evaporation be reduced to a negligible quantity.

It was found possible to do this by forming a thin film of a low-vapor-pressure oil over the surface of the water just prior to starting the tests, and by halting the tests at temperatures slightly below the point at which violent ebullition of the water began to take place. The success of this method is attested by the fact that the upper portions of the temperature-time curves remained straight after its adoption, where previously they had tended to curve to the right due to the evaporation loss. The loss of water by evaporation was reduced from approximately 7 per cent to 0.5 per cent, which made the evaporation heat loss negligible up to the boiling point.

## Calculation of Efficiencies of Heat Transfer

The efficiency of any piece of apparatus is defined as the amount of energy delivered by the apparatus expressed as a percentage of the energy delivered to it. Since the necessary values of energy input to, and heat transfer from, the surface units tested have been determined, it is now possible to calculate an efficiency of heat transfer for the units. This value may quite obviously be obtained by dividing equation 1 into equation 2, and may be expressed as follows:

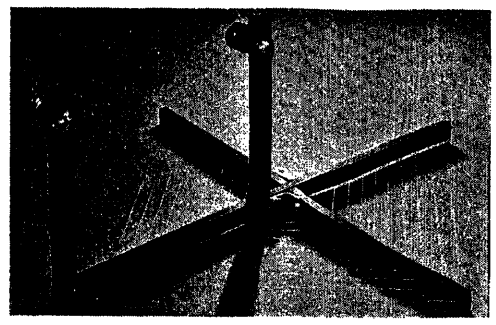


**Figure 4. Frame and wire for resistance thermometer**

$$\eta = 100\left(\frac{W_o}{W_t}\right) \qquad (3)$$

in which $\eta$ is the efficiency of heat transfer of the unit in per cent, $W_o$ is the heat energy transferred by the unit in calories up to, and including, the time $t$ seconds which have elapsed since the start of the test, and $W_t$ is the energy input to the unit in calories during the same time interval.

While the efficiency defined in equation 3 is important, because it is a direct measure of the amount of useful energy transferred by a given unit, it is taken over time intervals measured successively from the origin, and hence gives no clue as to the efficiency with which the unit is transferring heat energy to the utensil and water at any particular instant. The instantaneous efficiency of heat transfer may, however, be obtained by plotting energy output $W_o$ values against energy input $W_t$ values, and determining the slope at various points along the resulting curve. The values of elapsed time corresponding to the several slope values may be easily obtained by reference to a curve of elapsed time values plotted against corresponding energy input $W_t$ values. Mathematically, of course, the instantaneous efficiency may be indicated simply as follows:

$$\eta_t = 100\,\frac{dW_o}{dW_t} \qquad (4)$$

in which $\eta_t$ is the instantaneous efficiency of heat transfer in per cent.

Fundamentally, the instantaneous efficiency, $\eta_i$, is the quotient of 2 time rates, that is,

$$\eta_i = 100 \frac{\frac{dW_o}{dt}}{\frac{dW_i}{dt}} \qquad (5)$$

and when expressed as such is, perhaps, more capable of complete understanding. When expressed as indicated in equation 5, the instantaneous efficiency simply expresses the fact that the instantaneous rate at which useful energy is being transferred by a given surface unit is a certain percentage of the rate at which energy is being supplied to the unit.

The meaning of the 2 efficiencies defined by equations 3 and 4 may, perhaps, be made clearer by comparing them with the 2 efficiencies of, say, a power transformer. The efficiency defined by equation 3 is comparable with the over-all or all-day efficiency of the transformer, while that defined by equation 4 is comparable with the efficiency of the transformer at any particular load or instant during the day. Because of the similarity of the efficiency defined by equation 3 to the over-all or all-day efficiency of the transformer, it has been termed the over-all efficiency of the surface units, and will be referred to as such to distinguish it from the instantaneous efficiency.

## Experimental Procedure

The surface unit to be tested was in each case placed in the range for which it had been designed, connected as it would be in actual use, and the range then connected to a 3-wire a-c system, the voltage of which could be readily controlled. The instrument leads from the voltmeter and the potential circuit of the watt-hour meter were connected directly across the terminals of the test unit, so that the watt-hour meter readings would not include the losses occurring in the range wiring or the current circuit of the watt-hour meter.

In each case, rated voltage, that is, the value of rated voltage required to give rated wattage, was maintained constant at the terminals of the test unit. In order that the voltage at the terminals of the unit should be very close to its rated value at the instant the test unit circuit was closed, the voltage of the supply source was adjusted to a value slightly higher than the rated value previous to starting the test. The requisite supply voltage value was determined by previous experiment.

The following procedure was employed in determining the efficiency values for the 4 1,200-watt surface units tested. The identical procedure was used for all units with both bright- and black-bottomed aluminum pans.

The resistance thermometer was placed in the particular pan to be employed, and the utensil then placed upon one pan of a beam balance, and the combined weight noted. The usual amount of water, 1,250 grams, was then admitted to the utensil, care being taken to see that no drops of water were splashed on the exterior of the pan or the balance. Then, with the pan still upon the balance, a thin oil film was formed over the water surface by dropping a slight amount of apiezon oil on it from a dropper. The weight of the oil thus added was found to be insignificant. The utensil was then removed from the balance, and carefully centered over the particular unit to be tested. Connection of the resistance thermometer to a precision bridge was then made, after which the thermometer was carefully centered in the pan, and the bridge balanced. No lid was employed in any of the tests.

Then, with the bridge balanced, the supply circuit was closed on the test unit, not by means of the unit switch on the range, which was in all cases left on "high" during the tests, but by means of a knife switch in the supply lines. A stop watch was started at the instant the switch was

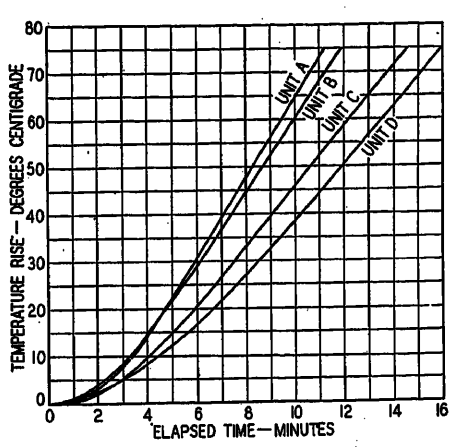



**Figure 5. Temperature rise of water in bright-bottomed aluminum pan placed upon several types of 1,200-watt electric-range surface units**

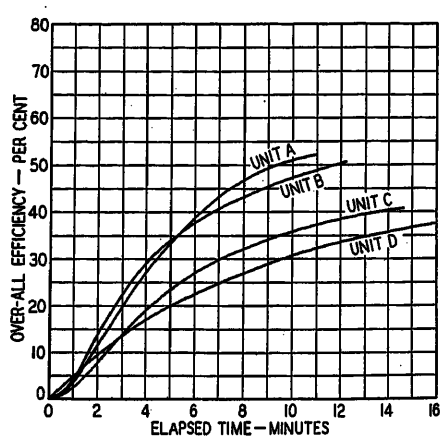



**Figure 6. Over-all efficiency of several types of 1,200-watt electric-range surface units when used with a bright-bottomed aluminum pan**

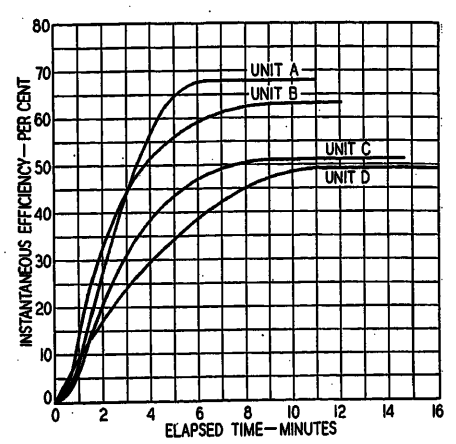



**Figure 7. Instantaneous efficiency of several types of 1,200-watt electric-range surface units when used with bright-bottomed aluminum pan**

Units at room temperature at start of test. Weight of water used, 1,250 grams (2.76 pounds); weight of pan, 418.8 grams (0.92 pound)

closed. Thereafter, at a signal from the observer operating the bridge, indicating that the bridge was in balance, simultaneous readings of elapsed time, revolutions of the watt-hour meter, and resistance of the resistance thermometer were noted and recorded.

Each test run was halted at a point slightly below the boiling point corresponding to barometric conditions prevailing at the time of the test. When the selected final temperature was reached, the test unit circuit was opened, the stop watch stopped, and the utensil removed from the unit. As soon as possible after removing the utensil from the unit, a well-fitting lid was placed on the utensil, and the utensil and contents weighed to determine what loss in weight, if any, had taken place. If an unusually large difference existed between the original and final weight values, the test was in all cases repeated until the difference was brought to within 0.5 per cent.

## Results

The results obtained from the data secured in the tests are presented in curve form in figures 5, 6, 7, 8, 9, and 10. Figures 5, 6, and 7, as indicated, are from data obtained on the test units using the bright-bottomed aluminum pan, while figures 8, 9, and 10 give corresponding values for the same units using the black-bottomed aluminum pan.

## Discussion of Results

An examination of figures 5 and 8 shows that the temperature rise of the water becomes a linear function of the elapsed time after a certain time interval. It follows, therefore, that the heat energy transferred by each unit also becomes a linear function of the elapsed time, and hence a linear function of the energy input to the heating unit, since the energy input is directly proportional to the elapsed time. Over the linear range, the heat energy, $W_o$, transferred by the unit may be expressed as follows:

$$W_o = cW_i - d \tag{6}$$

in which $c$ and $d$ are constants. If now both sides of equation 6 are divided by $W_i$, the following result is obtained:

$$W_o/W_i = c - d/W_i \tag{7}$$

The left-hand side of equation 7 will be immediately recognized as the over-all efficiency of the unit, $\eta$. Hence, equation 7 may be written,

$$\eta = c - d/W_i \tag{8}$$

Now, as time, and consequently $W_i$, increases, it is seen that the over-all efficiency approaches, as a limiting value, the constant $c$ in equation 8. Examination of figures 6 and 9 demonstrates that the over-all efficiency does tend to approach certain limiting values in both cases.

Now differentiate equation 6, obtaining the result,

$$dW_o/dW_i = c \tag{9}$$

The left-hand side of equation 9 is, of course, the instantaneous efficiency of the unit, $\eta_i$. Hence, over the linear portion of the curve,

$$\eta_i = c \tag{10}$$

and the instantaneous efficiency curves should become straight lines parallel to the time axis. Examination of figures 7 and 10 shows that such is the case.

The following deduction may now be drawn from a consideration of the preceding discussion and a critical examination of equations 8 and 10. When any of the surface units tested is used as previously indicated in this paper, the over-all efficiency of the unit approaches a limiting value which is identical with the maximum value attained by the instantaneous efficiency of the unit. The importance of the above statement may be made clearer by considering the fact that, under the condition stated, units

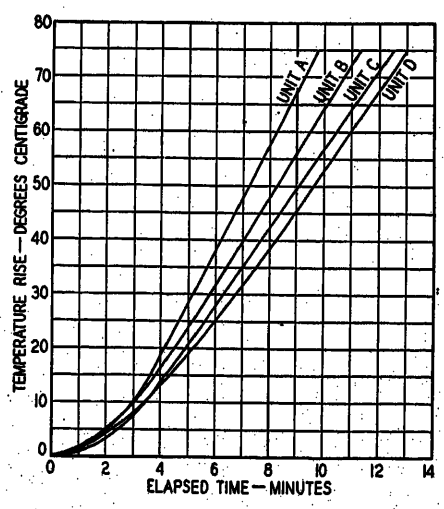



**Figure 8. Temperature rise of water in black-bottomed aluminum pan placed upon several types of 1,200-watt electric-range surface units**

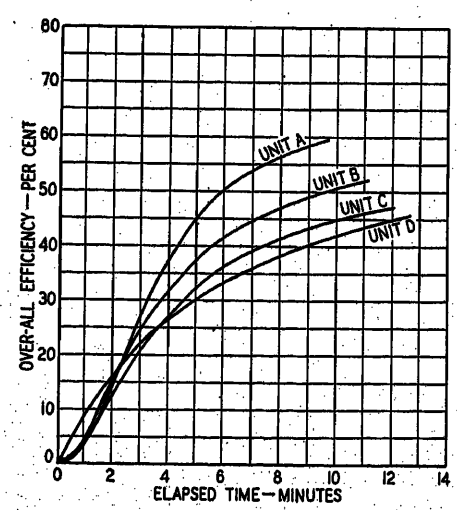



**Figure 9. Over-all efficiency of several types of 1,200-watt electric-range surface units when used with a black-bottomed aluminum pan**

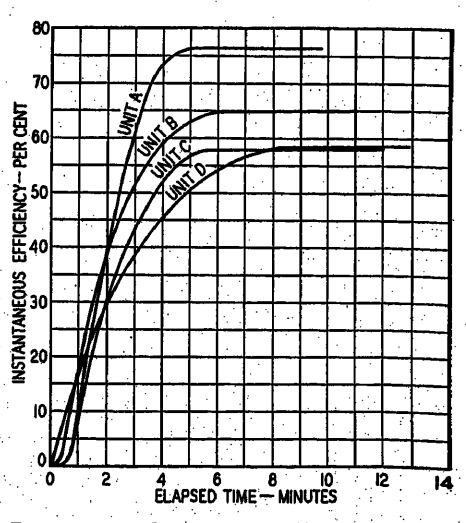



**Figure 10. Instantaneous efficiency of several types of 1,200-watt electric-range surface units when used with black-bottomed aluminum pan**

Units at room temperature at start of test. Weight of water used, 1,250 grams (2.76 pounds); weight of pan, 430.5 grams (0.95 pound)

such as $A$ and $B$ can never transfer more than approximately 65 per cent of the energy they consume, and units such as $C$ and $D$ can transfer only about 50 per cent of their energy input when, as is usually the case, bright-bottomed pans are used.

It may be seen from figure 10 that if a black-bottomed pan is used, approximately 76 per cent of the energy consumed by unit $A$ may possibly be realized. It may further be noted that but a small increase in the percentage of energy realizable is obtained by using the black-bottomed pan with such a unit as $B$. For units such as $C$ and $D$, it is seen, the percentage of consumed energy which may possibly be realized if the black-bottomed pan is used is approximately 58 per cent, which may be compared with the value of 50 per cent possible with the same units using the bright-bottomed pan. The magnitude of the increase in efficiency to be obtained by the use of a black-bottomed utensil is shown in table I.

As is to be expected, the open-coil type unit $D$ has the largest percentage increase in instantaneous efficiency. This is because this unit transfers heat chiefly by radiation, and the efficacy of the black-bottomed pan lies in the fact that a black surface is a more efficient absorber of radiant energy than other types of surfaces.

## Suggestions for Possible Improvement

*Unit A.* The already relatively high efficiency of this unit is due to the small amount of mass in the regions of high temperature, the use of a surface beneath the unit for reflecting the radiant energy directed downward by the unit, and the opportunity provided for air convection currents to pass easily from the lower surfaces of the heating elements to the bottom surface of the utensil. However, since this unit is constructed by spiraling lengths of circular tubing containing the heat-developing resistance, there is at best a series of line contacts between the heating element and the utensil. Irregularities in the units introduced by warping reduces the line contacts between unit and utensil to a series of point contacts, which permits but a very small amount of heat transfer by conduction to take place from the unit. The efficiency of this unit would undoubtedly be much improved if the upper surfaces of the heating element tubes were flattened, and if the tubes were so mounted that the flat surfaces would remain in the same plane. Some improvement in efficiency would also be expected if the reflector plate placed beneath the heating element was treated with a reflecting surface which would not be destroyed by the heat of the unit.

*Unit B.* This unit ranks second in efficiency, and is quite well designed for transferring heat to a utensil by thermal conduction. The surfaces of the heating elements are flat, and are rigidly supported to prevent warping. The mass of this unit could probably be reduced to some extent by a reduction in the size of the cast iron supporting structure, and the heat transfer efficiency of the unit improved by operating it at a higher temperature in order to obtain more heat transfer by radiation. The relatively small amount of heat transferred through the medium of radiation by this unit is shown by the fact that its instantaneous efficiency was increased but 2.8 per cent by using the black-bottomed utensil.

**Table I. Influence of Utensil Bottom Finish on Efficiency**

| Unit | Maximum Instantaneous Efficiency (Per Cent) | | Increase (Per Cent) |
|---|---|---|---|
| | Bright Bottom | Black Bottom | |
| *A* | 68.1 | 76.4 | 12.2 |
| *B* | 63.3 | 65.1 | 2.8 |
| *C* | 51.3 | 57.8 | 12.7 |
| *D* | 49.2 | 58.5 | 18.9 |

*Unit C.* The efficiency of this unit would undoubtedly be greatly improved if the surface it provides for the utensil to rest upon was flattened to increase the amount of heat transferred by conduction. As the unit is constructed at present, heat transfer from it to the utensil takes place largely through radiation as is shown by the 12.7 per cent increase in instantaneous efficiency secured by the use of the black-bottomed utensil. A reduction of the mass of material subjected to high temperatures would, no doubt, also improve the efficiency of the unit.

*Unit D.* The transfer of heat from this open-coil type of unit takes place almost exclusively through the medium of radiation. The character of the utensil bottom, therefore, has a marked influence on the efficiency of heat transfer of the unit. This is clearly shown by the 18.9 per cent increase in instantaneous efficiency secured through the use of the black-bottomed utensil. Not a great deal can be done to increase the efficiency of this type of unit through changes in construction, except, perhaps, changes in the form of the ceramic used to support the heating coils made possible by future research in the ceramics field.

## Conclusions

1. There is very definite need for marked improvement in the heat-transfer efficiency of electric range surface units.

2. When used under the conditions outlined in this paper, the efficiency of heat transfer of each unit approaches a limiting value which it cannot exceed.

3. A very definite increase in the limiting value of the heat-transfer efficiency of a given unit, used with a bright-bottomed pan, may be obtained by using a black-bottomed pan.

4. The percentage increase in efficiency obtained by employing a black-bottomed utensil is greatest for those units depending principally upon radiation as the medium of heat transfer.

5. The enclosed type of surface unit, in general, is superior to the open-coil type of unit.

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# Present-Day and Probable Future Electrical Applications in Aircraft

By W. V. BOUGHTON

THE ELECTRICAL system plays a very important part in present-day airplanes. In addition to lighting the plane and starting the engines, it is required to furnish power for radio, instruments, landing gear, flaps, and remote operations. The fact that electrical operation leads to more convenient and often lighter installations makes it desirable to use it whenever applicable.

A description of the electrical installation in the Douglas sleeper transports appears to present the best way of explaining present-day electrical applications in aircraft.

The airplane is wired in 2 main feeder circuits with the intermittent and continuous loads so divided that the total drain on each circuit is approximately equal for a given period. This is approximately as follows:

CIRCUIT NUMBER 1

| | |
|---|---|
| Interior lights | 408 watts |
| Navigation and passing light | 48 watts |
| Deicers | 48 watts |
| Argon lights | 36 watts |
| Maximum continuous load | 540 watts |
| One landing light | 444 watts |
| Cigarette lighter | 60 watts |
| Seat belt signs | 25 watts |
| Maximum intermittant load | 529 watts |

CIRCUIT NUMBER 2

| | |
|---|---|
| Cockpit and instrument lights | 32 watts |
| Electrical instruments | 16 watts |
| Airspeed head heater | 75 watts |
| Landing gear signal lights | 13 watts |
| Radio receivers | 120 watts |
| Maximum continuous load | 256 watts |
| Landing gear warning horn | 60 watts |
| Fuel and oil-pressure warning lights | 13 watts |
| One landing light | 444 watts |
| Radio transmitter | 890 watts |
| Maximum intermittent load | 1,407 watts |

The initial load on starting is about 2,520 watts for each engine dropping almost immediately to about 1,935 watts. This is usually carried by the battery cart at the airport. Each circuit is supplied from a 12-volt 85-ampere-hour storage battery and a 50-ampere 14.5-volt constant-potential generator, driven by the airplane engines. In case of mechanical or electrical failure of one source of supply, either or both circuits can be switched to either battery and generator. A remote-controlled master switch enables the pilot to open the battery circuits instantly in an emergency and also to connect the airplane circuits to a receptacle in the side of the fuselage for plugging in a battery cart while at the air terminal. This permits the use of the electrical equipment in the plane before taking off, without running down the batteries. The entire system is single wire with the metal airplane structure as the return.

The batteries are located in the fuselage in tight compartments, the bottoms of which are platforms mounted on telescoping tubes. When these platforms are lowered the batteries can be placed on them from the outside of the airplane, and, when raised into place the batteries are automatically connected into the circuits by means of plug- and jack-type connectors. As it is possible to change them by this method in less than 3 minutes, no delay in the departure of the plane would be occasioned because of the necessity of installing a fully charged battery.

The main electrical distribution box is located adjacent to the batteries and contains the master switch, circuit-selector switches, generator-control boxes, starter relays, landing-light relays, meter shunts and resistors, and individual circuit fuses. These are readily accessible in the air or on the ground.

Located above the windshield in the pilot's cockpit are the various switches for lights, ignition, starting, airspeed head heater, seat belt warning signs, and the meters in the generator circuits. Below the windshield is the instrument panel with the navigation and engine instruments. On this panel are located the landing gear warning lights, the door-open warning light, the airspeed head heater warning light, the fuel- and oil-pressure warning lights, the co-pilot-to-stewardess call light and button, and a number of electrically operated instruments.

In large airplanes, the use of mechanical tachometers, capillary tube thermometers, and mechanical fuel-quantity gages is impractical. These instruments are electrically operated in the Douglas sleeper transports. The tachometers consist of small magneto generators mounted on and driven by the airplane engines. The voltage output varies directly with the speed and the indicators in the cockpit are calibrated to read directly in revolutions per minute. The electric thermometers which are used to measure the temperature of the incoming carburetor air and the incoming oil are of the resistance bridge type. The fuel-quantity gauges consist of potentiometers with the moving arms actuated by the tank floats and voltmeters calibrated in gallons to measure the voltage drop through the resistances.

The cockpit is lighted by small automotive-type instrument lamps and 2 small spot lights with universal mountings. In addition 2 argon lamps are located so as

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**Figure 1**

to provide ultraviolet fluorescent illumination of the instrument dials for night flying when general illumination in the cockpit would be undesirable. These argon lights are supplied by a small rotary converter delivering 110 volts. The degree of illumination from all cockpit lamps is controlled by rheostats.

The front passage to the cabin, the cabin itself, the dressing rooms, lavatories, and rear compartments are lighted by ceiling lights. In addition, there is a reading light by each seat, a reading light for each upper berth and provision for plugging in a table light in each section. Located near the aisle floor are small night lights for use after the passengers retire.

Each seat and each berth has a push button to call the stewardess. Each station has a small light and colored jewel, visible from either end of the aisle to indicate the origin of the call. When the button is pushed, a buzzer sounds at the stewardess' station and the light at the calling station comes on and locks on electrically through a relay. The light is reset with a switch at the stewardess' station. An electric sign for use during landing and taking off is located at each section. It is controlled by the pilot and bears the wording "No Smoking. Please Fasten Seat Belts."

The airplane is equipped with a radio receiver and transmitter for 2-way communication with the ground, a radio beacon receiver for use with the beam transmitted by the Department of Commerce stations located along the airways and an auxiliary stand-by receiver. The transmitter is rated at 50 watts output and both it and the 2-way receiver are designed for continuous wave, interrupted continuous wave, and phone. The filaments of all the radios are supplied directly from the 12-volt system and the plate circuit is supplied from dynamotors operating from the 12-volt supply. Small batteries are carried for the emergency operation of the stand-by receiver. Two jacks, located in the side of the fuselage at the battery cart receptacle, provide means for plugging in a telephone set to communicate from the field to the pilot's cockpit before taking off. An interphone system between the cockpit and the cabin permits the stewardess to communicate with the pilot and co-pilot. Radio wiring and equipment weights are about as follows:

| | |
|---|---|
| Transmitter and receiver for 2-way communication | 71 pounds |
| Beacon receiver | 23 pounds |
| Auxiliary stand-by receiver | 18 pounds |
| Transmitting dynamotor / Receiving dynamotor | 47 pounds |
| Emergency batteries | 12 pounds |
| Conduit | 15 pounds |
| Junction boxes, brackets, and supports | 36 pounds |
| Wiring | 14 pounds |
| Total | 236 pounds |

For night flying, navigation lights are located on the wing tips and the rear of the fuselage. A landing light is located in the leading edge of each wing outboard of each engine nacelle and a red passing light is incorporated in the left-hand landing light. These landing lights are equipped with 12-volt 35-ampere bulbs which, because of their rather high design factor of 25 lumens per watt, have a life of only 100 hours.

In each engine nacelle, or on each engine, are mounted the carburetor air-temperature resistance bulb, oil temperature-resistance bulb, engine-temperature thermocouple, tachometer generator, 12-volt generator, starter, magnetos and booster coil, and exhaust-gas analyzer cell. The engine section wiring is connected into plugs at the firewall to permit rapid disconnection for engine change This helps to reduce maintenance delays in schedules.

Other electrical applications encountered in aircraft are electromechanical or electrohydraulic operation of landing gear and flaps. Deicing of wings and tail surfaces is accomplished by inflating and deflating rubber strips along the leading edge. The valve which controls this is electrically driven as is the pump which delivers alcohol to the propellers and carburetors for ice removal.

The wire used in these airplanes is in accordance with the United States Army Air Corps specifications. It consists of a multistrand flexible conductor, insulated with 2 layers of varnished cambric and a lacquered, woven cotton braid. This type of wire weighs less than rubber insulated wire and has a smaller outside diameter, permitting the use of smaller conduits

Because of the necessity for reliable radio operation, it is essential that all radio interference arising from the operation of the airplane be kept to the absolute minimum. The proximity of the antenna to the possible sources of interference makes it necessary to completely enclose every portion of the electrical system in a tight electrostatic shield, thoroughly bonded at frequent intervals to the airplane structure. This is accomplished by using a metal conduit and junction-box system and enclosing all equipment which is not inherently shielded by its construction, in shielding boxes. Aluminum and aluminum alloys are used for this purpose. The radio wiring is isolated from the main wiring by installing it in a separate conduit sys-

tem. The question of adequately shielding electrical equipment is one which the entire electrical industry may have to face in the near future, especially when television comes into general use.

Bonding consists of connecting electrically all metal parts of an airplane. Its purpose is: To increase the capacitance between the airplane and the radio antenna; to prevent absorption of the radiated energy of the radio transmitter by electrically isolated metal parts; to eliminate the danger of sparks occurring between metal members between which there exists a difference in potential caused by the collection of static charges; to eliminate noises produced in the radio receiver which are caused by the varying resistances between rubbing or vibrating metal parts; to lower the resistance of the metal shielding. The all-metal structure of the transports is inherently bonded and such parts as conduit, fuel and oil lines, etc., are bonded by their attaching parts. These attaching parts (clamps, brackets, etc.) are usually located at intervals of 18 to 20 inches. In places where this interval is greater, bonding strips of tinned copper braid are used to connect to the structure. This bonding interval of about 18 inches is necessary to prevent the secondary radiation of energy when standing waves are generated on long, ungrounded parts, and to provide sufficient low resistance paths to the structure to insure the effectiveness of the shielding. Fuel and oil tanks are bonded at diagonally opposite corners. All bonding connections should have a resistance of not more than 0.002 ohm.

The problem of weight is one with which the airplane designer is constantly confronted and the electrical installation in a plane the size of the Douglas sleeper transport requires serious consideration in this respect. It is estimated the completed installation will weigh about 772 pounds divided as follows:

| | |
|---|---|
| Wire | 135 |
| Conduit | 85 |
| Junction and shielding boxes | 136 |
| Equipment | 416 |

The equipment weights are divided as follows:

| | | |
|---|---|---|
| 2 | 85-ampere-hour 12-volt batteries | 155 pounds |
| 2 | Generators and regulators | 62 pounds |
| 2 | Battery compartments | 34 pounds |
| 2 | Starters | 66 pounds |
| | Lights | 57 pounds |
| | Switches, relays, etc. | 42 pounds |
| | Total | 416 pounds |

When designing electrical equipment for aircraft, this question of weight must be kept in mind as it is possible to effect considerable saving by the use of proper materials. As an example of what can be done, we have recently had designed and built a 3-position single-pole double-throw 200-ampere switch which weighed 2.2

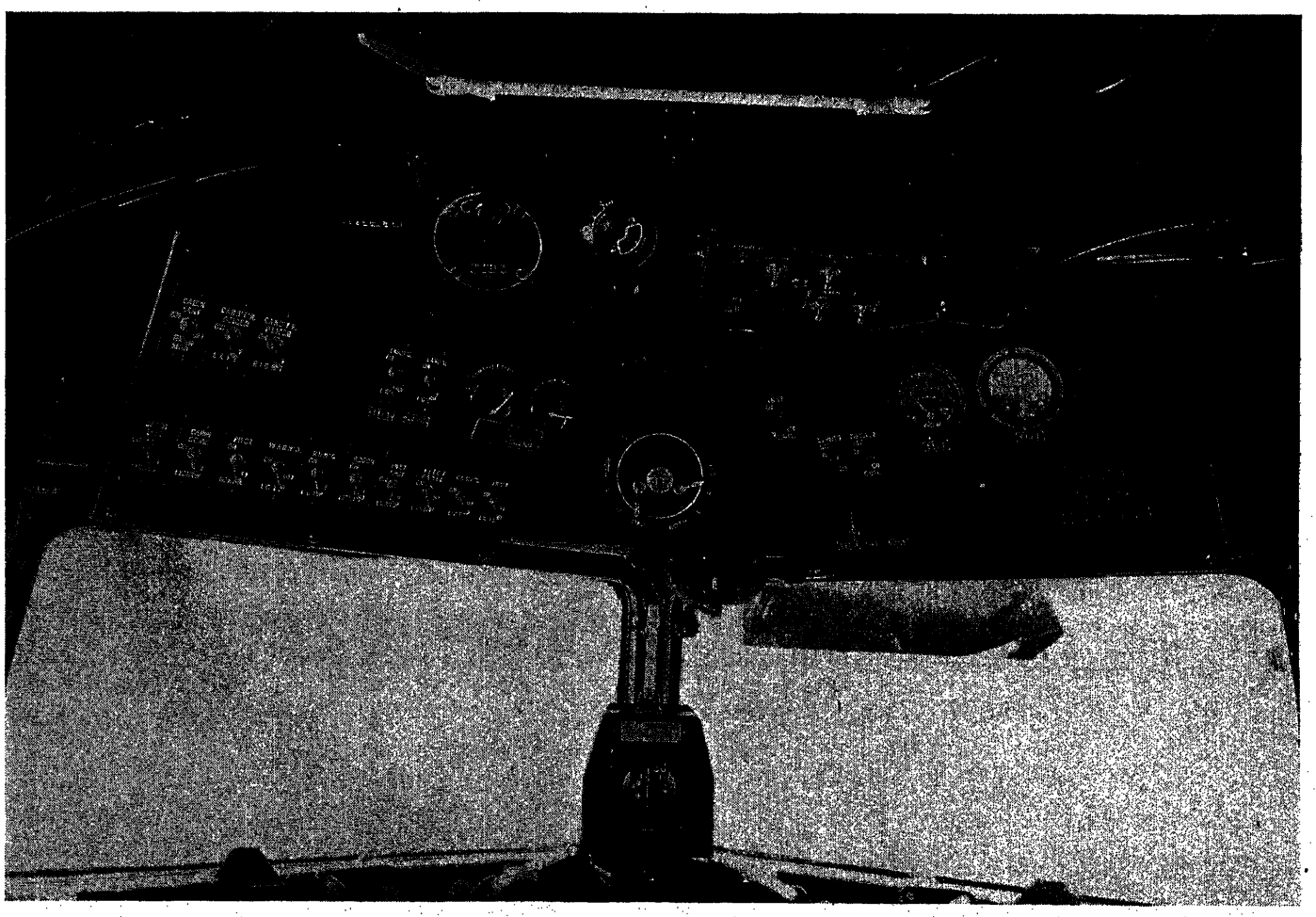


**Figure 2. Electrical panel above windshield. Radio controls above and below ignition switch**

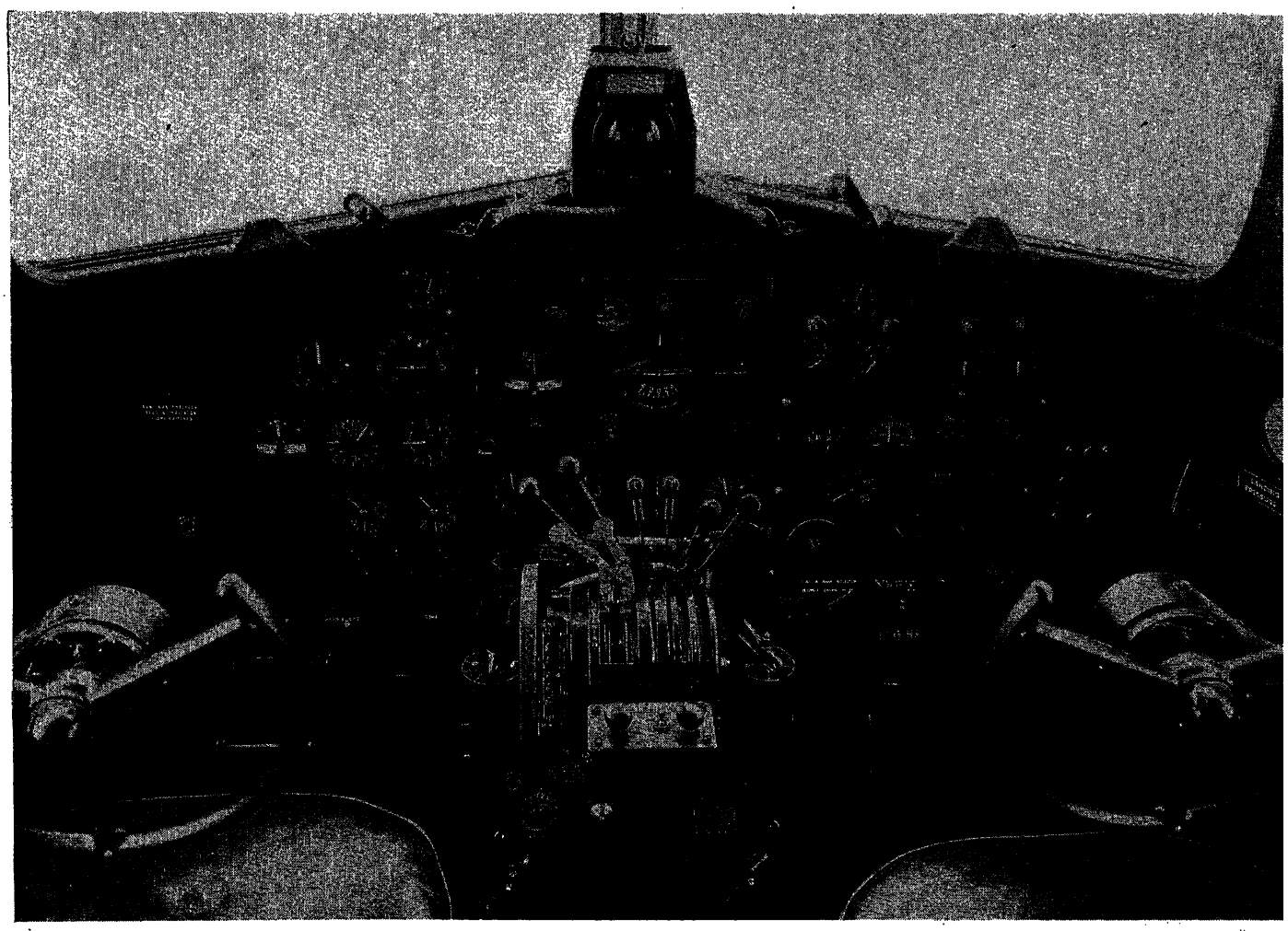


Figure 3

pounds. However, weight should never be saved at the expense of reliability.

Another factor which enters the design problem is the matter of operating temperatures. Equipment for use on aircraft must be capable of operating through a range of from −30 degrees Fahrenheit to +130 degrees Fahrenheit without change in lubricant or any other adjustment that is not wholly automatic. These extremes may be encountered within a period of 30 minutes.

Operating noise must be kept to the absolute minimum. Considerable weight, expense and time are spent in soundproofing the interiors and any equipment which introduces more noise is undesirable. The sound level in the present transports is such that the operation of the small toggle switches for the lights can be distinctly heard.

It becomes evident on studying today's large airplanes and tomorrow's larger ones, that an increase in the supply voltage would help considerably to keep the weight down. This would seem to be rather easily accomplished by placing the 2 12-volt batteries in series and using 24-volt generators. However, weight is not the only problem.

The amount of electrical equipment used is such that the present power supply is hardly adequate and with the increasing amount of equipment on larger planes, it is imperative that a larger source be made available. The larger airplanes require from 10,000 to 20,000 watts available continuously and this supply should be independent of the airplane engines. There are units being designed and built to meet these requirements. They consist of small 4-cycle gas engines driving generators and possibly some of the other accessories now driven by the airplane engines such as vacuum pumps, oil pumps, etc. To guard against failure, 2 such complete units will be carried.

A great deal of thought has been given to supply characteristics and it has been agreed that alternating current at 115 volts is the logical choice. This voltage makes available many commercial developments and the inherent flexibility of alternating current makes it very desirable.

A study of 60-cycle equipment shows that a large system such as has been outlined would involve considerable weight. Quite a saving could be made by using some frequency higher than 60 and a study has been made of frequencies as high as 800 cycles.

It is believed that the amount of power involved and the length of the transmission lines are such that no serious reactance trouble will be encountered. However, there is considerable doubt that satisfactory motor characteristics are possible at 800 cycles.

Development work on equipment for this frequency has been under way for some time and this problem may be solved shortly.

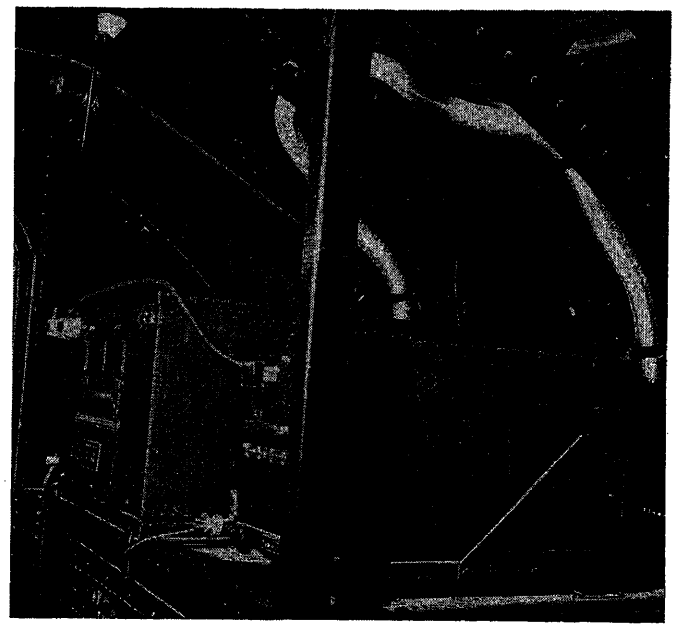


Figure 4. Transmitter and receiver for 2-way communication

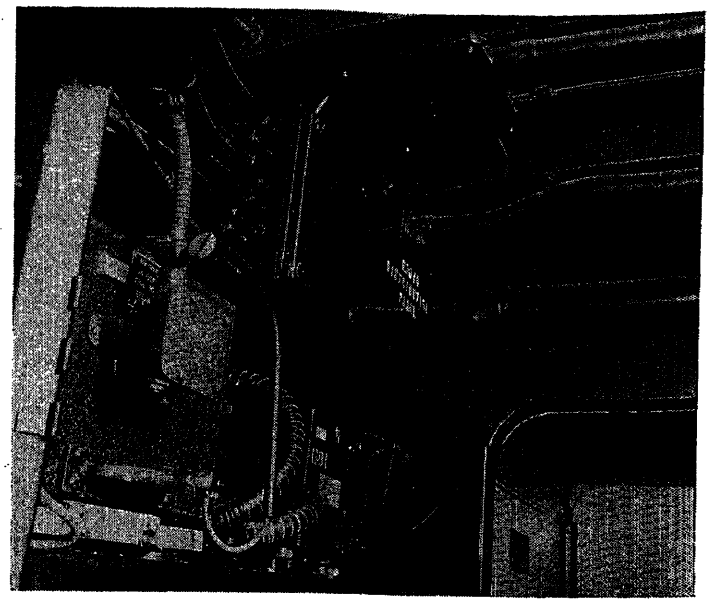


Figure 5. Radio beacon receiver, dynamotor, and stand-by receiver

It is known that satisfactory 360-cycle motors can be obtained and that radio filament supply at this frequency is feasible. A large percentage of the possible weight saving at 800 cycles is possible at 360 cycles. This or some other frequency lower than 800, may prove to be the best compromise. There is also the possibility that the various loads may become great enough to warrant the use of a double-frequency generator, supplying high frequency for radio plate supply, lighting and heating, and some lower frequency for motors and radio filaments.

Both single- and 3-phase supply have been considered and the advantages and disadvantages of each are about balanced. Of course, polyphase motors have an advantage over single-phase where power is required.

With airplanes steadily increasing in size and with a sufficiently large electrical supply, there is almost no limit to the possible applications in the future. All engine instruments will be electrical, possibly of the selsyn type. Various remote indicators for flaps, landing gear, fuel and oil quantity are already being used. Heater units to prevent carburetors and windshields from icing up and to provide hot water in the lavatories may be installed.

Lighting problems will be greatly simplified with a larger supply available. It will be possible to furnish adequate light for reading and general illumination comparable to that found in a modern home. Landing lights of much greater intensity have been developed. Development work on lamps has progressed to the point where satisfactory 115-volt lamps for aircraft are available in 6-, 15-, 20-, 25-, and 50-watt sizes. These are obtainable with the standard automotive bayonet base up to and including the 25-watt size. The 25- and 50-watt sizes are obtainable with the medium bayonet base. Landing-light lamps have been made in the 500-, 750-, 1,000- and 1,500-watt sizes with reasonably concentrated filaments. Tests indicate that all of these lamps are sufficiently rugged to have a reasonable life.

One of the problems of air transportation is that of serving satisfactory meals aloft. These large planes of tomorrow will have an electrically equipped galley where appetizing meals can be prepared. Light-weight hot plates, thermally insulated to prevent heat loss by radiation, electric mixers, and special cooking utensils will be needed. Making coffee at from 16,000 to 20,000 feet may require some experimenting, when the lower atmospheric pressure is considered. Electric refrigeration will be included.

Electric razors, now used by many airlines, curling irons and other modern conveniences will be available on overnight planes. Passenger comfort will be stressed and any electrical appliances contributing thereto will receive consideration.

Radio equipment of greater power for 2-way communication, radio direction finding and blind-landing equipment will be standard on all planes. With alternating current available, the high-voltage plate supply will be furnished by step-up transformers, rectifiers, and filters instead of by dynamotors. When transmitters with ratings of 1,000 to 2,000 watts output are considered, the size and weight of the power supply becomes very serious. It is here that great savings in copper and iron weight can be made by using a supply frequency well above 60 cycles. Transmitters of this power are not unreasonable when transoceanic flying, with the attendant need for absolutely reliable communication, is considered. Broadcast reception and television may be furnished for the passengers' amusement.

In planes designed for high-altitude flying, various indicators and controls, electrically operated will doubtless be used. Air conditioning will be necessary

The aviation industry is dependent upon the electrical engineers for these and other developments and it is hoped that this article has been able to present a general picture of the probable future needs.

# Proposals for the Administration of Federal Power in the Pacific Northwest

By H. V. CARPENTER
FELLOW AIEE

## Synopsis

This paper undertakes to state briefly the plans of organization of the Ontario Hydro-Electric Commission, the British Grid, the Tennessee Valley Authority, and then the proposals made by the planning bodies and in bills submitted to Congress for the public administration of power from Bonneville and Grand Coulee.

(I have not received Senate Bill No. 2092, and H.R. 6151, a bill prepared by the Senators of Oregon and Washington, which is more similar, I suspect, to their bill described herein which died with the 74th Congress. I would have been glad to add a summary of this bill if time had permitted.)

SINCE the depression has led the Federal Government into a number of great public-service construction projects, the method of administering the power to be produced has become of increased interest. Sale of power from Muscle Shoals has been a troublesome problem in the Congress at frequent intervals ever since the service became available. Now merged with the Tennessee Valley Authority the sale of the same power continues to find its way into the courts or to be the subject of legislation. This is not strange since the federal administration of such a utility is a new thing in the United States, and its promise of permanency gives the subject major importance.

Oldest of the government works for handling power on a large scale in North America is the Hydro-Electric Power Commission of Ontario. Under the wise and able administration of Sir Adam Beck, this organization has made a most valuable contribution to our fund of experience in governmental administration of a vast public utility. The Commission consists of 3 persons appointed by the Lieutenant Governor in Council, one of whom must be a member of the Executive Council of the Province. One member is named chairman and is the only one that is drawing a salary. The Commission chooses its staff, the staff members choose their own assistants, and the administration within the organization has been much the same as that of a private corporation, including a system of retirement funds and insurance for employees and the usual wide latitude granted to department heads in carrying out individual administrative duties. The Enabling Act refers to the Commission as a body corporate without capital. Its precise legal status has been determined gradually through later acts which have amended the original status, and through the results of legal procedure.

A unique feature of the legislation is that no action at law may be brought against the Commission or against its agents without the special consent of the Attorney General of Ontario. The Commission is given unusual power of eminent domain, permitting it to enter upon the property of anyone without any preliminary proceeding, or authorization whatever, adjustments to be made later by an evaluator appointed by the Lieutenant Governor. The relations of the Commission with municipalities purchasing power for local distribution is somewhat involved since it gives considerable authority to the Commission over the activities of a local group. Hydro is the third largest public utility in Canada, having a capital of about $285,000,000, exceeded only by the Canadian Pacific and the Canadian National Railways. All accounts are audited by independent auditors appointed by the provincial government. All revenues to support the undertaking must come from the sale of power and rates are set on the principle that service is furnished at "cost" where cost includes a sinking fund to liquidate the capital, a renewal reserve to replace the system in 25 years, and all expenses of operation and maintenance. Similar careful financing in the local municipalities has led to a rather stable financial status. An elaborate bookkeeping system assesses against each municipality served the proportional amount of cost, including the cost of transmission. Funds for construction work are provided by sale of bonds or through funds borrowed through or from the Provincial Treasury.

The Commission has been able to maintain a staff of technicians and an extensive laboratory, and a certain amount of research work is usually under way. Thorough analyses are made of all constructions, designs, and materials so that their work has been well protected from technical mistakes. On the business side, the Commission has not been quite so fortunate. Following the death of Sir Adam Beck in 1925, certain contracts were made for the purchase of power from private companies in larger quantities than could be used, payments for which threatened the Commission with disaster and required cancellation of these contracts by the legislative assembly in order to avoid bankruptcy. This illustrates one weakness of public organizations of this type in which administrative authority is placed in persons whose own capital and interests may really be elsewhere.

The possibility of satisfactory administration of transmission networks as a federal function has been encouraged also in this country by the success of the British experience

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with what is commonly called the "British Grid" administered by the Central Electricity Board, known as the C.E.B. Beginning 20 years ago, our British friends spent nearly 10 years considering the problem of reducing coal consumption by substituting high-grade modern steam plants for some 500 old and small industrial and public generating stations. These had grown up supplying individual industries or very small districts with a multitude of frequencies and voltages and the condition was rapidly becoming worse with continuing high coal consumption and legal limitations against the combination of small districts into larger ones.

Finally, in 1926, the C.E.B. was established with considerable arbitrary power to build transmission systems, purchase the entire output of modern generating plants, and sell power to industries and communities at rates which have brought about the closing down of a few hundred old-fashioned stations. The organization and administration of the British Grid is involved in such a greatly different legal setup from ours as to make it impossible in this summary to give a worth-while comparison with the conditions in the United States. The Grid has met with considerable success and has over 3,000 miles of 132-kv lines covering most of the island. With sound management, they can hardly fail to be a success due to the great difference in economy between the old-style small steam plant and modern practice. There are problems still existing but they are being worked out and the C.E.B., which resembles in most ways an American corporation, seems likely to be of vast usefulness to the English communities and industrialists.

The most ambitious undertaking by the United States of the type under consideration is the Tennessee Valley Authority, familiarly known as the T.V.A. The T.V.A. Act established a corporation with the purpose of maintaining and operating United States property, to aid agriculture and industries, and to control floods and contribute to the national defense in the valley of the Tennessee River. The authority is vested in a board of 3 directors appointed by the president and subject to recall only by joint action of House and Senate. This board hires all employees without civil service limitations, is to pay prevailing wages, and has the usual corporate power to sue and be sued, make contracts, etc., is given the power of eminent domain to be exercised in the name of the United States, and is authorized to construct dams and reservoirs needed to complete and maintain a 9-foot channel to Knoxville with appertinent power plants and transmission system. It may produce, distribute, and sell electric power and go into the phosphate- and nitrogen-fertilizer business. Power is to be furnished for navigation locks free, and the surplus sold with preference for public groups of users. They may limit the rate schedules of any privately owned distributors to whom power is supplied, or cancel their privilege to buy. Earnings go to the United States Treasury, except for maintaining a continuing fund of one million dollars for operating capital. Any works on the river proposed by other parties are subject to approval by the T.V.A. Board.

The approaching completion of the construction work at Bonneville and the rapid progress at Grand Coulee, both on the Columbia River, add to the interest in a suitable plan for federal administration. Each new plant and each new region entered brings up new conditions and indicates an added need for flexibility in any scheme under which these utilities are to be operated. Every effort is being made to ensure that the benefits accruing from them shall be widely distributed.

Under authorization of the National Resources Committee, a thorough study of the Pacific Northwest and its resources was made during 1935 by the Pacific Northwest Regional Planning Commission made up of the heads of the planning boards of the 4 Northwest states, under the chairmanship of Marshall N. Dana, of Portland, Ore. This Commission, with the co-operation of a consulting staff of some 25 members, presented among other things recommendations for the administration of federal power in the Columbia Basin. These recommendations are based on the results of many hearings and consultations held throughout the region and represents closely the consensus of the Pacific Northwest opinion. These recommendations include: first, that federal construction work, including Bonneville and Grand Coulee, should be continued under the present departments, Bonneville being under construction by the engineers of the United States War Department and Grand Coulee by the United States Bureau of Reclamation. Much praise for the work of these 2 departments has been expressed by those familiar with their work on these projects. So since the operation of Bonneville will be associated with the operation of the lock in the Columbia and since a substantial portion of the power at Grand Coulee is to be used for irrigation pumping at Grand Coulee Dam, it is also recommended that the operation of these 2 plants be left permanently with the departments constructing them.

Second, the disposal of commercial power from Bonneville and Grand Coulee should be considered as a separate undertaking and placed in the hands of a new and separate agency. This power agency should have the form of a public corporation with the financing and other power usually accorded to such bodies. Its board of directors should be made up of 3 or 5 members to be appointed by the president with the approval of the Senate. One of these directors should be qualified for administration and management of the power system, another with special qualifications for planning, development, and promotion, and the third to have special qualifications in public relations and in the fields of social and economic development. If 5 are named, one might be at the suggestion of the Secretary of Interior and one by the Secretary of War, these probably to serve as part-time advisory directors. The following functions and powers should be entrusted to this power agency:

1. Major transmission lines, planning, designing, construction, maintenance, and operation.
2. Interconnection plans.
3. Interchange and dispatch of energy and its measurement.
4. Design of power facilities (including the review of any such designs carried out by other federal constructing agencies).

5. Development of power markets.

6. Specific planning for the further extension and development of its power system.

7. Sale of power at wholesale from points on its transmission system with contractual requirements that will insure that rates to the consumer pass on the economies in generation and transmission. With due respect to the interests of other agencies, the power agency should be given power to specify the maximum resale rates of any distributor which buys all or a major portion of its electric energy from the power agency.

8. Co-ordination and control of power production at federal power plants.

9. Regulation of release of water from federal storage reservoirs subject to state rights and irrigation needs.

10. The power agency should be authorized to interchange power with other agencies.

The power agency should be endowed with the accessory and usual powers, rights, and obligations of a corporation necessary to the exercise of the functions named. Initial federal financing should be provided and the obligation to contribute to state tax funds in proportion to the levies which are made upon similar private enterprises should be recognized. Public and nonprofit agencies should be given priority in the purchase of power and the power agency should be given the right of eminent domain as to purchase and lease of property useful in its operations. It should have the right to make contracts, to sue and be sued, and to conduct itself otherwise as a corporate autonomy. The agency should also be authorized to carry on research and experimentation to widen power utilization and markets and should be responsible for all recommendations as to future federal multiple purpose projects within the Basin.

The first official attempt to crystallize Northwest opinion into law was introduced May 12, 1936 as Senate Bill No. 4695, by the 4 Senators of Oregon and Washington and was analyzed and reported on by the committee on commerce, Report No. 2280. As finally presented it places the Bonneville plant construction, maintenance, and operation, and later installation of remaining machines, under the Secretary of War, through the chief of engineers. They also control the sale of power subject to approval by the Federal Power Commission. The War Department also is authorized to construct, operate, maintain, and improve transmission lines and related facilities. Navigation has first claim on the power; district and municipal organizations organized to serve rather than for profit come next. Within limitations surplus power may be sold to commercial operating companies. Contracts may be made for not to exceed 10 years but may give preference for an additional 10 years.

The War Department may purchase or condemn any or all real and personal property (including any existing electrical facilities) necessary to carry out the act. All receipts go to the United States Treasury. The Federal Power Commission may fix and revise rates without regard to existing statutes, rates to be based on costs.

The president may designate a federal agency to handle everything here assigned to the United States Engineers. This bill was brought up for consideration but failed in passage before the adjournment of the 74th Congress.

The first bill of the 75th Congress, dealing with power on the Columbia, was introduced by Representative Smith of Washington on January 5, H.R. 92. This bill placed the development of the plant at Bonneville and the building of transmission lines in the charge of the Secretary of War. The sale of power, also, was to be handled by the engineers of the War Department, but with almost every detail of power policy and, to some extent, contracts subject to the approval of the Federal Power Commission. The bill did not find satisfactory support and aroused considerable objection since it implied a control of rates at Boulder Dam. Largely, I believe, on this account this bill has been superseded by Mr. Smith's bill of February 19, 1937, when he offered House Bill No. 4948 incorporating what he stated were the desires of the President for control of power in the Northwest. The bill is to authorize maintenance and operation of the Bonneville project for navigation, flood control, and other purposes. The bill would leave completion of construction of Bonneville to the Secretary of War and also reserves to the Army Engineers, the operation of the lock which is to permit ocean boats to proceed upstream about 45 miles to The Dalles. Otherwise, the administration of operation, maintenance, sale of power, and promotion is to be by a Columbia River Administrator appointed by and responsible to the Secretary of the Interior. The Administrator is to act in consultation with an advisory board composed of 3 representatives, one to be designated by the Secretary of War, one by the Secretary of Interior, and one by the Federal Power Commission. This form of administration for Bonneville is stated to be intended as provisional until the establishment of permanent administration of Bonneville and other federal projects in the Columbia River Basin. The Administrator is authorized to operate, maintain, and improve Bonneville and related facilities, and is directed to carry on primarily for the purpose of promoting navigation and controlling floods, which, by the way, are 2 matters practically beyond his power. So far as consistent with these and to prevent waste, he shall add and improve machines and facilities for generation and transmission of such power as may be saleable. He shall encourage use of energy, construct, operate, maintain, and improve transmission lines and appurtinences to bring Bonneville's power to markets, existing and potential, and is authorized to interconnect with other federal projects and private or other public systems for exchange and emergency service. Public and co-operative agencies are to be given preference in purchase of power and half of the firm power available is to be held for them until January 1, 1939. Rates are to be approved by the Federal Power Commission. Contracts are to be made on a wholesale basis, except that sale may be made direct to large consumers. No contracts for more than 20 years may be made and these are to be subject to rate readjustment at ntervals of not over 5 years. Sales to privately owned agencies may be cancelled on 5 years notice if the power is needed for public agencies. Contracts with private companies for resale may contain stipulations concerning resale rates in order that the consumer may be protected. Rates are to be fixed with a view to

encouraging use but are to consider costs of generation, transmission, and amortization of capital investment over a reasonable number of years, the power to bear its fair share of the total cost of Bonneville. Except in emergencies, bids are to be called for on all items amounting to more than $500, but the Administrator may use usual business discretion in awarding contracts to responsible parties and in judging the materials offered.

The Administrator is to report to Congress each year. He appoints his own lawyers, engineers, and other experts and fixes their salaries, and appoints others under civil service rules.

All receipts are to go to the United States Treasury, except an operating fund of $500,000. Authorization of appropriations necessary to carry on is included. The Administrator, in the name of the United States, may bring suits and, by implication, may be sued.

On April 14, 1937, Representative Walter M. Pierce of La Grande, Oregon, introduced still another bill for establishing a suitable administration for Bonneville. He would place an administrator in full charge of both generation and distribution and make him responsible solely to the Secretary of the Interior, except that rate schedules and revisions become effective after approval by the Federal Power Commission. This places the responsibility for operation of the Bonneville plant for power production in the hands of the Administrator subject to completion of construction of the plant, including locks, fishways, power, and appurtinences and the continued operation of locks and fishways only by the United States Engineers under the Secretary of War. This administration is to be provisional, pending the establishment of permanent administration for Bonneville and other projects in the Columbia River Basin. The authority carries with it the right to condemn property, franchises, etc., needed for carrying out the purpose of the act and the preferential rights of public nonprofit bodies domestic and rural consumers, is carefully guarded through reservation of 50 per cent or more of the energy until January 1, 1941, for such nonprofit bodies, provided, however, that such energy reserved but not actually purchased by nonprofit groups prior to January 1, 1941, may be disposed of temporarily to any purchaser. The Administrator is further authorized to contract for interchange of power with any other system as mutual emergency protection of service. The Administrator is also instructed to consult and co-operate with nonprofit groups within economic transmission distance of Bonneville in order to assist them in securing their privileges. In other ways the bill closely resembles other earlier measures.

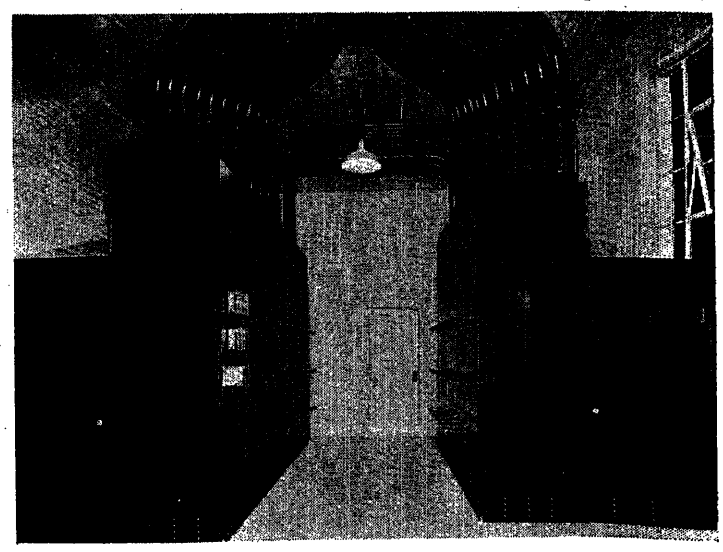
This bill by Representative Pierce is based to some extent upon the recommendation of President Roosevelt, dated February 24, in which he approves the progress report of the President's Committee on National Power Policy. The recommendations of this committee are quite closely followed by Representative Pierce, except that the Committee advises that the Administrator should act in consultation with an advisory board composed of representatives designated by the Secretary of War, Secretary of the Interior, and the Federal Power Commission. Included in the Committee's statement is:

> "In computing the cost of electric energy developed from water power created as an incident to the construction of Bonneville project for other purposes, there may be allocated to the cost of electric facilities not simply the cost of such facilities, but also such a share of the cost of facilities having joint value for the production of electric energy and other purposes as the power development may fairly bear as compared with such other purposes. The rate schedules may provide for uniform rates or rates uniform throughout prescribed transmission areas with a view to distributing the benefits of an integrated transmission system and encouraging the equitable distribution of the electric energy developed."

Since power will be available at Bonneville before the end of 1937 early action is important. This is true not only to conserve a national asset but to enable the public utilities of the Northwest to determine their program for ensuring a sufficient power supply. They have operated all available steam plants most of the time in recent months and must build or buy power to prevent a serious shortage within the next few months.

## Compact Distribution Center

Westinghouse Photo



FIFTY-TWO distribution circuits are concentrated in this switchboard recently installed in a Philadelphia, Pa., industrial plant. Dead-front air-break circuit breakers are used throughout. On the left is a 440-volt 3-phase 60-cycle power-distribution switchboard supplied from 3 500-kva stepdown transformers, which has 30 400-ampere distribution-feeder breakers with 7 submetering current transformers and watt-hour meters. The switchboard on the right is for lighting distribution, and has 22 300-ampere circuit breakers for the 3-phase 4-wire grounded-neutral system, which is supplied with 120 and 208 volts from 3 333-kva transformers. Each circuit breaker controls a main feeder circuit to a definite plant section.

# The Ultrahigh-Speed Reclosing Expulsion Oil Circuit Breaker

By A. C. SCHWAGER
MEMBER AIEE

DURING the last few years, the problem of increasing the continuity of service of electric transmission systems has been given considerable study. Of all the proposals by which it is intended to bring about a reduction in outages, the practice of ultrahigh-speed reclosing of oil circuit breakers gives promise of the most effective and most economical solution.

The advantages of automatic-reclosing circuit breakers have been known for a long time and records are available showing that approximately 90 per cent of all outages can be eliminated during the first opening followed by reclosure. This value was first determined for a reclosing interval of 15 seconds but later confirmed for immediate reclosure.[1]

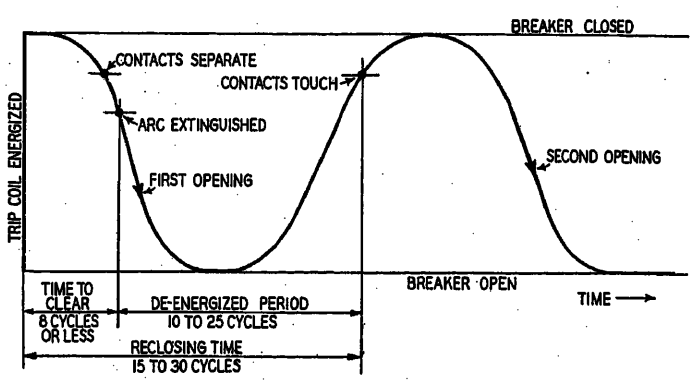



**Figure 1. Travel-time chart of ultrahigh-speed reclosing breaker**

"Immediate reclosure" in the above sentence defines operations in which the interval from trip coil energized to circuit reclosed amounts to from 30 to 80 cycles, the lower value applying to lower, the upper limit to higher voltages.

It is obvious that additional advantages could be obtained by reducing the reclosing interval still further. A reduction to from 15 to 30 cycles would in many instances prevent the loss of synchronous equipment load and would in general eliminate the remaining disadvantages of outages of too long a duration.

Figure 1 shows a travel-time chart of the reclosing cycle taking place within the above-mentioned periods. The term ultrahigh-speed reclosing has been previously applied to this type of operation and will be used in the following.[2] The de-energized period according to figure 1 amounts to from 10 to 25 cycles. This is sufficient time to allow the dielectric strength of the fault path to recover to such a degree as to withstand reapplication of line voltage, provided that the short circuit is due to the most common causes such as insulator flashover or line swinging.

In designing an oil circuit breaker which will meet the specifications outlined in figure 1, the manufacturer is confronted with the following 2 major problems:

1. Develop an operating mechanism which will meet the specifications as to mechanical performance, when applied to present designs of breakers.

2. Assure the behavior of the rupturing devices under immediate reclosing conditions. Although a great deal of interrupting capacity test data on modern breakers is available, information on 2 successive interruptions within an interval of a few cycles is lacking. If possible, tests should be carried on with time intervals smaller than those employed in service.

## Problem 1—Operating Mechanisms

For a considerable period of time, the solenoid control represented the standard design of operating mechanism. With the demands for shorter opening and closing times, spring-actuated motor-wound mechanisms were developed and during the past 10 years have found a great field of application. In addition to increased operating speeds, they had the advantage of requiring small operating currents, in many instances eliminating the necessity for expensive batteries. These controls provide stored energy for one closing and one opening operation of the breaker. Rewinding of the springs occurs immediately after the opening stroke and in general requires several seconds. It is obvious that in spite of the above-mentioned advantages this latter type of control is not suitable for immediate reclosing.

The conventional solenoid control was, therefore, re-

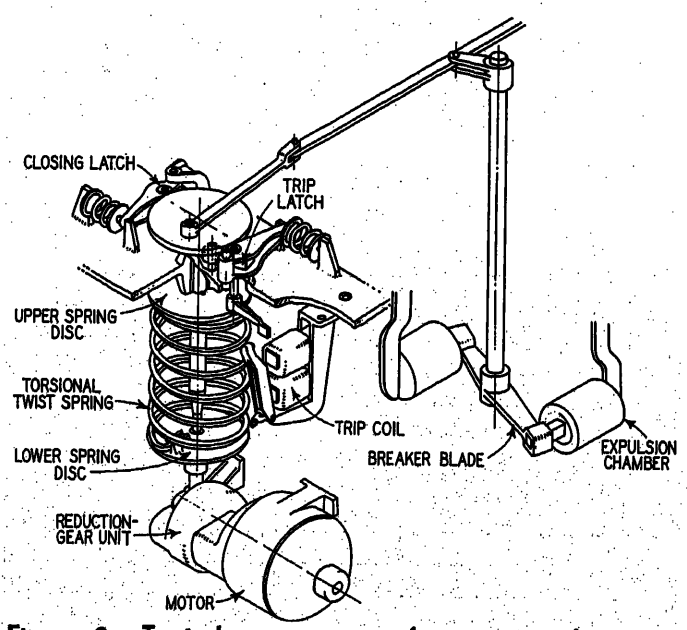



**Figure 2. Typical arrangement of motor-wound spring-actuated reclosing mechanism**

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1. For all numbered references, see list at end of paper.

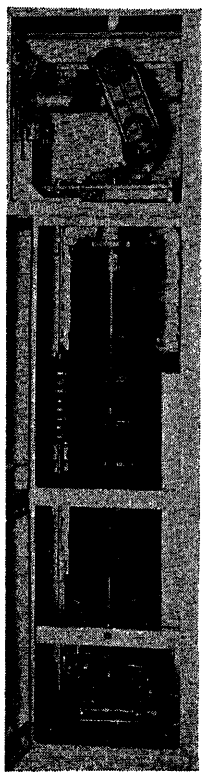


**Figure 3. Fast-reclosing operating mechanism for 69-kv breaker**

considered with a view to improving its performance to comply with the specifications contained in figure 1. No difficulty was encountered in meeting high speeds in opening, which is generally accomplished by springs. In closing, however, the upper limit of the specifications was not even approached. This is due mainly to the fact that an excess of time is lost in accelerating the heavy plunger. A combination of 2 prewound motor controls would, of course, solve the problem in an academic way, but it does not seem feasible economically and introduces complications due to the presence of double closing and trip coils. The problem was, therefore, attacked on a more fundamental basis along the following lines of thought.

Some type of motor-wound spring-actuated mechanism, designed to produce the required operating cycle with the least number of parts and in a thoroughly reliable manner seemed preferable. The mechanical design should be such as to produce the greatest possible speed and shortest operating time. The simplest mechanism is one which incorporates only one spring to perform the entire cycle of opening, closing, and opening.

A control of the type shown in figure 2 seems to meet the above specifications in the most direct manner. It is shown applied to a conventional rotary-type oil circuit breaker, although it is equally suitable for the drop bar type and has been developed for breakers from 7.5 to 138 kv. A reduction-geared motor winds up a torsional twist spring. Suitable closing and tripping latches retain and release the upper spring disk. A motor limit switch is provided which rewinds the spring automatically to a predetermined torque whenever an operation of the breaker has released part of the spring energy. Although the length of the spring is chosen to give one immediate reclosing cycle it is possible to meet possible future requirements for more than one immediate reclosure by lengthening of the spring. The motor is of such size that the spring is wound for additional time-delayed reclosure in an interval smaller than that available in the conventional automatic reclosing timers. Figure 3 shows a control of this type as applied to a 69-kv breaker. The simplicity of the design is apparent, the essential parts such as motor and spring constituting the major portion of the mechanism. In the particular case shown the unidirectional rotary motion of the upper spring disk is transformed into a reciprocal radial motion of the horizontal breaker operating shaft by means of a bevel link.

**Table I**

| Test Number | Amperes (Root-Mean-Square) | Voltage Across Breaker (Root-Mean-Square Kilovolts) | Time to Clear. Trip Coil Energized to Arc Interruption (Cycles) | Reclosing Time (Cycles) | De-energized Period (Cycles) |
|---|---|---|---|---|---|
| 1 | 400 | 12.3 | 5.3 | 11.3 | 6.0 |
| 2 | 920 | 12.3 | 5.3 | 11.3 | 6.0 |
| 3 | 1,800 | 12.3 | 5.1 | 10.8 | 5.7 |
| 4 | 2,600 | 12.3 | 5.0 | 11.5 | 6.5 |
| 5 | 3,760 | 12.3 | 5.5 | 10.2 | 4.7 |

## Problem 2—Interrupting-Capacity Tests

In order to satisfy the questions brought up under the heading of the second problem, the need for an analysis of the arc-interruption phenomena within expulsion chambers during quickly repeated interruptions was indicated.

The expulsion-chamber arc-rupturing device consists essentially of an explosion chamber which is vented in a direction opposite to the direction of opening the blade. The gases produced during interruption, therefore, escape into

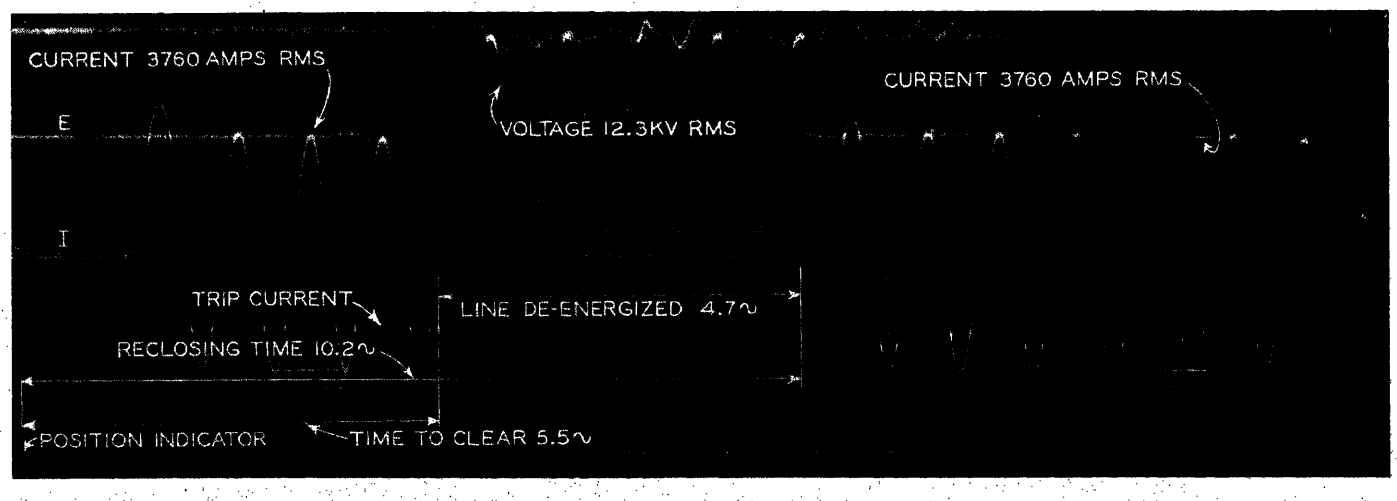



**Figure 4. Oscillogram of interrupting-capacity test on 15-kv expulsion breaker and fast reclosing control**

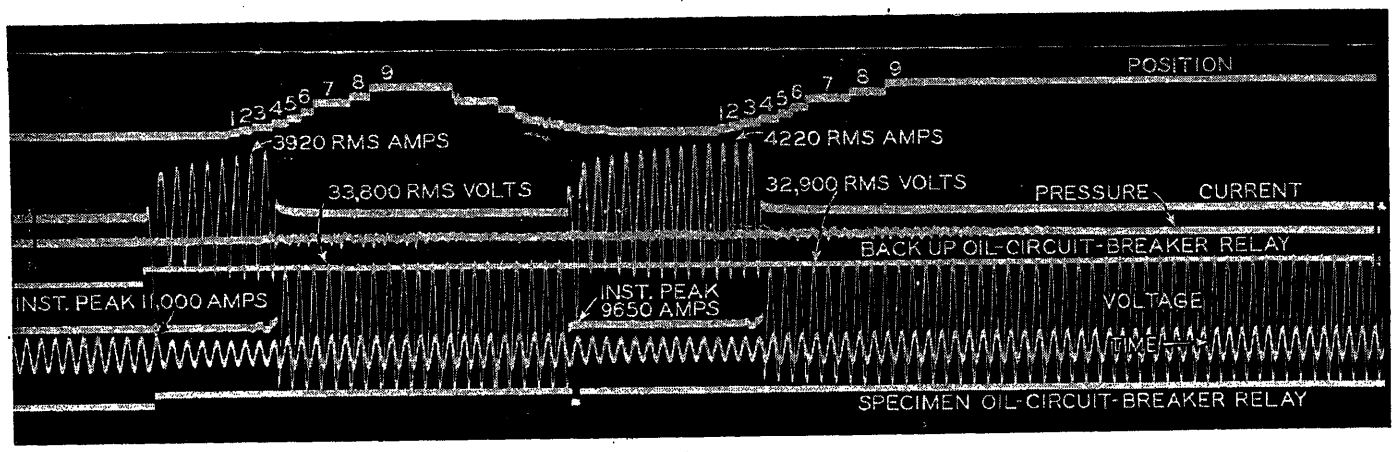



**Figure 5. Oscillogram of 69-kv field interrupting-capacity test on expulsion breaker operated by means of ultrahigh-speed control**

a space remote from that in which the blade opens. Contrary to many other modern arc-rupturing devices, no contamination of the major break path takes place, a fact which allows the accomplishment of a large number of successive rapid interruptions without any loss in effectiveness of the expulsion chamber.

For the purpose of interrupting capacity tests the control shown in figure 2 was connected to a single phase of a 15-kv expulsion circuit breaker. In this manner the smallest time interval between 2 successive interruptions was obtained. The results are shown in table I.

**Table II**

| Cause of Interruption | Fault Cleared After Immediate Reclosure | Fault Not Cleared After Immediate Reclosure |
|---|---|---|
| Lightning | 27 | 2 |
| Birds | 4 | |
| Insulation | 1 | 1 |
| Unknown | 1 | |

Interruption occurred in all cases without disturbance, without oil throw and without noticeable tank pressure. The arcing times for the first and second opening were substantially the same. The suitability of the expulsion chamber for ultrahigh-speed reclosing operation is, therefore, established for intervals in the order of 10 cycles. Figure 4 shows an oscillogram of the interruption corresponding to test 5, table I.

## Field Tests

A 69-kv expulsion oil circuit breaker equipped with the ultrahigh-speed reclosing control shown in figure 3 was given a field test to determine operation under immediate reclosing duty. Generating capacity of 75,000 kw was available at the test location, and an additional 90,000 kw capacity was feeding from remote sources into the short circuit. As shown on oscillogram figure 5, the equivalent 3-phase short circuit amounted to 400,000 kva during the first opening and to 420,000 kva during the second opening, the reclosing and de-energized period being 28½ cycles (including relay time) and 19½ cycles, respectively.

## Field Experience

The 69-kv breaker reported on under field tests has been in continuous operation since February 29, 1936; it protects a single-circuit 60-kv line, 113 miles long which is subject to severe lightning conditions. Up to December 31, 1936 the breaker was called to clear 36 short circuits, in 33 cases the fault was eliminated by means of the immediate reclosure and only in 3 cases did the breaker trip out a second time. Table II shows the causes of the short circuits.

It is hoped that additional field experience will soon be available on a reclosing breaker recently installed on a 115-kv tie line.

## Conclusion

An extremely simple motor-operated spring-actuated operating mechanism, suitable for ultrahigh-speed reclosing has been developed. In conjunction with expulsion oil circuit breakers it has been shown to provide an ideal means for immediate re-energizing of transmission systems. A 90-per-cent reduction in outages, previously reported by others is confirmed on an additional system. From limited experience the exact field of application cannot be completely defined, but indications are that ultrahigh-speed reclosing circuit breakers of this type will become more and more common. The simplicity of design of the mechanism gives promise of its use as a standard operating means, and if at a later date ultrahigh-speed reclosing is desired, but a slight change in wiring and instruments is required.

## References

1. Automatic Reclosing of Oil Circuit Breakers, A. E. Anderson. Electrical Engineering, volume 53, January 1934, pages 48–53.

2. Ultrahigh-Speed Reclosing of High-Voltage Transmission Lines, Philip Sporn and D. C. Prince. Electrical Engineering, volume 56, January 1937, pages 81–100.

# Radiotelephone Noise Reduction by Voice Control at Receiver

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## Introduction

IN TRANSMITTING speech over radiotelephone circuits there are a number of conventional methods of increasing the signal with respect to the noise. Examples of such methods are the use of higher power, directive antennas, diversity reception, and filters to narrow the received frequency band. In addition, there are other methods of a special character which reduce the effect of the noise interference with the speech transmission. One example of such a device limits the noise interference by eliminating the high peaks of noise of very short duration and depending upon the persistence of sensation of speech in the ear to bridge the gaps. Another method diminishes the noise in intervals of no speech. This is the method which will be discussed here.

## Speech and Noise Considerations

Speech signals may be represented by a group or band of frequencies occupying a certain interval of time. In using the conventional method of narrowing the received frequency band, filters eliminate all noise outside the band actually required. In fact we sometimes go beyond this and remove some of the outer frequency components of speech which are weak and submerged in the noise and therefore contribute little or nothing to the intelligibility. Experiments have shown the effect on voice transmission of removing portions of the frequency range.[1] Articulation tests were used to afford a quantitative measure of the recognizability of received speech sounds. These show that the upper frequencies may be cut off down to about 3,000 cycles without serious reduction in articulation. After such treatment, as the noise level increases, the weaker and less articulate sounds become more and more submerged in the noise and additional reduction in the detrimental effect of the noise is required.

In addition to the speech waves covering a frequency band they occupy intervals of time. The unoccupied intervals between the speech sounds contain noise. Reduction of the noise reaching the ear in these intervals has been found to result, under certain conditions, in an improvement in speech reception. This may possibly be explained by considering the characteristics of the ear.[1] It has been shown that noise present at the ear has the effect of shifting the threshold for hearing other sounds or has a deafening effect. That is, there is a reduction of the capacity of the ear to sense sounds in the presence of noise. For example, if a person has been listening to a noise for a certain period, his ear is made insensitive so that speech signals following are not so easily distinguished. The ear has a sensory build-up time, that is, a time needed for the noise to build up to a steady loudness. By reducing the noise in the intervals of no speech the average threshold shift seems to be diminished. Aside from this the presence of the noise tends to distract the attention from the perception of the speech. Removal of noise during the intervals of no speech tends to reduce this effect.

## Requirements

In considering the elimination of the noise during these intervals it is necessary to bear in mind certain characteristics of speech.[2] Speech waves may be regarded as nonperiodic in that they start at some time, take on some finite values and then approximate zero again. In connected speech it is usually possible to approximately distinguish between sounds and to ascribe to each an initial period of growth, an intermediate period which in some cases approximates a steady state and then a final period of decay. The duration intervals of various syllabic sounds vary from about 0.03 to as much as 0.3 or 0.35 second. When noise is high the weaker initial and final sounds become obscured so that they contribute little to the intelligibility.

In connected speech, silent intervals occupy about $^1/_5$ to $^1/_3$ of the total time. Also there are frequent intervals when the sounds are rather weak. However, if we attempt to suppress noise during all these intervals, experi-

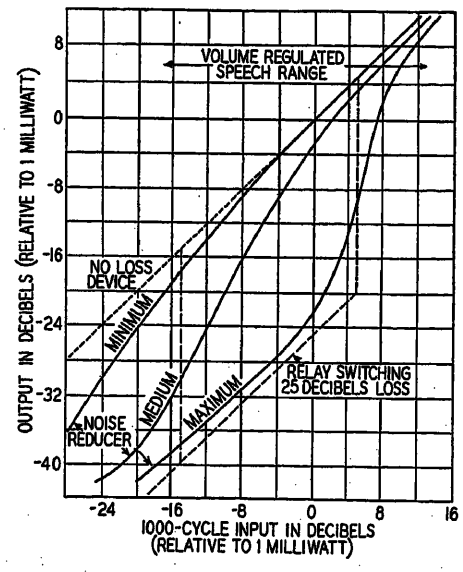



**Figure 1. Input-output comparison of noise reducer and voice-operated relay**

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1. For all numbered references, see list at end of paper.

ence shows that the suppression becomes too obvious, and the speech is apt to sound mutilated. For this reason the function of any device to be used for reduction of noise in the intervals between speech is to operate rather quickly to remove suppression and pass the speech and approximately to sustain this condition for sufficient periods to override weaker intervals so that obvious speech distortion does not occur.

To reduce the noise in the intervals between speech it is necessary to depend for control upon either the speech

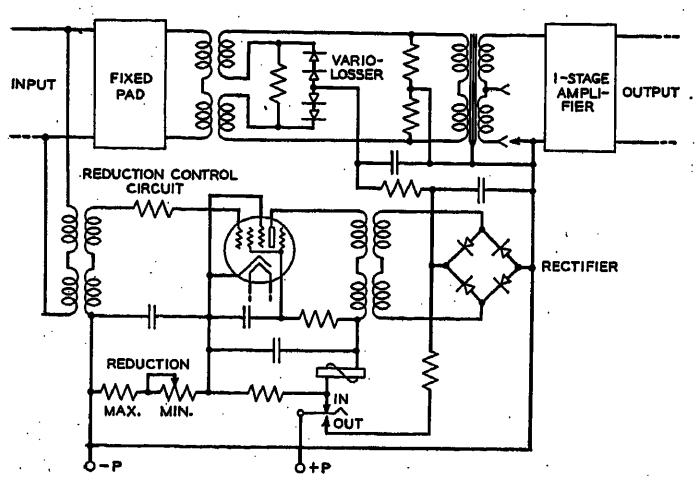



**Figure 2. Simplified schematic of noise reducer**

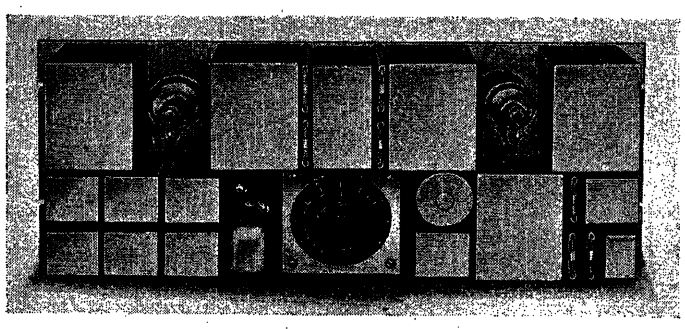


**Figure 3. Noise reducer panel**

itself or upon some auxiliary signal usually under the control of the speech at some point in the circuit where the signal-to-noise ratio is better. This latter condition is illustrated on a circuit where the carrier is transmitted only during speech intervals. The carrier then acts as an auxiliary signal which operates a device at the receiver to remove loss.[3,4] The device to be discussed below utilizes the speech itself at the receiver to perform this function.

In using the speech in this way it is obvious that control can only be accomplished when the speech energy sufficiently exceeds the noise energy so that the presence of the speech is distinguishable. The device could operate abruptly as, for example, a relay which removes a fixed loss in the operated position and restores it when nonoperated. Experience indicates that the use of such a device makes the suppression too obvious if it is to follow the speech sounds closely. It is desirable, then, to perform this reduction by more or less gradually removing loss as the speech increases to accentuate the difference between levels of speech sounds and levels of noise which occur in the gaps between speech.

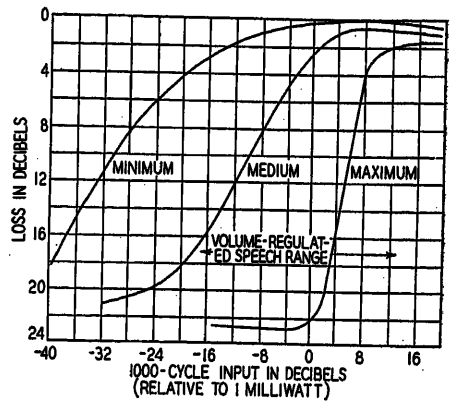
## Noise Reducer

This kind of performance has been secured in a device known as a noise reducer. A comparison of the action of the noise reducer and a relay having similar maximum loss is shown in figure 1. This figure shows the input-output characteristics of these devices over the voice amplitude range to which they are subjected on a radio circuit. The noise reducer may be likened to a relay with a variable loss, the loss not varying instantaneously but over a short period of time. The loss, for any short period, may be any value within the loss range and the device has, therefore, been likened to an elastic or shock absorbing relay.

The noise reducer has no loss for strong inputs, considerable loss for weak inputs and changes this loss gradually over a short interval of time. It introduces loss in the absence of speech but reduces this loss in proportion to the amplitude and duration of waves impressed upon it. The time required for the loss change is such that abruptness of noise change is absent and very short impulses of static do not effectively control the loss. This contrasts with a very fast limiter acting on high peak crashes only.

The noise may control the loss if its average amplitude is strong enough. Therefore, the control is made adjustable so that the noise waves are not permitted to control for any noise condition within the range of usefulness of

**Figure 4. Loss versus input for several settings of the reduction control**




this device. Thus the noise in the absence of speech is always reduced and the portions of the initial and decay periods of the speech sounds which are also reduced vary with this adjustment for noise intensity. Of course, if the speech-to-noise ratio becomes too small or if other transmission conditions interfere, an improvement becomes impossible.

## Circuit Arrangement

Figure 2 shows the circuit of the noise reducer in simplified schematic form.[5] Incoming waves pass from left

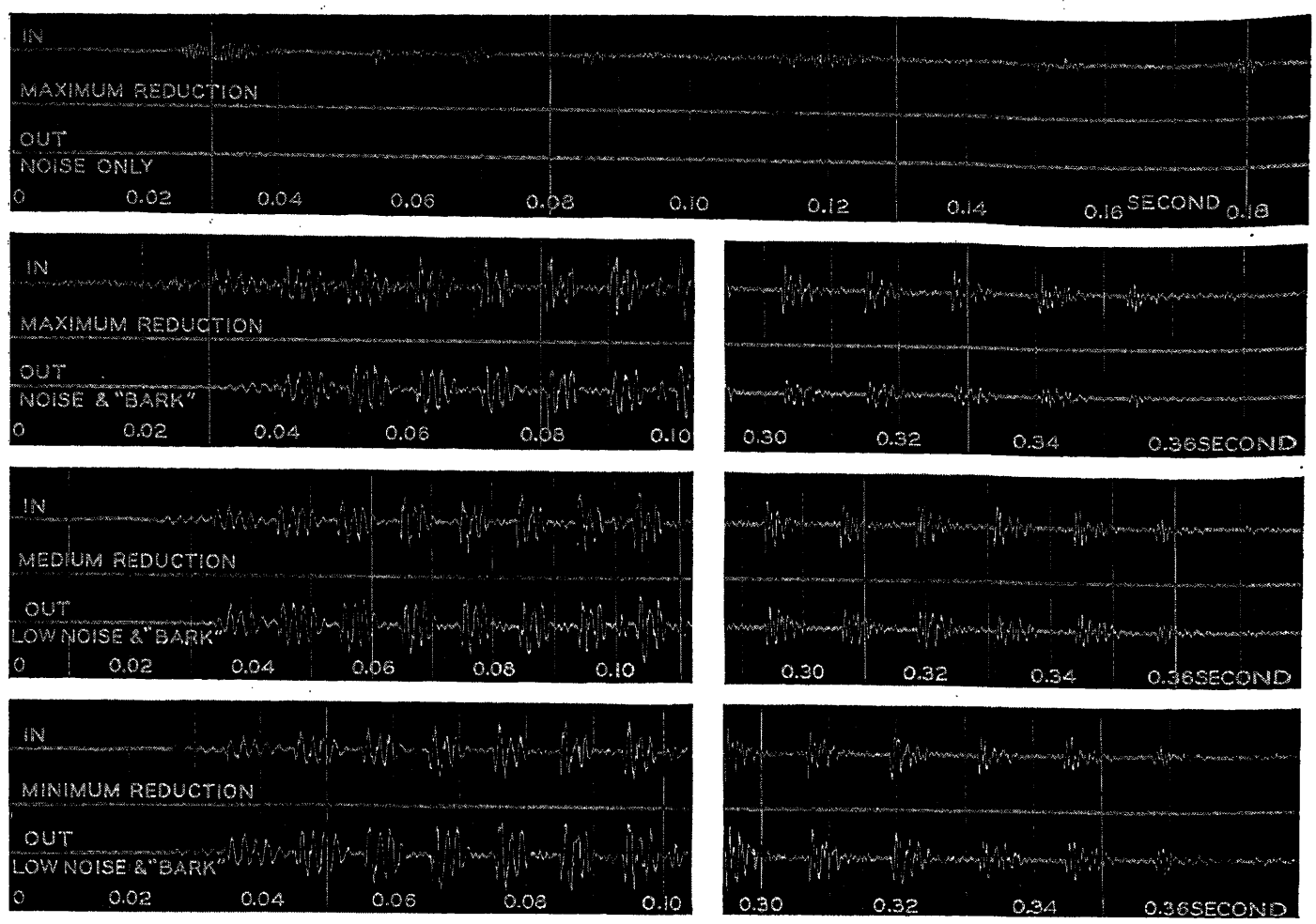



**Figure 5. Input and output for (top to bottom): high noise with maximum reduction; high noise with the beginning and ending of the word "bark"—maximum reduction; low noise, the word "bark"—medium reduction; low noise, the word "bark"—minimum reduction**

to right through the fixed pad, the vario-losser and the amplifier to the output. At the input, part of these waves pass through the reduction control branch circuit which includes a variable resistor, an amplifier, and a rectifier. The direct current produced by the rectifier is applied through the condenser and resistance filter to the copper-oxide losser circuit. For current below a threshold value, no appreciable change occurs in the losser and the loss introduced is about 20 decibels. As input increases, rectified current reaches a value where the loss begins to change rapidly. It becomes zero decibles at an input about 20 decibels above the point at which the loss starts to change. The design is such that the loss remains substantially constant for higher inputs.

The vario-losser makes use of the resistance variation with current of copper-oxide rectifier disks. This variable resistance shunts a fixed resistance in series with the windings of a repeating coil as shown in figure 2. The maximum loss is determined by the fixed resistance when small current is flowing through the disks while the varying loss is determined by the shunting copper-oxide resistance which decreases rapidly with increasing current above a threshold value until a low value is reached. The minimum loss is limited by the output of the control tube approaching a maximum and the shunting resistance becoming so small that additional decrease affects the loss inappreciably.

The variable resistor setting in the reduction control circuit determines the input amplitude at which reduction begins and therefore the point above which the loss remains substantially constant. If there is a difference in amplitude between speech and noise, the reduction control may be so adjusted that the noise on the circuit, when no speech is present, is appreciably reduced. The action then is as follows: In the absence of speech noise is reduced usually the maximum value of 20 decibles, during intervals of lower speech amplitudes the loss decreases in proportion to the increase in amplitude and during speech of high amplitude both noise and speech are transmitted without loss. As the noise encroaches upon the range of speech amplitude, it becomes necessary to reduce greater amplitudes, thereby also further reducing the weaker parts of speech.

The noise reducer is contained on a $7^1/_4$-inch panel for relay rack mounting. Figure 3 gives a front view. The panel contains the reduction control resistor and an "in-out" key which, in the "out" position, gives the device a fixed loss. Both resistor and key may be duplicated external to the panel with the wiring arranged to give remote control.

## Characteristics

Figure 4 gives the 1,000-cycle input-loss characteristic for 3 settings of the reduction control. For any setting, there is an input volume above which the loss remains constant, while for volumes below this the loss increases with decreasing input until the maximum loss is reached. The volume-regulated speech range encountered on radio circuits at some point in the circuit which is 5 decibels above reference volume as measured on a volume indicator is indicated as extending from +13 decibels to −17 decibels referred to one milliwatt for the purpose of showing approximate corresponding speech amplitudes.

Figure 5 shows oscillograms giving the input and output characteristics of noise for maximum reduction and of speech for maximum, medium, and minimum reduction. The upper trace is the input and the lower trace the output. The middle trace is not used. It will be noted by inspecting the "in" and "out" traces at the beginning and ending of the word "bark" that there is some distortion in speech for the maximum reduction condition, but very little distortion for minimum reduction. Maximum reduction would be used only in case of high noise where this distortion is less objectionable than the noise.

## Performance

Laboratory tests have been made in an attempt to evaluate the advantages to be gained by the use of the noise reducer. It was shown that, for the rather limited and controlled conditions which were tested, definite advantage can be observed in judgment tests of the effectiveness of speech transmission through noise with and without the noise reducer. This advantage is of the order of magnitude of 3 to 5 decibels at the border line between commercial and uncommercial conditions on the noisy circuit.

This figure is in approximate agreement with results obtained from records of performance on commercial connections. A curve is available which shows the approximate relation between percentage lost circuit time and transmission improvement for a long-range short-wave radiotelephone circuit.[6] From the records of lost circuit time as affected by the noise reducer use an improvement of 4 decibels is obtained from this curve.

Observations were made and records kept for 12 months of the use of the device at the land terminal of the high seas ship-to-shore circuit and for shorter periods on New York-London circuits. These observations indicate that the noise reducer most satisfactorily reduces objectionable effects where the interference consists of noise of a fairly steady character. As might be expected it is somewhat less effective on crashy static. If the noise is very low there is no improvement; as the noise increases the benefit increases up to a certain point; when the noise amplitudes begin to approach too closely the peak amplitudes of the voice waves it becomes impossible to distinguish between them without producing objectionable speech distortion and there is again no advantage. Where volume fading is present there is a tendency to accentuate the volume changes and it becomes necessary to adjust the reduction control to limit this. Otherwise this effect may offset the possible noise improvement. The operating practice is to adjust the reducer control circuit for each noise or transmission condition so that optimum reception as judged by the technical operator is obtained. The general rule is to use the minimum reduction possible.

## Use of Noise Reducer With Voice-Switched Circuits

On radiotelephone circuits for connection to the land telephone system, control terminal equipment is used at the junction of the land lines and the 2 one-way radio channels (one transmitting, the other receiving) necessary for 2-way communication. In making this connection a widely used method is one in which the 2-wire land circuit is normally connected to the receiving radio channel and is switched to the transmitting channel when the land subscriber talks. This switching is done by voice operated relays.[7,8] The noise reducer in addition to improving the intelligibility of the speech protects these voice-operated relays against false operation by the received noise.

Figure 6 shows the application of the noise reducer to

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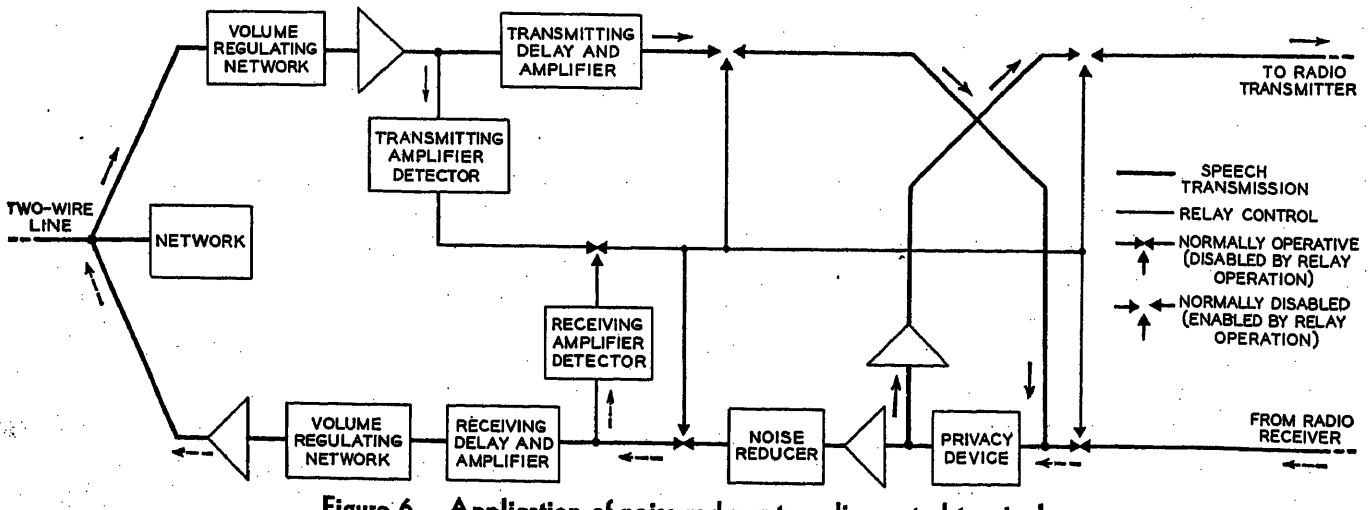



**Figure 6. Application of noise reducer to radio control terminal**

# Analysis of
# Series Capacitor Application Problems

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## Introduction

IN THE past several years series capacitors for the compensation of line drop in power circuits have found increasing use,[1-9] because improved and automatic voltage regulation can, in many cases, be obtained more economically by this method than by any other means.

Most of the applications have been entirely successful in improving the system performance. However in a few instances unforseen difficulties of an unusual character have been encountered. These difficulties were the occasion of a systematic and detailed analytical study of series capacitor performance. This study has been paralleled, as far as possible with laboratory tests and correlated with field experience. It is believed that a satisfactory explanation and understanding of the abnormal system behavior have now been obtained and that adequate methods for predetermining the system performance have been developed, although it is recognized that the investigation cannot be regarded as absolutely final and complete.

The objects of this paper are to present a survey of some of the troubles which may be encountered in the application of series capacitors to power circuits, to present criteria for determining the range and probability of abnormal operation, and to describe methods for minimizing the difficulties.

Three types of abnormality have been investigated:

1. Distorted and excessively large transformer exciting currents, due to saturation.
2. Hunting of synchronous machines.
3. Self-excitation of induction motors.

In case 1, the application of voltage to an unloaded or very lightly loaded transformer through a series capacitor may result in abnormally large and distorted exciting currents. These large currents are not simply transients but persist as a steady-state condition. This type of circuit, that is, a saturable inductance in series with a capacitor, has been found to have at least 2, and probably more, different steady states, depending on how the voltage is applied.

Solutions of the equations for this type of circuit have been found by the differential analyzer[10] at the Moore School of Electrical Engineering and are discussed in section I.

In case 2, interconnected synchronous machines will oscillate or "hunt," under certain circuit conditions. The tendency to hunt becomes more pronounced as the effective ratio of line resistance to line reactance increases, and putting in a series capacitor to decrease the reactance obviously increases this ratio. Consequently, if the machines are susceptible to hunting, the condition is further aggravated by the addition of capacitors. The case of hunting of a single synchronous machine operating from an infinite bus was investigated several years ago.[11,12] In section II of the present paper, further analytical methods are developed involving 2 or more machines which enable the size and location of a capacitor to be so chosen as to product the least tendency to hunt consistent with proper voltage regulation.

In case 3, under certain circuit conditions an induction motor operating with series capacitors will be self-excited and will generate other voltages of lower than normal frequency and thus produce objectionable voltage fluctuations. Analytical methods are presented in section III, which make it possible to determine the effectiveness of methods for eliminating this trouble.

It has been found in this investigation that the addition of a resistor in shunt with the series capacitor will eliminate the difficulties of cases 1 and 3, while the synchronous machine hunting of case 2 is minimized or not obtained by proper choice and location of the capacitor. The shunt resistor is of such a high value as not to interfere with the capacitor's effective operation as a line drop compensator and the value of the power loss in the resistor necessary to ensure complete freedom from these circuit troubles will in general be less than 10 per cent of the resistance loss in the line to be compensated. The proper value of resistance to be used in any given case may be determined from the analysis presented here. It is concluded, therefore, that the material offered in this paper, will enable practical and economically sound series capacitor applications to be made with confidence that the operating results will be in accordance with predictions.

## Section I—Distorted and Excessively Large Transformer Exciting Currents

### A. General

In the usual case of application of voltage to an unloaded transformer it is known that if the voltage is applied at or near the zero point of the voltage wave a high inrush current may result. This is because the transformer flux tends to rise, in the first half cycle, to double its normal value, with consequent excessive magnetizing current due to the very high degree of saturation. Stated in another

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1. For all numbered references, see list at end of paper.

way, at high values of flux the effective inductance of the transformer becomes very low. The high inrush current lasts for several cycles and then the transformer draws only its usual low value of exciting current. On the other hand, if the transformer is supplied through a series capacitor an abnormal current may persist in the steady state. That is, the energizing of an unloaded or very lightly loaded transformer through a series capacitor may result in a continuous abnormal flow of exciting current. This current may be equal to or even greater than full load current and is of an apparently very low frequency, resulting in a badly distorted current wave. Under this condition of excitation the secondary voltage is also badly distorted, and it likewise is largely composed of a lower frequency component. Oscillographic records of the magnetizing current, the secondary voltage and the voltage across the capacitor when a circuit is in this state of excitation are shown in figure 1.

These abnormal steady-state currents flow when the voltage is applied at or near the zero point of the wave just as the high transient occurs for this condition in the ordinary case without the series capacitor.

This phenomenon has been reported before[13–16] in the technical press and is sometimes called "ferro-resonance." The peculiar circuit behavior depends essentially on the nonlinear transformer characteristics and not on any secondary features such as hysteresis, eddy currents, etc.

The nonlinear characteristic of the transformer makes the mathematical analysis very difficult and to the authors' knowledge there has been no satisfactory analytical solution made as yet.

The differential analyzer at the Moore School of Electrical Engineering was used, with the able assistance of Irven Travis and C. N. Weygandt, to obtain solutions to the nonlinear differential equations of this circuit. Appendix *A* gives the equations of the circuit and the form into which they were put to adapt them to the analyzer.

The single-phase circuit, as shown by figure 2, was set up and investigated thoroughly before the 3-phase case was studied, as it was believed that the essential features of the phenomenon could be obtained more directly in this manner. A schematic diagram giving the analyzer set-up for equations 2*a* and 3*a* is shown in figure 3.

The 3-phase circuit was set up as a final check and the results obtained indicated that the single-phase results were qualitatively applicable.

Typical curves drawn by the analyzer as solutions to equations 2*a* and 3*a* are shown in figures 4, 5, and 6.

A short simplified explanation of the physics of the phenomenon will be made here, for the sake of completeness.

## B. Qualitative Explanation of Phenomenon

These abnormal currents may be explained as follows: Consider that the voltage is applied to the transformer at the zero point of the wave. During the first part of the cycle the flux in the core builds up just as though the capacitor were not present, since the current drawn is so small that there is no appreciable voltage drop across the capacitor. However, as soon as saturation is reached, the current drawn becomes very large and a voltage soon appears across the capacitor. The voltage absorbed by the capacitor prevents the flux from building up to as high a value as it would have without the capacitor, so the first half cycle inrush current is somewhat less. Moreover, as the flux tends to remain offset it does not reach a high value in the negative direction in the second half cycle. To the contrary, it may hardly dip below zero. Thus the exciting current remains very small (or, the transformer inductance remains very large) for the interval following. The charge is therefore left on the capacitor, which simply acts as an additional voltage source. This additional voltage tends continually to depress the transformer flux, just as in the first half cycle it prevented the flux from reaching double its normal value. Thus in the second cycle the flux may not go high enough to saturate the core so no additional charge is put on the capacitor. On the other hand, as practically no charge has leaked off, the capacitor voltage is still decreasing the flux. The general effect is as shown in figures 4*b* and 4*c* and is that of first

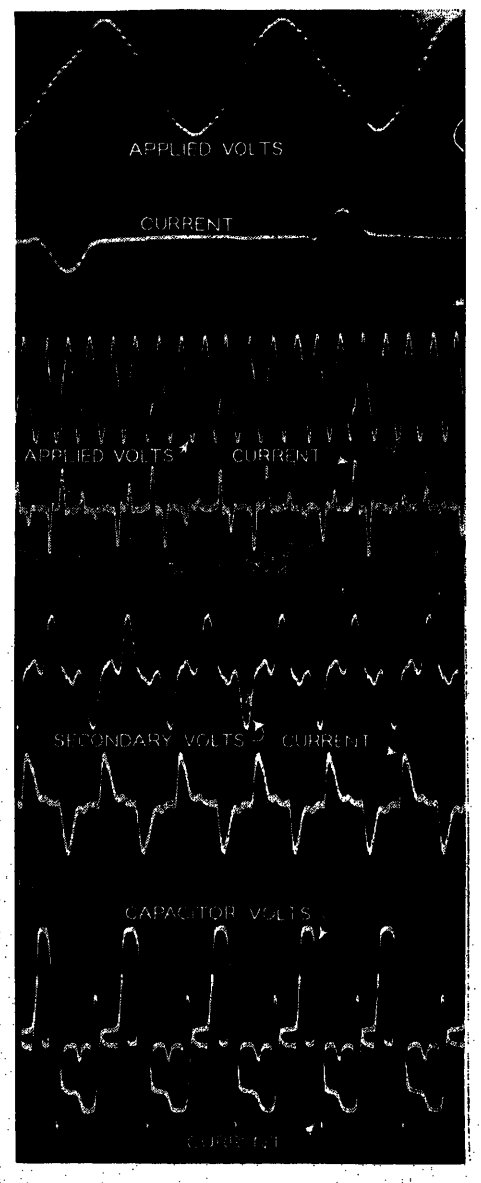



**Figure 1. Oscillograms of abnormal currents and voltages obtained when transformer is excited through series capacitor**

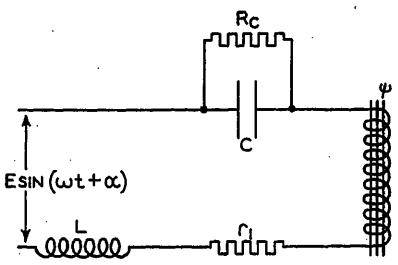



**Figure 2. Circuit diagram of transformer energized through a series capacitor, series impedance, and shunting resistance $R_c$**

tending to reduce the offset and then actually to build up an offset in the negative direction. This process continues, at a rate proportional to the magnitude of the voltage trapped on the capacitor, until saturation is reached in the negative direction. When this occurs a large negative current is drawn, discharging the capacitor. This large negative current may discharge the capacitor partially, completely, or may put on a charge in the reverse direction. It is easily seen that, except for a fortuitous combination of circumstances, the discharge will be either partial or an overshoot. If it is partial the flux will reach a larger negative value at the next cycle, and then the capacitor will receive an opposite charge. This negative charge will, of course, have the effect of reducing the negative offset and then building up a positive offset, so that the cycle of abnormal operation is complete.

Since the rate of decrease of offset is proportional to the voltage on the capacitor, the apparent frequency of occurrence of these large currents (due to saturation being reached) is necessarily dependent on the voltage applied and on the angle at which it is applied. For instance, the larger the initial charge on the capacitor, the sooner it will build the linkages down to the saturable place on the negative side, and give a higher frequency appearance to the exciting current.

In order to demonstrate this property of the circuit, solutions, as given by the analyzer with different values of voltage applied at the zero point of the wave, are shown in figure 4. The periodicity increasing with the applied voltage is clearly seen. If the voltage is increased sufficiently, the circuit can be made to saturate every half cycle and results such as those obtained by Suits[17] are then obtained.

## C. Summary of Results Obtained From the Differential Analyzer

It is felt that the major contribution this investigation made was that of explaining and clarifying to a certain degree the physics of the phenomenon. In order to appreciate the "goings on" in the circuit, fundamental circuit concepts must be kept in mind, as vector diagrams, resonance, sustained harmonic solutions, and other linear circuit concepts fail when nonlinear parameters are employed.

The effect of a damping resistor shunting the capacitor was investigated and the results are summarized in figure 7.

In these figures, the region above each curve represents an unstable or abnormally excited circuit condition; that is, if a given circuit has a value of capacitance and shunting resistance that fall in the area above the corresponding

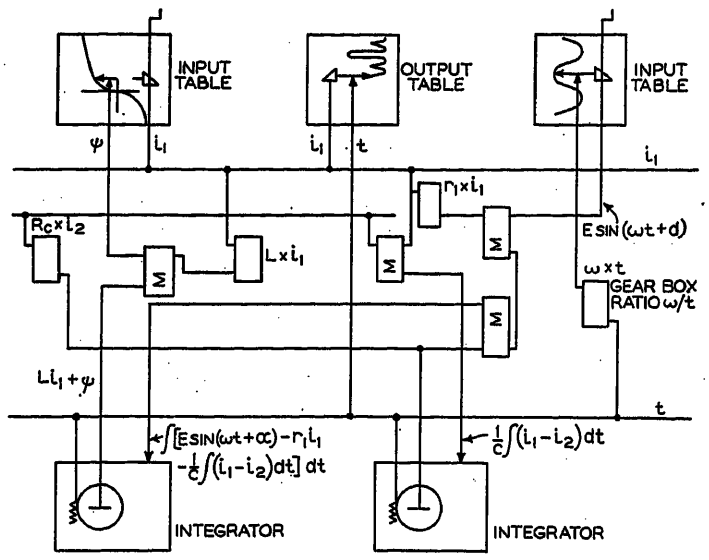



**Figure 3. Schematic diagram of differential analyzer connections for solution of circuit equations**

curve and the voltage is applied at or near the zero point on the wave, the circuit will draw a sustained large distorted magnetizing current. All points below each curve represent a so-called stable area where the circuit will have its normal low value of magnetizing current. The various curves show the effect of changing the line reactance, the line resistance, and the transformer iron characteristic. The 2 iron characteristics are shown in figure 8. Curve 1 represents the magnetization curve of a modern transformer. Curve 2 was taken arbitrarily to have the current scale of curve 1 multiplied by 3 merely to show the effect of a different magnetizing characteristic or of a larger transformer.

In figure 7 the value of capacitance, to which the left side of each curve is asymtotic, represents the value of capacitive reactance that must be used to prevent the circuit from going into a state of overexcitation without a damping resistor. Unfortunately these values are so low, that they can seldom be useful in correcting a bad voltage condition.

These curves were all determined for normal voltage applied at the zero point of the wave. In certain cases, it may be found that a resistance sufficient to insure normal operation under these conditions will not be low enough if the system is operated at a different voltage. For example, figure 5 illustrates a case in which reducing the voltage caused an abnormal state of excitation. Curve 1 shows normal operation at normal voltage, while curve 2 shows the overexcited condition occurring when 0.75 voltage is applied. Both voltages were applied at the zero point of the wave. This indicates also that in some cases the application of voltage at the zero point of the wave may not be the worst condition since in a sense a shift of angle is partially equivalent to a reduction of voltage, at least as far as the initial charge given to the condenser is concerned.

A circuit having a resistance shunting the saturable inductance, simulating a load being taken off the circuit

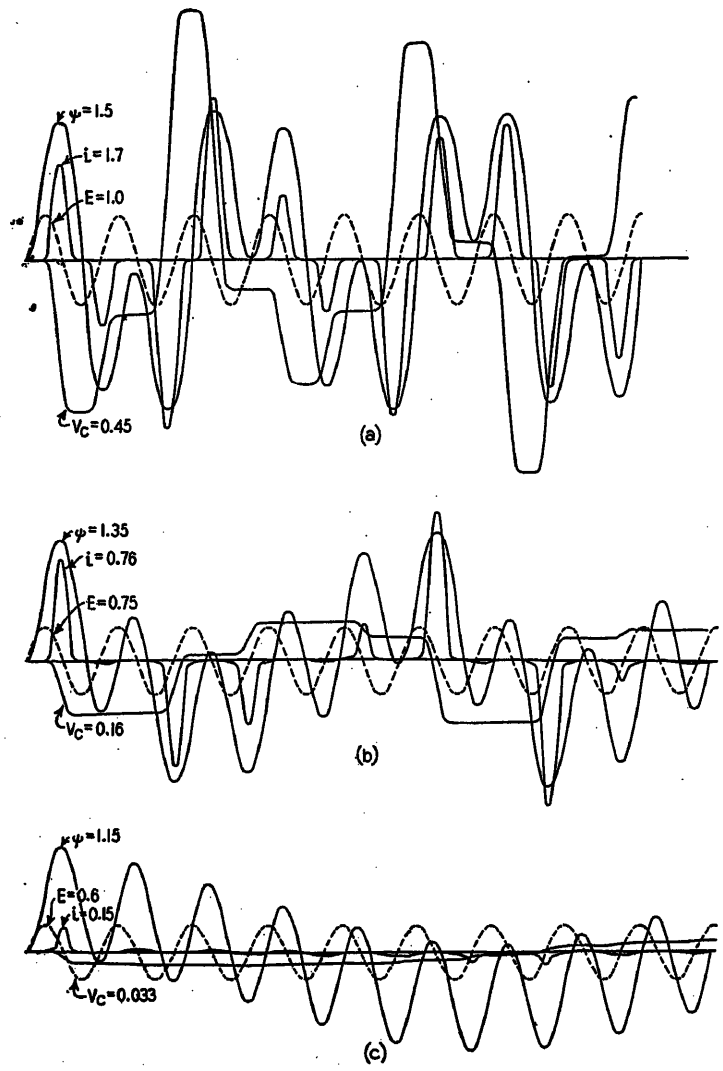



**Figure 4. Effect of applied voltage on the apparent periodicity of exciting current**

| | | |
|---|---|---|
| $r_1 = 0.049$ | $1/C = 0.214$ | (a) $E = 1.0$ |
| $R_e = \infty$ | Magnetization curve 1 | (b) $E = 0.75$ |
| $L = 0.197$ | $\alpha = 0$ | (c) $E = 0.6$ |

between the transformer and the capacitor, was also investigated on the differential analyzer. The critical points obtained with this circuit agreed very well with the points for the same resistance when it was shunting the capacitor, indicating that it made little difference where the resistor was located.

From figure 2 it may be seen that the 2 locations of the resistor are equivalent to 2 locations of the applied voltage, the circuit remaining unchanged. Further, in the canonical equations for a general linear circuit, consisting of any number of meshes, the characteristic determinant is independent of the magnitude or location of the applied voltages. It is therefore evident that the *form* of the transient response, or the building up or dying away of a transient current, is also independent of where the voltage is applied.

This reasoning, showing that in a *linear* circuit, the location of the resistor does not affect the periodicity of the circuit, combined with the differential analyzer results for the nonlinear circuit, indicate that this may well be a general conclusion. It has been known in practice that intervening or secondary loads prevent this overexcitation condition, but the effect had not been previously investigated quantitatively.

## D. Conclusions

An unloaded transformer, operating at normal densities, if excited through a series capacitor of reasonable reactance, is susceptible to conditions of large distorted magnetizing currents. These abnormal conditions can be restored to normal by the addition of a suitable shunting resistor to the capacitor, as indicated by figure 7, or by the locating of a certain amount of load on the load side of the capacitor.

The resistor shunting the capacitor, introduces additional losses. However, in general, this loss is less than 10 per cent of the normal line loss and this can usually be justified by the improvement in voltage regulation. Moreover, since the presence of the abnormal condition depends on the initial transient, it may be eliminated by shorting out the capacitor only while the starting switch is being closed, or by having the resistor connected only during the energizing period. The shorting switch or temporary resistor may readily be arranged so as to function automatically whenever the abnormal condition tends to develop.

# Section II—Hunting of Synchronous Machines

## A. General

An electric power system consists in general of a group of interconnected synchronous machines together with impedance and induction motor loads. Any such system is subject at practically every instant of its existence to disturbances caused by changes in load, switching, pulsating loads, pulsating driving torques, changes in excita-

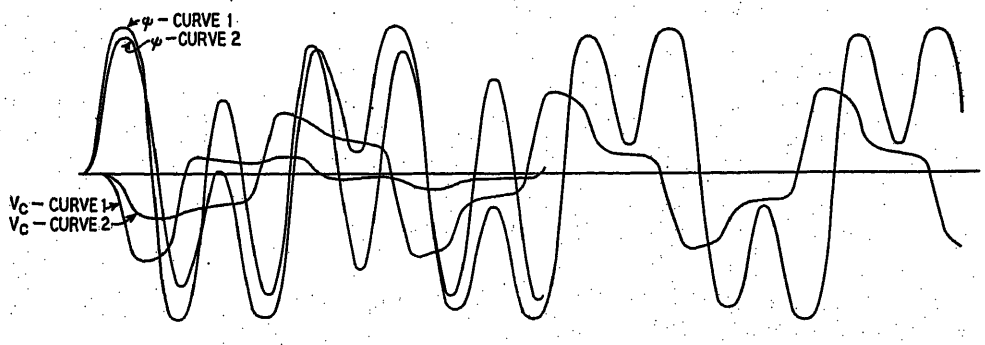



**Figure 5. Effect of voltage on excitation**

Curve 1 $E = 1.0$. Normal excitation, capacitor voltage decreases
Curve 2 $E = 0.75$. Abnormal excitation, capacitor voltage builds up
$1/C = 0.35$ $L = 0.394$
$R_e = 6.3$ $r_1 = 0.197$
$\alpha = 0$ Magnetization curve 2

tion, etc. These disturbances tend to set up rotor oscillations of the synchronous machines, with consequent voltage and frequency pulsations. Therefore, for satisfactory operation, the system constants must be such as to cause any such oscillations to disappear rapidly if due to a momentary disturbance, or to remain of small amplitude if due to a continuous pulsating force. A momentary disturbance will, in general, produce oscillations of the synchronous machines at all of the principal natural frequencies of the system, while a sustained pulsating force of any frequency will of course produce machine oscillations of the same frequency.

## B. Effect of Line Resistance and Series Capacitance

The inherent damping of the system is usually sufficient to prevent severe hunting. However, in certain cases the damping may be either too small to be effective or may actually be negative. That is, the rotor oscillations may be amplified rather than damped out. There are present in all systems 2 conflicting effects. Resistances in the rotor circuits, some types of load, and mechanical friction will produce true damping of rotor oscillations, while resistance in the lines or armature circuits tend to produce amplifying rotor oscillations (or negative damping).

In the case of a single synchronous generator connected to an infinite bus, it has previously been shown[11,12] that the ratio of line resistance to line reactance determines whether or not there is negative damping, and that if all rotor circuits except the field winding are neglected, there is a critical operating angle determined by this ratio above which the machine is unstable. The critical angle is always decreased by the presence of rotor windings, so the method provides a conservative criterion.

If a series capacitor is used in the line the ratio of line resistance to line reactance is increased, since the reactance has been reduced. Consequently the tendency toward negative damping is increased.

## C. System of Several Machines

In case of a system consisting of several machines, it is shown in appendix $B$ that there is a corresponding relation among the line resistances and reactances which determines the negative damping and that therefore such damping will be affected by the insertion of series line capacitors. However, it cannot be expected now to be a simple resistance-to-reactance ratio; instead the criterion for stable operation is a ratio of certain combinations of line constants. For example, if the case treated in reference 11 is extended to include shunt loads taken off the line, the criterion becomes the ratio of the resistance to the reactance components of the transfer impedance between the synchronous machine and the infinite bus (see appendix $B$, equation 8$b$).

In appendix $B$ a system consisting of 2 synchronous generators, an infinite bus, and a shunt load (see figure 9) has been analyzed. This is believed to be sufficiently general to form a basis for the study of almost any particular case which may arise. The critical operating angle of either generator in this general case is shown to be dependent not only on the ratio of combinations of the line constants, but also on the operating angle of the second machine and on its relative amplitude and phase of oscillation. The line constants enter the equation as ratios of the resistance to the reactance components of the several transfer and driving point impedances and so are correlated to the criterion developed by Nickle and Pierce.[11]

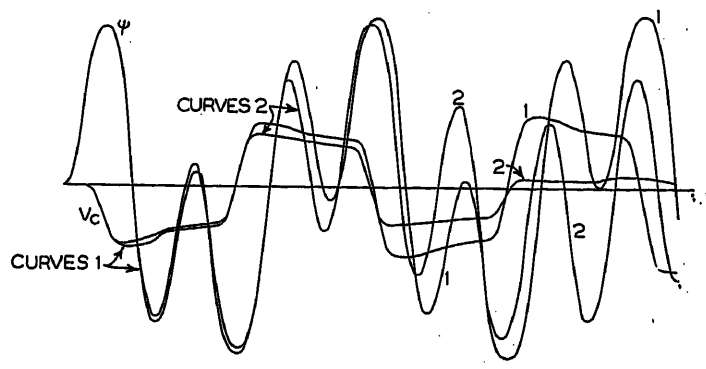



**Figure 6. Linkage and capacitor voltage curves with critical values of $R_c$**

Curve 1— $R_c = 6.7$. Abnormal, capacitor voltage builds up
Curve 2— $R_c = 4.2$. Normal, capacitor voltage decreases
$\alpha = 0$ $r_1 = 0.197$ Magnetization curve 1
$L = 0.394$ $1/C = 0.21$

The equations of appendix $B$ may be used to study any particular proposed series capacitor application to determine whether or not it is in the danger zone and, if it is, to determine the optimum location and maximum permissible reactance of the series capacitor consistent with proper line drop compensation. These equations also enable the effectiveness of putting additional series reactance in certain machine circuits to be evaluated.

## D. Discussion of Results

As an example of the method of analysis, a problem in which the circuit may be represented as in figure 9 has been worked out. In this case the synchronous generators at 1 and 4 ordinarily supply the load, line 3 merely acting as a tie to the large system at 3. However, occasionally power must be supplied to 4 from 3. Under this condition the voltage regulation at 4 is rather poor and it is desired to correct it by the insertion of a series capacitor between points 3 and 4. As considerable line drop occurs in line 3 the logical place to put the capacitor might seem to be in that line so as to give loads at 2 some benefit. Unfortunately, when this is done the hunting of machine 1 is found to be excessive, while if the capacitor is placed in line 4 hunting is no worse than without the capacitor. The desired result of correcting the bad voltage condition at 4 is accomplished by putting the capacitor in line 4. However in this location the additional advantage of correcting the voltage at the junction is not obtained.

Table I shows the results of calculations of the minimum permissible load angle of machine 1 for stability, under the 3 conditions of no capacitor, capacitor in line 4, and capaci-

tor in line 3, and also for different reactances in branch 4 and with and without shunt load. It is evident from this table that the capacitor in 4 causes a much smaller difference from the original condition than it does when in branch 3.

Although a picture can thus be obtained of the relative tendencies toward hunting of several proposed arrangements, it has not been absolutely determined by calculation that one arrangement will operate satisfactorily and another will not. This is still a matter of judgment fortified by a correlation of field experience with the calculations.

The critical angles recorded in table I are the load angles $\delta_1$–$\delta_1'$ where $\delta_1$ is found as described in appendix *C* and $\delta_1'$ is the no-load angle of machine 1 referred to the infinite bus 3. The oscillation of machine 4 was neglected (i.e., $k = 0$), since it was assumed that the machine being investigated would have the largest amplitude of oscillation. Also it was found that the necessary load angles were only slightly affected by the operating angle $\delta_4$ of machine 4. It is therefore possible to use the simplified formula (8*b*.1) for nearly every case by simply substituting the value of $z_3$ ($z_3 = r_3 + jx_3$) paralleled with $z_4$ for the $z_3$ of equation (8*b*.2).

A more exact study of a system may be made by taking the amortisseur windings of the machines into account and computing the damping coefficients by the methods of reference 25 for every probable mode of vibration. The modes of vibration corresponding to the 2 principal natural frequencies of the system of figure 9, or to any impressed forces, can be very simply calculated if the inertia constants of the machine are known. This will not usually be necessary, however, since sufficient information can be obtained from a study of the system neglecting amortisseur windings and a knowledge of the general effects of such windings. (See, for example, reference 19.)

**Table I**

| Condition | Critical Load Angle ($\delta_1 - \delta_1'$) of Machine 1 (Degrees) |
|---|---|
| No capacitor.....$r_2 = \infty$, $x_4 = 0.2$, $r_4 = 0.05$ | 1.38 |
| Capacitor in number 4....$r_2 = \infty$, $x_4 = 0.2$, $r_4 = 0.05$ | 1.32 |
| Capacitor in number 3....$r_2 = \infty$, $x_4 = 0.2$, $r_4 = 0.05$ | 4.14 |
| No capacitor.....$r_2 = 1$, $x_4 = 0.2$, $r_4 = 0.05$ | 1.48 |
| Capacitor in number 4....$r_2 = 1$, $x_4 = 0.2$, $r_4 = 0.05$ | 1.40 |
| Capacitor in number 3....$r_2 = 1$, $x_4 = 0.2$, $r_4 = 0.05$ | 3.94 |
| No capacitor.....$r_2 = \infty$, $x_4 = 1.07$, $r_4 = 0.049$ | 1.72 |
| Capacitor in number 4....$r_2 = \infty$, $x_4 = 1.07$, $r_4 = 0.049$ | 1.70 |
| Capacitor in number 3....$r_2 = \infty$, $x_4 = 1.07$, $r_4 = 0.049$ | 2.46 |
| No capacitor.....$r_2 = 1$, $x_4 = 1.07$, $r_4 = 0.049$ | 1.88 |
| Capacitor in number 4....$r_2 = 1$, $x_4 = 1.07$, $r_4 = 0.049$ | 1.88 |
| Capacitor in number 3....$r_2 = 1$, $x_4 = 1.07$, $r_4 = 0.049$ | 2.67 |

See figure 9 for circuit.

$r_1 = 0$ $\quad r_3 = 0.023$ $\quad x_g = 0.65$ $\quad x_3 = 0.0516$
$r_2 = \infty$ or 1 $\quad r_4 = 0.05$ $\quad x_2 = 0$ $\quad x_4 = 0.20$ or 1.07
$x_c = 0.105$ = capacitive reactance

Note: $x_g$ and $x_4$ include both line and machine reactances.

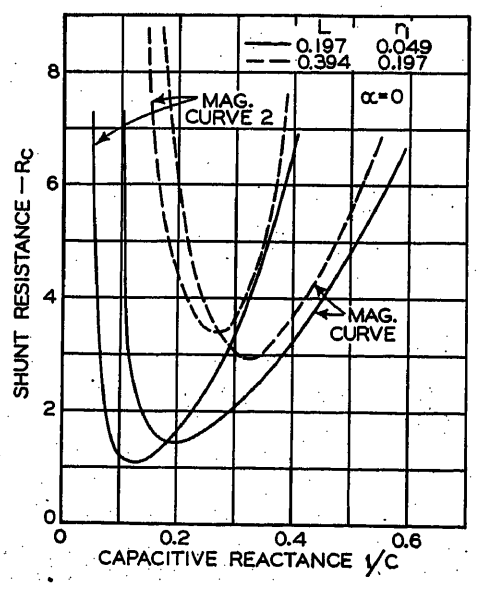



**Figure 7. Limits of normal excitation as a function of $R_c$ and 1/C. Area below each curve is normal. Area above each curve is abnormal**

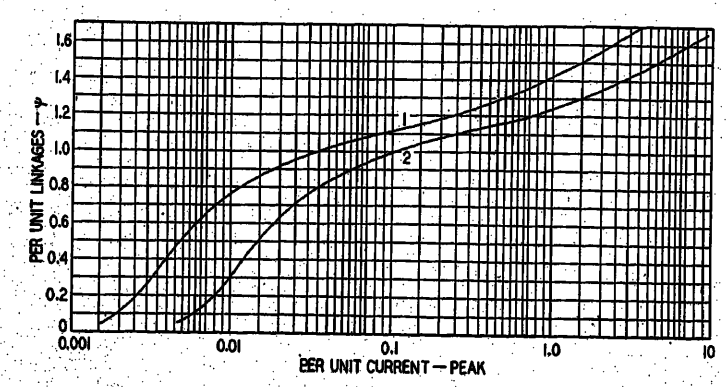



**Figure 8 (below). Magnetization curves. Curve 2 is curve 1 with current scale multiplied by 3**

## Section III—Self-Excitation of Induction Motors

### A. General

It is well known that an induction machine will operate as a generator and that such operation depends on the supplying of excitation from either a synchronous machine or a capacitor even though in case of the capacitor the operation has not previously been very well understood.

Now consider an induction motor supplied through a line containing a series capacitor. Then in addition to the currents flowing due to normal operation of the motor, under certain conditions the motor may act as an induction generator of current of lower than normal frequency. This low-frequency current is limited only by the impedance of the supply circuit at the low frequency, and may reach relatively large values. These large low-frequency currents manifest themselves not only as current surges and voltage swings but also as strong oscillations of the motor rotor caused by the large pulsating torques produced.

This phenomenon of self-excitation will not always take place and may always be entirely eliminated by sufficient line or shunt resistance, or by judiciously locating the capacitor. It may, moreover, be calculated with reasonable certainty and accuracy by equations given in appendix *C*, if the circuit constants and operating conditions are known.

Figures 10 to 13 show the regions in which self-excitation is likely to occur for the case of a purely induction motor load. Figures 10 and 11 show the effect of series

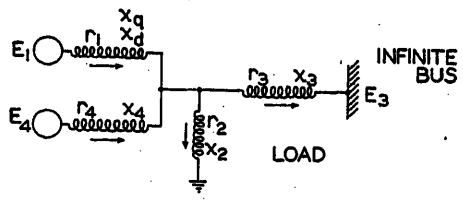



**Figure 9. Circuit diagram of 2 synchronous machines connected to infinite bus and impedance load**

line resistance in preventing self-excitation, while figures 12 and 13 show how a resistance in shunt with the capacitor can eliminate the phenomenon. For any practical case the reactance of the series capacitor will of course be much less than $x'$, probably about half of $x'$, since $x'$ is the short-circuit reactance of the motor including line reactance and since the capacitor reactance will usually be no greater than line reactance. Therefore figure 14 is given, showing the shunt resistance necessary to prevent self-excitation in the useful range of capacitance, for 2 sets of system constants.

The values of shunt resistance given in the curves will usually be conservative because the effect of series line resistances and machine losses, which themselves tend to damp out self-excitation, has been neglected. Equations are given in appendix *C* which take both shunt and series resistance into account and which should be used to analyze any specific problem. These are based on the analysis presented in reference 20. Figure 15 shows an example of how the value of $\alpha$ necessary for stability decreases with increasing line resistance.

## B. Discussion of Results

Figure 10 shows that as long as the capacitive reactance is less than half of the system short-circuit reactance, self-excitation will not occur for a normally loaded group of induction motors. This is because the line resistance is usually great enough to damp out any tendency to self-excite. However, as soon as a certain critical value of short-circuit reactance is exceeded the amount of series resistance required begins to increase rapidly. This critical value of reactance is, of course, a function of the motor characteristics and the impedance of the connected circuit. If the line is relatively short (i.e., if its reactance is less than the motor reactance) it may be compensated more than if it is long, unless a shunt resistor is added to prevent self-excitation.

Figure 11 shows that as the motor speed decreases the region of self-excitation moves down along the $x_c$ ordinate. That is, the tendency to self-excite occurs at a lower value of capacitive reactance at lower motor speeds. Such low speeds occur during starting and during periods of overload. We should thus expect some oscillations as the motor comes up to speed. This is especially true if a starting resistance is used in the rotor, as figures 10 and 12 indicate that an increase of rotor resistance increases the tendency to self-excite. In general it will not be necessary to eliminate these transient oscillations. Actually, in service when the system behaves correctly under normal operating conditions no trouble during starting has been experienced. If, however, the system does not have very much margin at normal load, a sustained overload may produce self-excitation.

## C. Calculations and Test Results

In order to check the theory offered for this so-called "self-excitation phenomenon," tests were conducted on a miniature set-up, in order to get good control of the variables. A 3-phase $^3/_4$-horsepower wound-rotor induction motor was connected to a power source through a series capacitor and 0.39 per unit external reactance. The values of series capacitance were varied over the complete range of self-excitation, and the corresponding value of shunting resistance to insure normal operation was determined. These tests results, and corresponding calculated points on the curve are shown plotted in figure 16. The agreement between test and calculated values was very gratifying. It is felt that the equations offered can be used with confidence in predetermining these regions of abnormal operation.

The motor was tested running light, hence the speed was taken as unity to simplify the calculations. The armature resistance of the motor and external circuit was 0.10 per unit. This high circuit resistance is the reason for the curve in figure 16 intersecting the $\alpha = 0$ point at such a high value of $x_c$. The rotor resistance was likewise very high, hence the motor had a correspondingly small rotor time constant. The small rotor time constant gives the motor a greater tendency to self-excite as shown in figures 10 and 12.

In view of the type of motor tested, that is, one having high resistances, these test results should not be generalized as significant of normal motor performance.

The line of demarkation between normal operation and

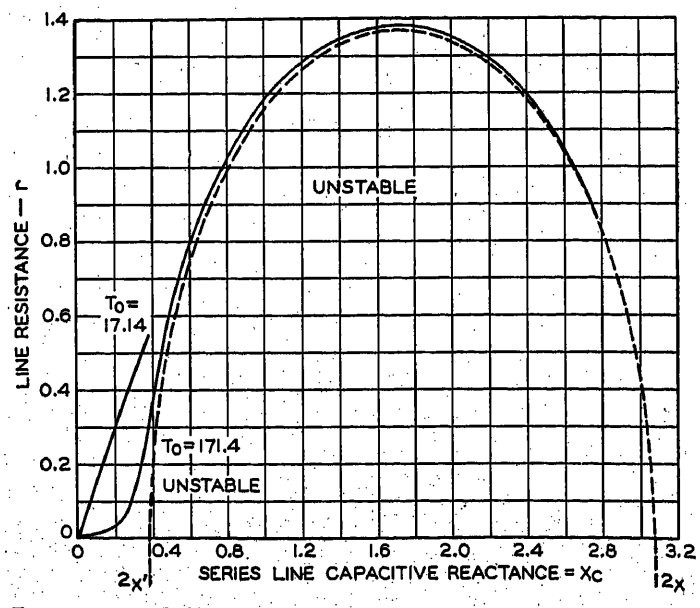



**Figure 10. Self-excitation of induction motors with series capacitors**

Showing series resistance required for stable operation as a function of the line capacitance and showing effect of varying rotor resistance

$x' = 0.4$ $x = 3.24$ $T_o = 171.4$ and 17.14 $\omega = 0.975$

self-excitation was very sharp up to $x_c = 0.6$. Calculations and tests both showed this. Beyond $x_c = 0.6$ the calculated curve became more difficult to determine because it seemed to be very broad in the upper regions, that is, it was difficult by ordinary slide rule methods to get a smooth curve, indicating the critical region was not very sharply defined. Tests bore this point out in the upper regions. The test points plotted are the largest values of $\alpha$ found for each value of $x_c$. The current wave was watched through an oscilloscope and self-excitation could be readily recognized by a change in the wave. In the lower regions below $x_c = 0.6$, the phenomenon was more violent and critical. A change of a few per cent in the value of shunting resistance $R$ in this region, would be sufficient to change the circuit from normal to a definite state of self-excitation. The region of self-excitation in the practical and useful range of $x_c$ can be readily recognized by calculation since this range is below $x_c = 0.6$.

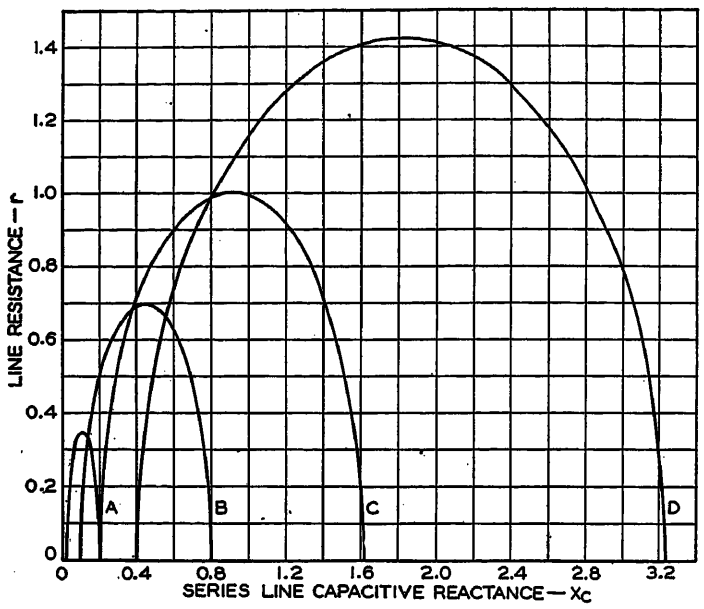



**Figure 11. Self-excitation of induction motors with series capacitors**

Showing effect of varying motor speed
$A$—$\omega = 0.25$ $B$—$\omega = 0.5$ $C$—$\omega = 0.707$ $D$—$\omega = 1.0$
$x' = 0.4$ $x = 3.24$ $T_o = 171.4$

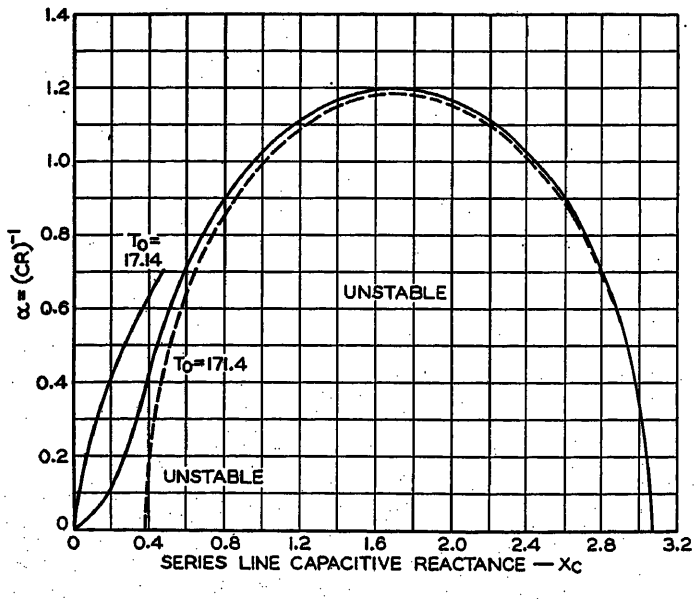



**Figure 12. Self-excitation of induction motors with series capacitors**

Showing resistance (in shunt with the capacitor) required for stable operation as a function of the line capacitance and showing effect of varying rotor resistance
$x' = 0.4$ $x = 3.24$ $\omega = 0.975$ $r = 0$

Figure 17 is an oscillogram of the current flowing in one phase during the motor starting period, and of the subsequent flow of current when the circuit is in the state of self-excitation. It will be noted that in this case the motor came up to speed in the normal manner, with normal inrush and sustained current. However in several cycles the current built up to several times normal with obvious superposed frequencies, which are identified as the natural currents of the system having positive decrement factors. These currents are ultimately limited in magnitude by saturation and the current builds up until the circuit constants change to a value that will not permit further self-excitation.

## D. Self-Excitation of Synchronous Machines

It has been stated above that in circuits containing series capacitors and induction motors, there may be a tendency to self-excite and that in circuits containing series capacitors and synchronous machines there may be a tendency toward hunting. It is evident, however, that the tendency to self-excite (that is, to generate amplifying current oscillations even though the rotor inertia prevents hunting) exists also in synchronous machines. It has been possible to obtain a satisfactory explanation of operating experience with synchronous machines on the basis of hunting alone but it is conceivable that under certain conditions purely electrical self-excitation may be encountered.

While this matter has not been thoroughly studied, the phenomenon is familiar in relation to the determination of the line charging capacity of synchronous generators. S. B. Crary,[21] M. Takahashi,[22] and Y. H. Ku[23] have made a study of this subject and have shown the tendency of line resistance to reduce the self-excitation. By means of the theory given in reference 20, it may further be shown that a resistance in shunt with the capacitor may also be used to eliminate the self-excitation (see appendix *D*). Figure 18 shows, for the same generator as in figure 1 of reference 21, the effect of shunt resistance.

Since the effect of rotor circuits in addition to the main field has not yet been determined, no definite conclusions can be drawn from this curve, but it is believed worthwhile to point out the existence of such self-excitation and to indicate that it may be corrected exactly as in the case of induction motors. The phenomena of self-excitation and hunting may of course exist simultaneously and are mutually dependent to a limited extent. Their mutual effects have not yet been studied exactly.

The ideal procedure, from a mathematical point of view,

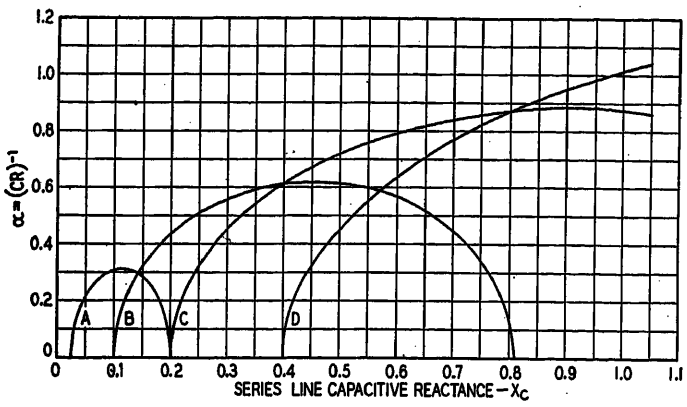



**Figure 13. Self-excitation of induction motors with series capacitors**

Showing effect of varying motor speed

$A$—$\omega = 0.25$ $x' = 0.4$ $B$—$\omega = 0.5$ $x = 3.24$ $C$—$\omega = 0.707$ $T_o = 171.4$ $D$—$\omega = 1.0$ $r = 0$

would be to set up the equations of motion of the circuit including both electrical and mechanical motions, and then to find out whether the system as a whole was stable or unstable. This method brings out very clearly the basic identity of the phenomena of hunting and self-excitation but is, from an engineering point of view, at present impracticable because of the excessive labor involved in the calculations. It is believed that the results obtained by the approximate studies are practically the same as would be found by the unified method.

## Nomenclature

### Section I

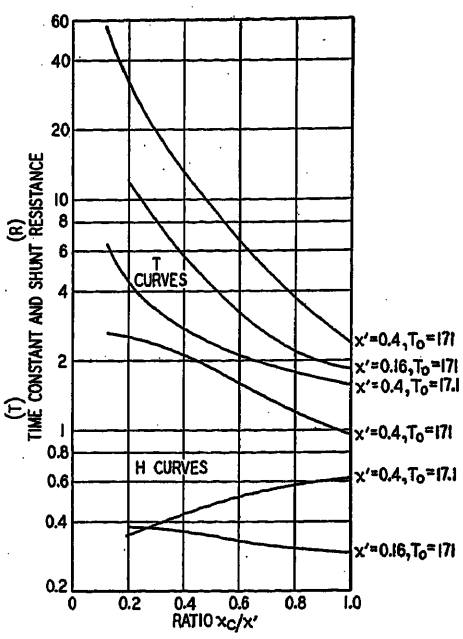
$E$ = applied voltage, maximum value
$t$ = time in radians
$\alpha$ = phase angle of applied voltage
$r_1$ = line resistance
$i_1$ = line current
$i_2$ = current through $R_c$
$R_c$ = resistance shunting the capacitor
$L$ = line inductance
$C$ = capacitance
$\psi$ = flux linkage
$V_c$ = voltage across capacitor

### Sections II and III

$E$ = internal voltage
$e_d$, $e_q$ = direct and quadrature axis terminal voltages
$\psi_d$, $\psi_q$ = direct and quadrature axis flux linkages
$i_d$, $i_q$ = direct and quadrature axis currents
$x_d$, $x_q$ = direct and quadrature axis synchronous reactances (section II)
$r$ = stator line resistance per phase
$\delta$ = angle of voltage $E$ from some reference point
$\theta$ = angular displacement of rotor
$\omega = p\theta$ = rotor speed
$x_c$ = line series capacitive reactance
$T_o$ = rotor time constant with open-circuited stator
$x$ = direct or quadrature axis synchronous reactance of induction motor including line reactance
$x'$ = direct or quadrature axis transient reactance of induction motor including line reactance
$\alpha = x_c/R$

**Figure 14. Self-excitation of induction motors with series capacitors**

Showing resistance (in shunt with the capacitor) required for stable operation as a function of the line capacitance for various systems
$x = 3$ $r = 0$
$\omega = 0.975$




$R$ = resistance in shunt with the capacitor
$k = \dfrac{\partial \delta_m}{\partial \delta_n}$
$m, n$ = subscripts given to currents, voltages, impedances, and angles in relating them to certain machines and circuits as used in section II

## Appendix A—Derivation of Equations Set Up on the Differential Analyzer

The single-phase circuit analyzed is represented in figure 2. The magnetization curves shown in figure 8 are the 2 iron characteristics that were investigated and discussed in the body of the paper.

The differential equations applying to this circuit are:

$$E \sin (t + \alpha) = r_1 i_1 + L\frac{di_1}{dt} + \frac{1}{C}\int (i_1 - i_2)dt + \frac{d\psi}{dt} \qquad (1a)$$

$$i_2 R_c = \frac{1}{C}\int (i_1 - i_2)dt \qquad (2a)$$

Rearranging and integrating (1$a$) into a form applicable to the differential analyzer, there is:

$$Li_1 + \psi = \int \left[ E \sin (t + \alpha) - r_1 i_1 - \frac{1}{C}\int (i_1 - i_2)dt \right] dt \qquad (3a)$$

The schematic hook-up of the analyzer, giving the solution to equations 2$a$ and 3$a$ is shown in figure 3. The input voltage was actually not cranked in by an operator. Instead an auxiliary set-up was made that gave the solution to the differential equation

$$\frac{d^2x}{dt^2} = -x \qquad (4a)$$

which is a sinusoid, and it was impressed automatically into the hook-up. An operator was needed to crank the current into the system by keeping a pointer representing $\psi$, the linkage, on the linkage-current characteristic. Values of applied voltage, linkage, capacitor voltage, and total current were plotted by the output tables.

The procedure used to determine the points on the resistance-capacitive reactance curves of figure 7 was as follows. The differential analyzer was started at a point corresponding to application of the voltage at the zero point of the wave and the several dependent variables of the circuit plotted automatically on an output table.

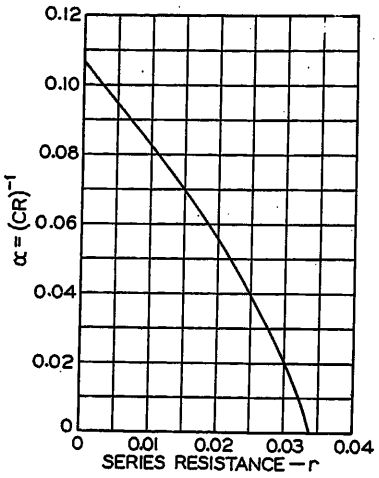



**Figure 15. Relation between line resistance and $\alpha$ required to prevent self-excitation**

$x = 3.24$ $x' = 0.4$
$x_c = 0.2$

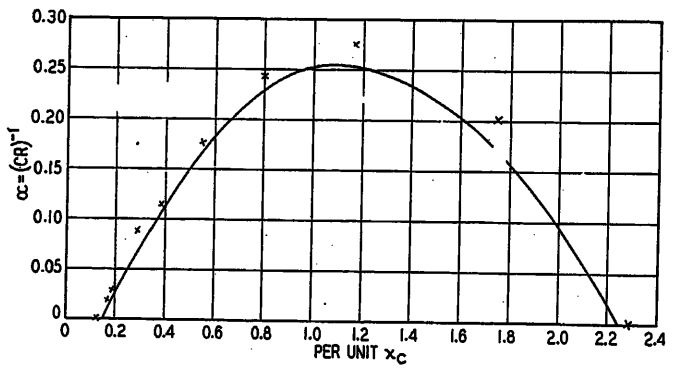



**Figure 16 (below). Self-excitation of induction motors with series capacitors**

Comparison of calculated and test results
X—Test points
Curve—Calculated
$x' = 1.03$ $x = 2.32$
$\omega = 1.0$ $r = 0.10$

As indicated by the equation above there are several variables which can be used in the interpretation of the analyzer results. The quantities which would ordinarily be measured in test of an actual circuit are the transformer voltage and current. However, it was found by experience that the most significant quantities, as far as the efficient determination of a criterion for proper circuit operation was concerned, were the capacitor voltage and transformer flux. Since, as shown in the oscillograms, the current only appears as an appreciable magnitude at widely separated intervals of time (e.g., figures 1*a* and 4*c*) and, when it does appear, it is likely to bear no obvious relation to its previous value, thus it is very difficult to use current as a continuous indication of the behavior of the circuit. On the other hand, the transformer flux, which bears a direct functional relation to the current as given by the saturation curve, is always of a reasonably large magnitude and of a nearly sinusoidal wave shape. It appears, as shown in figures 4 to 6, as a sinusoidal wave having a slowly varying displacement, and the rate of change and magnitude of this displacement were found to be useful factors in determining as quickly as possible from a given analyzer run, whether or not the circuit would approach its proper steady state.

The capacitor voltage was found to be still more useful in this respect; that is, if one had to judge from the behavior of only one quantity whether the circuit was to approach a normal or abnormal condition, one would choose the capacitor voltage. This voltage determined by its magnitude the rate of change of flux wave displacement, by its rate of discharge the effectiveness of the shunt resistor, by its duration the continuance of the shifting of displacement of the flux wave. In general, it was discovered that if ever the capacitor voltage increased in magnitude from cycle to cycle (it will be understood here that by "cycle" is meant the apparent cycle of the low frequency current pulsations and not that of the applied voltage), for example, if it ever went higher the second time than it did the first, the system behavior was abnormal. On the other hand, if it continually decreased in magnitude from cycle to cycle the circuit operation was sure to be normal. This is illustrated by figure 6 which shows curves of capacitor voltage taken at 2 different values of shunt resistance, one just sufficient to produce normal operation, the other slightly higher.

## Appendix B—Criteria for Negative Damping of Synchronous Generators Neglecting Amortisseur Winding

Consider the circuit of figure 9 with 2 generators connected to an infinite bus with a shunt load at the branch point and with resistances and reactances as indicated.

The effects of salient poles will be considered only in machine number 1, the stability of which is being investigated, while machine number 4 is considered to be round rotor. Moreover, the reactance $x_4$ will usually be taken as the transient reactance or some modified value depending on the frequency of the oscillation being studied.

The steady-state equations for this circuit are:

$$\begin{array}{cccccc}
 & & -i_{q1}+i_{q2}+i_{q3}-i_{q4} & = & 0 & \\
x_d i_{d1}+x_2 i_{d2} & & +r_1 i_{q1}+r_2 i_{q2} & = & E_1 & \\
x_2 i_{d2}-x_3 i_{d3} & & +r_2 i_{q2}-r_3 i_{q3} & = & E_3\cos\delta_1 & \\
-i_{d1}+i_{d2}+i_{d3}-i_{d4} & & & = & 0 & \\
-r_1 i_{d1}-r_2 i_{d2} & & +x_q i_{q1}+x_2 i_{q2} & = & 0 & \\
r_2 i_{d2}-r_3 i_{d3} & & -x_2 i_{q2}+x_3 i_{q3} & = & E_3\sin\delta_1 & \\
x_2 i_{d2} & +x_4 i_{d4} & +r_2 i_{q2} & +r_4 i_{q4} & = E_4\cos(\delta_1-\delta_4) & \\
r_2 i_{d2} & +r_4 i_{d4} & -x_2 i_{q2} & -x_4 i_{q4} & = E_4\sin(\delta_1-\delta_4) & \text{(1b)}
\end{array}$$

If the effect of the amortisseur windings is neglected it has been shown[12] that the load angle below which negative damping of generator number 1 may occur is accurately given by the condition (when the frequency of the mechanical oscillation is small compared to normal-voltage frequency),

$$\frac{d}{d\delta_1} i_{d1} = 0 \qquad \text{(2b)}$$

Solving equations 1*b* for $i_{d1}$, we find

$$\Delta i_{d1} = \begin{vmatrix}
0 & 0 & 0 & 0 & -1 & 1 & 1 & -1 \\
E_1 & x_2 & 0 & 0 & r_1 & r_2 & 0 & 0 \\
E_3\cos\delta_1 & x_2 & -x_3 & 0 & 0 & r_2 & -r_3 & 0 \\
0 & 1 & 1 & -1 & 0 & 0 & 0 & 0 \\
0 & -r_2 & 0 & 0 & x_q & x_2 & 0 & 0 \\
E_3\sin\delta_1 & r_2 & -r_3 & 0 & 0 & -x_2 & x_3 & 0 \\
E_4\cos(\delta_1-\delta_4) & x_2 & 0 & x_4 & 0 & r_2 & 0 & r_4 \\
E_4\sin(\delta_1-\delta_4) & r_2 & 0 & r_4 & 0 & -x_2 & 0 & -x_4
\end{vmatrix} \qquad \text{(3b)}$$

where $\Delta$ is the determinant of the coefficients of the currents in equations 1*b*.

Differentiating with respect to $\delta_1$, there is

$$\Delta\frac{d}{d\delta_1} i_{d1} = \begin{vmatrix}
0 & 0 & 0 & 0 & -1 & 1 & 1 & -1 \\
0 & x_2 & 0 & 0 & r_1 & r_2 & 0 & 0 \\
-E_3\sin\delta_1 & x_2 & -x_3 & 0 & 0 & r_2 & -r_3 & 0 \\
0 & 1 & 1 & -1 & 0 & 0 & 0 & 0 \\
0 & -r_2 & 0 & 0 & x_q & x_2 & 0 & 0 \\
E_3\cos\delta_1 & r_2 & -r_3 & 0 & 0 & -x_2 & x_3 & 0 \\
-E_4(1-k)\sin(\delta_1-\delta_4) & x_2 & 0 & x_4 & 0 & r_2 & 0 & r_4 \\
E_4(1-k)\cos(\delta_1-\delta_4) & r_2 & 0 & r_4 & 0 & -x_2 & 0 & -x_4
\end{vmatrix} \qquad \text{(4b)}$$

where $k = \frac{\partial\delta_4}{\partial\delta_1}$, i.e., $k$ is the ratio of the motion of machine number 4 to that of machine number 1. For sinusoidal oscillations $k$ may be taken as the ratio of the amplitude of the machine oscillations.

Equation 4*b*, together with equation 2*b*, may be written

$$0 = \Delta\frac{d}{d\delta_1} i_{d1} = -E_3(M_{31}\sin\delta_1 + M_{61}\cos\delta_1) - E_4[M_{71}\sin(\delta_1-\delta_4) + M_{81}\cos(\delta_1-\delta_4)](1-k) \qquad \text{(5b.1)}$$

or

$$\tan \delta_1 = -\left[\frac{M_{61} + (1-k)\frac{E_4}{E_3}(M_{81}\cos\delta_4 - M_{71}\sin\delta_4)}{M_{81} + (1-k)\frac{E_4}{E_3}(M_{71}\cos\delta_4 + M_{81}\sin\delta_4)}\right] \tag{5b.2}$$

The relation $\frac{d}{d\delta_1} i_{d1} = 0$ thus leads to a transcendental equation which may be solved numerically for $\delta_1$ as a function of $\delta_4$.

In equations 5*b*, there is

$$M_{31} = \begin{vmatrix} x_2 & 0 & r_1 & -r_2 & 0 \\ -r_2 & 0 & x_q & -x_2 & 0 \\ r_2 + r_3 & -r_3 & x_3 & x_2 + x_3 & x_3 \\ x_2 & x_4 & 0 & -r_2 & r_4 \\ r_2 & r_4 & 0 & x_2 & -x_4 \end{vmatrix} \tag{6b.1}$$

$$M_{61} = \begin{vmatrix} x_2 & 0 & r_1 & r_2 & 0 \\ x_2 + x_3 & -x_3 & -r_3 & r_2 + r_3 & -r_3 \\ -r_2 & 0 & x_q & x_2 & 0 \\ x_2 & x_4 & 0 & r_2 & r_4 \\ r_2 & r_4 & 0 & -x_2 & -x_4 \end{vmatrix} \tag{6b.2}$$

$$M_{71} = \begin{vmatrix} x_2 & 0 & r_1 & -r_2 & 0 \\ x_2 & x_3 & 0 & -r_2 & -r_3 \\ -r_2 & 0 & x_q & -x_2 & 0 \\ r_2 & r_3 & 0 & x_2 & x_3 \\ r_2 + r_4 & -r_4 & x_4 & x_2 + x_4 & -x_4 \end{vmatrix} \tag{6b.3}$$

$$M_{81} = \begin{vmatrix} x_2 & 0 & r_1 & r_2 & 0 \\ x_2 & -x_3 & 0 & r_2 & -r_3 \\ -r_2 & 0 & x_q & x_2 & 0 \\ r_2 & -r_3 & 0 & -x_2 & x_3 \\ x_2 + x_4 & x_4 & -r_4 & r_2 + r_4 & r_4 \end{vmatrix} \tag{6b.4}$$

In the special case for which the motions of the 2 machines are the same ($k = 1$), equations 5*b* reduce to

$$\tan \delta_1 = -\frac{M_{61}}{M_{81}} \tag{7b}$$

but this is not likely to be a useful case. If $k = 0$, there is no simplification.

If machine number 4 is eliminated by letting $x_4$ and/or $r_4$ be infinite, $M_{71}$, $M_{81}$ become negligible compared to $M_{31}$, $M_{61}$, and equations 5*b* reduce to:

$$\tan \delta_1 = \frac{\begin{vmatrix} x_2 & -r_1 & r_2 \\ x_2 + x_3 & r_3 & r_2 + r_3 \\ -r_2 & -x_q & x_2 \end{vmatrix}}{\begin{vmatrix} x_2 & r_1 & -r_2 \\ -r_2 & x_q & -x_2 \\ r_2 + r_3 & x_3 & x_2 + x_3 \end{vmatrix}} \tag{8b.1}$$



**Figure 17. Starting and self-excited current of induction motor with series capacitance in primary circuit**

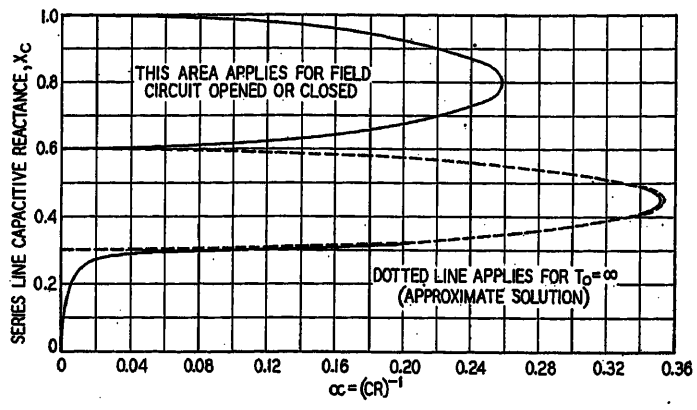



**Figure 18. Regions of self-excitation of synchronous machine with armature capacitance as affected by shunt resistance R**

$x_d = 1.0$ $x_q = 0.6$ $x_d' = 0.30$ $T_o = 1{,}000$ $r = 0$

or

$$\tan \delta_1 = \frac{Z_2^2(r_1 + r_3) + x_q(r_3x_2 - x_3r_2) + r_1(x_2x_3 + r_2r_3)}{Z_2^2(x_q + x_3) + x_q(x_2x_3 + r_2r_3) + r_1(x_3r_2 - x_2r_3)} \tag{8b.2}$$

where

$$Z_2^2 = r_2^2 + x_2^2$$

The right-hand side of equation 8*b*.2 is recognized as the ratio of the real to the imaginary part of the transfer impedance from machine number 1 to the infinite bus if $x_q$ is used for the machine reactance. Further, if the shunt load is removed ($Z_2 = \infty$) it checks the criterion of reference 11.

If the shunt load is removed but machine number 4 is kept, the form of equation 5*b* is unchanged but equations 6*b* are reduced to:

$$-M_{31} = \begin{vmatrix} -r_3 & x_q + x_3 & x_3 \\ x_4 & -r_1 & r_4 \\ r_4 & x_q & -x_4 \end{vmatrix} \tag{9b.1}$$

$$-M_{61} = \begin{vmatrix} x_3 & r_1 + r_3 & r_3 \\ -x_4 & r_1 & -r_4 \\ r_4 & x_q & -x_4 \end{vmatrix} \tag{9b.2}$$

$$-M_{71} = \begin{vmatrix} -x_3 & r_1 & r_3 \\ r_3 & x_q & x_3 \\ -r_4 & x_q + x_4 & -x_4 \end{vmatrix} \tag{9b.3}$$

$$-M_{81} = \begin{vmatrix} x_3 & r_1 & r_3 \\ -r_3 & x_q & x_3 \\ -x_4 & r_1 + r_4 & -r_4 \end{vmatrix} \tag{9b.4}$$

If in equations 5*b* $E_4 = 0$, or if $x_4$ and/or $r_4 = \infty$, there is,

$$\delta_1 = -\tan^{-1}\frac{M_{61}}{M_{31}} \tag{10b}$$

which is equation 7*b* if $E_4 = 0$, and is equation 8*b* if $x_4$ or $r_4 = \infty$. If $E_4 = 0$ but $x_4$ and $r_4$ are finite, equation 10*b* may of course be put in the form 8*b* by paralleling $Z_2$ and $Z_4$, i.e., in equation 8*b* replace $r_2$ and $x_2$ by the corresponding real and imaginary parts of the parallel values of $Z_2$ and $Z_4$. This reasoning shows that since tan $\delta$ in (8*b*.2) equals the ratio of the real and imaginary components of the transfer impedance from machine number 1 to the infinite bus (number 3) therefore $-M_{61}/M_{31}$, where $M_{61}$ and $M_{31}$ are given by (6*b*.1) and (6*b*.2), must also be the ratio of the real and imaginary parts of the transfer impedance of machine number 1 to the infinite bus with $Z_4$ finite. In fact, directly from equation 3*b* it may be seen that since:

$$\Delta i_{d1} = -M_{31}E_1 + M_{61}E_3\cos\delta_1 - M_{61}E_4\sin\delta_1 + M_{71}E_4\cos(\delta_1 - \delta_4) - M_{81}E_4\sin(\delta_1 - \delta_4) \tag{11b}$$

Then:

$-M_{21}/\Delta$ is the imaginary part of the driving point admittance at machine number 1

$M_{31}/\Delta$ is the imaginary part of the transfer admittance from 1 to 3

$M_{61}/\Delta$ is the corresponding real part

$M_{71}/\Delta$ is the imaginary part of the transfer admittance from 1 to 4

$M_{81}/\Delta$ is the corresponding real part

It follows that since

$$\left(\frac{\text{real}}{\text{imaginary}}\right)_{\text{admittance}} = -\left(\frac{\text{real}}{\text{imaginary}}\right)_{\text{impedance}} \tag{12b}$$

we have

$$-\frac{M_{61}}{M_{31}} = \left(\frac{\text{real}}{\text{imaginary}}\right)_{\text{impedance 1–3}} \tag{13b}$$

and

$$-\frac{M_{81}}{M_{71}} = \left(\frac{\text{real}}{\text{imaginary}}\right)_{\text{impedance 1–4}} \tag{14b}$$

All of these transfer impedances and admittances are computed for *a direct-axis current* in machine number 1. Also, since it is only the relative magnitude of the components of impedance which enter into the final criteria, the impedances calculated entirely by means of $x_q$ can be used. That is, even though $x_d$ occurs in $\Delta$ and affects the true values of the impedances, $\Delta$ does not appear in the results.

The method of extension to more than 2 machines is evident from equations 2*b*, 3*b*, and 4*b*.

## Composite Loads

If the shunt load of figure 9 is a composite load[18] of any kind all the criteria given here may be used unchanged if $r_2$, $x_2$ are defined by the relation:

$$\frac{de_2}{di_2} = r_2 + jx_2 \tag{15b}$$

at the load voltage $e_2$.

# Appendix C—Self-Excitation of Induction Motors

The object of this appendix is to present criteria to determine the limits of stable operation of induction motors with series line capacitors. Under certain conditions of load it is found in practice that there will exist undamped current pulsations of apparently low frequency and large magnitude. These pulsations are here considered to be caused by undamped or negatively damped (amplifying) free electrical oscillations. Thus, to determine whether a given (electrical) system is stable or unstable the natural currents are examined. The time variation of these natural currents is specified by the roots of the characteristic determinant of the system. If the real part of any one or more of these roots is positive the system is unstable since then the corresponding component of the transient current is amplifying rather than decaying and will tend to increase indefinitely until limited by changes in the circuit caused by saturation, slowing down or oscillating of the motor rotor, etc. Thus, it is not necessary actually to solve for the roots but only to find the signs of their real parts. To find the actual frequency of the unstable oscillation it is necessary to solve the equation, which is of the sixth degree (or of the third degree if expressed with complex coefficients) and has in general 3 conjugate pair of complex roots or 3 natural frequencies.

## Analysis

For an induction or synchronous machine with capacitance and resistance in shunt connected to the terminals, there are the equations (see reference 20):

$$\begin{aligned}(p+\alpha)[e_d - p\psi_d + ri_d + \omega\psi_q] + x_c i_d &= \omega[e_q - p\psi_q + ri_q - \omega\psi_d] \\ (p+\alpha)[e_q - p\psi_q + ri_q - \omega\psi_d] + x_c i_q &= -\omega[e_d - p\psi_d + ri_d + \omega\psi_q]\end{aligned} \tag{1c}$$

where, for an induction motor with completely symmetric rotor and stator,

$$\begin{aligned}\psi_d &= -x(p)i_d \\ \psi_q &= -x(p)i_q\end{aligned} \tag{2c}$$

and

$$x(p) = \frac{x'T_0p + x}{T_0p + 1} \tag{3c}$$

Substituting (2*c*) in (1*c*) and rearranging; there is:

$$\{(p+\alpha)[px(p) + r] + x_c - \omega^2x(p)\}i_d - \omega\{(p+\alpha)x(p) + px(p) + r\}i_q = -(p+\alpha)e_d + \omega e_q \tag{4c}$$

$$\omega\{(p+\alpha)x(p) + px(p) + r\}i_d + \{(p+\alpha)[px(p) + r] + x_c - \omega^2x(p)\}i_q = -\omega e_d - (p+\alpha)e_q$$

and for constant rotor speed the characteristic determinant (the denominator of the expression for current as a function of voltage),

$$\Delta = \{(p+\alpha)[px(p) + r] + x_c - \omega^2x(p)\}^2 + \omega^2\{(p+\alpha)x(p) + px(p) + r\}^2 \tag{5c}$$

Substituting (3*c*) in (5*c*) and rearranging in descending powers of $p$, there is:

$$\begin{aligned}(T_0p+1)^2\Delta = \Delta' = {} & p^6(x'^2T_0^2) \\ & + p^5[(2x'T_0)(x + \alpha x'T_0 + rT_0)] \\ & + p^4[(x + \alpha x'T_0 + rT_0)^2 + (2x'T_0)\times \\ & \qquad (\alpha x + \omega^2x'T_0 + r + \alpha rT_0 + x_cT_0)] \\ & + p^3[2x'T_0(x_c + \omega^2x) + 2(x + \alpha x'T_0 + rT_0)\times \\ & \qquad (\alpha x + \omega^2x'T_0 + r + \alpha rT_0 + x_cT_0)] \\ & + p^2[(\alpha x - \omega^2x'T_0 + r + \alpha rT_0 + x_cT_0)^2 + \\ & \qquad 2(x + \alpha x'T_0 + rT_0)(x_c - \omega^2x) + \\ & \qquad (\alpha x'T_0 + 2x + rT_0)^2\omega^2 + 4\omega^2x'T_0(\alpha x + r)] \\ & + p[2(\alpha x - \omega^2x'T_0 + r + \alpha rT_0 + x_cT_0)\times \\ & \qquad (x_c - \omega^2x) + 2\omega^2(\alpha x'T_0 + 2x + rT_0)\times \\ & \qquad (\alpha x + r)] + (x_c - \omega^2x)^2 + (\alpha x + r)^2\omega^2\end{aligned} \tag{6c}$$

Equation 5*c* is of the form ($\Delta' = a^2 + b^2$) and so may be factored as [$\Delta' = (a + jb)(a - jb)$] thus at once reducing the order of the equations to be solved by half. However, this is accomplished at the price of introducing complex coefficients. The real parts of the roots of the 2 factors are identical in pairs; the imaginary parts equal and opposite. Thus only one factor need be considered, but it is found that all methods for determining the character of the roots or solving the equation require about the same amount of work as doubling the order and in effect obtaining equation 6*c*.

In complex form the equation may be written as:

$$\begin{aligned}a + jb = {} & x'T_0p^3 + [(x + \alpha x'T_0 + rT_0) + j\omega 2x'T_0]p^2 + \\ & [(x_cT_0 - \omega^2x'T_0 + \alpha x + r + \alpha rT_0) + j\omega(2x + \alpha x'T_0 + \\ & rT_0)]p + [(x_c - \omega^2x) + j\omega(\alpha x + r)]\end{aligned} \tag{7c}$$

with a similar conjugate expression for $(a - jb)$.

It will be observed that equations 6*c* and 7*c* are almost symmetrical in $r$ and $\alpha$ except that $\alpha$ has sometimes the coefficient $x'$ and sometimes $x$, which destroys the symmetry. It is therefore expected that all the conclusions and curves obtained will be very similar if the effect of shunt and series resistances are investigated separately, using $\alpha$ as the variable in case of the shunt resistance. Here $\alpha$ may be thought of as the reciprocal of the time constant of the $RC$ circuit considered by itself. It is the negative of the coefficient of time in the exponential solution of the $RC$ circuit equations.

### Approximate Criterion for Instability

It will be found that a very simple and sufficient condition for instability is that the coefficient of $p$ in equation 6*c* be negative. That is, if this coefficient is negative the system is surely unstable,

but if it is positive the system is not necessarily stable. Putting the coefficient equal to zero there is:

$$x_c = \frac{1}{2}\left[(x+x')\omega^2 - \alpha r - \frac{(\alpha x + r)}{T_o}\right] = \left\{\frac{(x-x')^2\omega^4}{4} - \frac{\omega^2}{2}(x+3x')\alpha r + \frac{1}{4}\left[\alpha r + \frac{(\alpha x + r)}{T_o}\right]^2 - \omega^2(xx'\alpha^2 + r^2) - \frac{\omega^2}{2}(3x+x')\frac{(\alpha x + r)}{T_o}\right\}^{1/2} \quad (8c)$$

The 2 values of $x_c$ obtained from (8c) for a given system determine the limits of a region which is theoretically surely unstable.

If a set of circuit constants is selected, leaving $r$ and $x_c$ free, then $r$ is varied and $x_c$ computed, a region is outlined as in figure 10 (dashed curve). This figure shows $r$ as a function of $x_c$ if there is no shunt resistor ($\alpha = 0$). If the effect of shunt resistance alone is determined, letting $r = 0$, the dashed curve of figure 12 is obtained.

Equation 8c outlines the unstable region very close to the true boundary over most of the range of instability. However it indicates that instability lies wholly in the range,

$$\omega^2 x' < x_c < \omega^2 x \quad (9c)$$

so that if $x_c < \omega^2 x'$ the system is stable when in fact there is required a certain finite series or shunt resistance to assure stability. Equation 8c is therefore not a good criterion when $x_c$ is small as in the case of series capacitors for line reactance compensation except when the motor is running at low speeds.

### Exact Criterion

To find the true boundary in the region $x_c < \omega^2 x'$ the criterion of Routh[24] is used. This is carried out numerically by assigning values to all of the system constants and testing equations 6c or 7c for stability with various values of line or shunt resistance. The boundaries found in this manner are shown in figures 10 and 12 (solid lines). These figures are calculated for a motor of 0.16 per unit transient reactance and an external reactance of 0.24. In figures 10 and 12 there are also plotted boundaries corresponding to operation at the same speed but with some external rotor resistance, the total rotor resistance being 10 times the rotor winding resistance.* The effects of series and shunt resistors have been determined separately in order to show as simply as possible the orders of magnitude of the various quantities involved. However, since there is always some line resistance present, the value of $\alpha$ required need not be as large as that given by the curves of figure 12. Figure 15 shows an example of how the $\alpha$ necessary for stability can be decreased with increasing line resistance, and has been computed from equation 6c by Routh's[24] method.

### Effect of Rotor Speed

Equations 6c or 7c may be used to determine exactly the regions of unstable operation at any rotor speed. However, the effect of speed may be more clearly and easily seen from the approximate expression (8c). Since the rotor open-circuit time constant is usually rather large, equation 8c may be further simplified by neglecting terms containing $T_o$, whence

$$\frac{x_c}{\omega^2} = \frac{1}{2}\left[x + x' - \left(\frac{\alpha}{\omega}\right)\left(\frac{r}{\omega}\right)\right] = \sqrt{\frac{(x-x')^2}{4} - \left[xx'\left(\frac{\alpha}{\omega}\right)^2 + \left(\frac{r}{\omega}\right)^2\right] - \frac{(x+3x')}{2}\left(\frac{\alpha}{\omega}\right)\left(\frac{r}{\omega}\right) + \frac{1}{4}\left(\frac{\alpha}{\omega}\right)^2\left(\frac{r}{\omega}\right)^2} \quad (10c)$$

Equation 10c shows that as the speed $\omega$ is varied the scales of the $r$ versus $x_c$ or $\alpha$ versus $x_c$ diagram are simply changed so that

$x_c$ is proportional to $\omega^2$
$r$ and $\alpha$ are proportional to $\omega$ (11c)

* If rotor resistance is zero ($T_o = \infty$) there is no instability. Also if $T_o = 0$ or $\omega = 0$ there is obviously no instability.

Since at low speeds the capacitive reactance at which the maximum series resistance or shunt conductance is required is shifted toward the actual capacitive reactance likely to be used in the circuit, equation 10c or 8c then becomes a useful criterion. Having the boundary curve of instability at any one speed, those at any other speed may then be quickly estimated by the relations 11c. Figures 11 and 13 show the effect of varying the rotor speed as determined by equation 10c. Figure 11 shows the effect on the value of series resistance requirod if there is no shunt resistance, while figure 13 shows a similar curve of $\alpha$ versus $x_c$ if $r = 0$.

Equation 10c also provides a means of determining quickly an approximate expression for the value of $\alpha$ required to eliminate instability completely at any speed. This expression is found by equating the radical in equation 10c to zero, which locates a point very close to the maximum of the $\alpha$ versus $x_c$ or $r$ versus $x_c$ boundary curve. Then

$$\left(\frac{\alpha}{\omega}\right)_{max} = -\frac{(x+3x')r'}{4xx' - r'^2} + \frac{1}{4xx' - r'^2} \times \sqrt{(x+3x')^2 r'^2 + (4xx' - r'^2)[(x-x')^2 - 4r'^2]} \quad (12c)$$

where $r' = r/\omega$.

If $r = 0$, there is

$$\left(\frac{\alpha}{\omega}\right)_{max} = \frac{(x-x')}{2\sqrt{xx'}} \quad (13c.1)$$

which occurs at

$$\frac{x_c}{\omega^2} = \frac{x+x'}{2} \quad (13c.2)$$

Similarly if $\alpha = 0$, there is

$$\left(\frac{r}{\omega}\right)_{max} = \frac{(x-x')}{2} \quad (13c.3)$$

which occurs at the same $x_c$ as in equation 13c.2. These last relations determine equations,

$$r^2 = \frac{(x-x')^2 x_c}{2(x+x')} \text{ for } \alpha = 0 \quad (14c.1)$$

and

$$xx'\alpha^2 = \frac{(x-x')^2 x_c}{2(x+x')} \text{ for } r = 0 \quad (14c.2)$$

which are the equations of the loci of the maxima of the $r$ versus $x_c$ and $\alpha$ versus $x_c$ curves as the speed $\omega$ is varied. Then, if the capacitive reactance $x_c$ in a given circuit is known equations 14c determine the value of $r$ or $\alpha$ needed to eliminate self-excitation at all speeds. However, as mentioned in the body of the paper, it will not in general be necessary to do this.

### Frequency and Time Constant of the Amplifying Oscillation

The frequencies and time constant of all these components of the transient currents may of course be found directly by solving equations 6c or 7c. However, it has been found that within the normal range of circuit constants only one of these currents is amplifying and so likely to be observed as a large current pulsation. Moreover, this current is that corresponding usually to a small root of 7c, over most of the range of $x_c$. It should therefore be possible to find the root approximately by neglecting higher powers of $p$ in equation 7c whence the solution is

$$p_1 = \frac{(x_c - \omega^2 x) + j\omega(\alpha x + r)}{[(x_c - \omega^2 x')\alpha r)T_o + \alpha x + r] + j\omega[(\alpha x' + r)T_o + 2x]} \quad (15c)$$

A further obvious simplification is obtained by neglecting the terms in the denominator which do not contain $T_o$. If $p_1 = p_r + jq$ then $p_r$ is the decrement factor and $(\omega + q)$ the frequency of the possibly amplifying oscillation. The frequency is $\omega + q$ rather than

$q$ since the solution is for $i_d$, $i_q$. The phase currents are obtained by Park's[25] equations

$$i_a = i_d \cos\theta - i_q \sin\theta, \text{ etc.}$$

and it may be shown that the component of phase current of frequency $\omega - q$ vanishes identically.

If the real part $p_r$ of $p_1$ is equated to zero (corresponding to the point at which the oscillation is just neutral) equation 8$c$ is arrived at by a different route.

The approximate equation 15$c$ holds only for $x_c > \omega^2 x'$ and so in the useful range of capacitance at normal motor speeds, equation 7$c$ must be solved directly. It is still possible to avoid the solution of a cubic equation if it is desired to find the frequency only at points on the boundaries between the stable and unstable regions, since at such points the root is obviously pure imaginary and if $p = jq$, equation 7$c$ may be split up as

$$\begin{aligned} a + jb = &-[(x + \alpha x' T_o + r T_o) q^2 + \omega(2x + \alpha x' T_o + r T_o) q - \\ &(x_c - \omega^2 x)] - j[x' T_o q^3 + \omega 2x' T_o q^2 - (x_c T_o - \omega^2 x' T_o + \\ &\alpha x + r + \alpha r T_o) q - \omega(\alpha x + r)] \end{aligned} \tag{16c}$$

and the real and imaginary components of (16$c$) equated separately to zero. Sets of system constants on the boundary may then be first found by Routh's[24] method and $q$ then obtained by solving the quadratic equation $a = 0$ in equation 16$c$. Of the 2 real roots thus found only one will in general satisfy the cubic equation $b = 0$ of (16$c$) and this will of course be the proper frequency. For example, taking circuit constants corresponding to the points $x_c = 0.2$, $r = 0.035$ in figure 10, the frequency is found to be very nearly 0.7 times normal (rotor speed). At values of $x_c > x'$ the frequency is always very close to, and slightly less than that corresponding to the rotor speed.

M. Takahashi[22] has an approximate solution of equation 7$c$ for the case of no shunt resistance and has determined regions of self-excitation for this case. His results are in general agreement with those given here.

## Appendix D—Self-Excitation of Synchronous Machines

From equations 15 of reference 20, the equations of a synchronous machine operating at synchronous speed, with only one rotor winding, with series capacitance and resistance in the armature circuit, and with additional resistors shunting the capacitors, are:

$$\begin{aligned} (p + \alpha)(e_d - p\psi_d + r i_d + \psi_q) + x_c i_d &= e_q - p\psi_q + r i_q - \psi_d \\ (p + \alpha)(e_q - p\psi_q + r i_q - \psi_d) + x_c i_q &= -e_d + p\psi_d - r i_d - \psi_q \end{aligned} \tag{1d}$$

where

$$\psi_d = -x_d(p) i_d = -\frac{x_d' T_o p + x_d}{T_o p + 1} i_d \tag{2d}$$

$$\psi_q = -x_q(p) i_q = -x_q i_q \tag{3d}$$

If (1$d$) are solved for the currents $i_d$, $i_q$ in terms of the applied voltages $e_d$, $e_q$, it is found that the operational common denominator of the 2 formulas for current is:

$$\begin{aligned} \Delta' = &\; p^5 x_q x_d' T_o \\ &+ p^4[x_q x_d + r T_o(x_q + x_d') + 2\alpha T_o x_q x_d'] \\ &+ p^3[(2x_q x_d' + x_c\{x_q + x_d'\}) T_o + r(x_d + x_q + r T_o) + \\ &\quad \alpha(2x_d x_q + \alpha x_q x_d' T_o) + 2\alpha r T_o(x_q + x_d')] \\ &+ p^2[2x_d x_q + x_c(x_d + x_q) + r(T_o\{2x_c + x_q + x_d'\} + r) + \\ &\quad \alpha(T_o x_c\{x_q + x_d'\} + 2T_o x_q x_d' + \alpha x_d x_q) + \alpha r(2x_d + \\ &\quad 2x_q + 2T_o r + T_o\alpha\{x_q + x_d'\})] \\ &+ p[T_o(x_c - x_q)(x_c - x_d') + r(x_d + x_q + 2x_c + r T_o) + \\ &\quad \alpha(x_c\{x_d + x_q\} + 2x_d x_q + \alpha x_q x_d' T_o) + \alpha r(2x_c T_o + 2r + \\ &\quad \alpha\{x_d + x_q\} + \alpha r T_o)] \\ &+ [(x_d - x_c)(x_q - x_c) + r^2 + \alpha^2 x_d x_q + 2\alpha r x_c + (\alpha r)^2] \end{aligned} \tag{4d}$$

If the same generator as in reference 21 is taken, with $r = 0$, and the stability of the system as affected by $\alpha$ is studied by means of Routh's[24] criterion, the results of figure 18 are obtained. Also in a manner similar to that of reference 21 there is found an approximate formula for the lower region:

$$+ \alpha^2 = \frac{(x_q - x_c)(x_d' - x_c)}{-x_q x_d'} \tag{5d}$$

or

$$x_c = \frac{x_q + x_d'}{2} \pm \sqrt{\frac{(x_q - x_d')^2}{4} - x_q x_d' \alpha^2} \tag{6d}$$

Similarly, an exact formula for the upper region is obtained by replacing $x_d'$ by $x_d$ in equation 5$d$, whence

$$+ \alpha^2 = \frac{(x_q - x_c)(x_d - x_c)}{-x_q x_d} \tag{7d}$$

or

$$x_c = \frac{x_q + x_d}{2} \pm \sqrt{\frac{(x_q - x_d)^2}{4} - x_q x_d \alpha^2} \tag{8d}$$

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# Transformer Current and Power Inrushes Under Load

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## Introduction

THE PHENOMENON of starting currents in transformers has been quite fully studied by several investigators,[1,2] especially when the transformer is without load. Little information, however, can be found in the technical literature on this subject when the transformer is loaded, let alone the effect of various load power factors.

This paper presents results of studies on starting currents and powers when loaded transformers are connected to their supply lines. Both primary and secondary switching are investigated, and unity, lagging, and leading load power factors are considered.

In this study the moving average is introduced as a means of analyzing oscillographic records. By its use the trends of the effective current and average power may be more readily observed. This in turn makes possible the determination of the primary transformer power factor variation during the transient period.

## Galvanometer Connections

A schematic diagram of the galvanometer connections employed is shown in figure 1. The transformer used was a distribution-type transformer having similar primary and secondary windings designed for 220–110-volt operation. A one-to-one transformation ratio was used throughout the investigation. In the figure,

$e$ represents the primary voltage galvanometer
$i_p$ represents the primary current galvanometer
$i_s$ represents the secondary current galvanometer
$w$ represents the primary watt galvanometer

A special relay[3] developed for these studies was used for closing the primary or secondary circuit at the desired point on the primary voltage wave. In all cases of primary switching the core was completely demagnetized before the transformer was energized.

Figure 2 is a photograph of the laboratory setup showing all equipment in place.

## No-Load Transients

Since the no-load starting current transient was needed for the predetermination of starting current transients with load, it is included herewith as oscillogram 1. In this oscillogram the circuit was closed on the zero of the voltage wave, this being the condition for maximum current inrush with zero residual flux. As previously mentioned, the transformer core was demagnetized before the switch was closed. Still larger values of starting current will result if positive residual flux is present at starting, and smaller values if negative residual magnetism is present. These extreme inrushes, however, are not considered in this paper because of the difficulty in controlling the magnitude of such residuals.

## Predetermination of Starting Current Under Load

An approximate value of the maximum primary transient current under load (for zero residual flux) may be found by adding the primary no-load transient current of oscillogram 1 to a load component equal and opposite to the assumed secondary current. Greater accuracy, however, can be obtained by taking account of the effect of the increased $iR$ drop in the primary winding due to the presence of the load component upon the magnetizing flux.

To include this effect the fundamental primary voltage equation,

$$Ri_m + N\frac{d\phi^*}{dt} = E_M \sin(\omega t + \lambda) \tag{1}$$

must be modified thus,

$$R(i_m + i_L) + N\frac{d\phi}{dt} = E_M \sin(\omega t + \lambda) \tag{2}$$

or

$$N\frac{d\phi}{dt} = E_M \sin(\omega t + \lambda) - R(i_m + i_L) \tag{3}$$

Equation 3 shows that the induced voltage under load conditions differs from the induced voltage under no-load conditions by the factor $Ri_L$. This factor decreases the peaks of the magnetizing current. The extent of the decrease naturally depends upon the magnitude of $i_L$ as well as upon its phase position.

Figure 3 shows 3 assumptions of load component currents. They represent, respectively, a unity power factor or resistance-load current, a 45-degree lagging or $RL$ load current (with natural secondary transient d-c component), and a 50-degree leading or $RC$ load current.

The adjusted no-load current component inrush may be determined by writing equation 3 as follows, and using the "finite difference method"

$$N\Delta\phi = [E_M \sin(\omega t + \lambda) - Ri_m]\,\Delta t - Ri_L\,\Delta t$$

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1. For all numbered references, see list at end of paper.

* $\phi$ represents both the primary leakage flux and the mutual flux of the transformer.

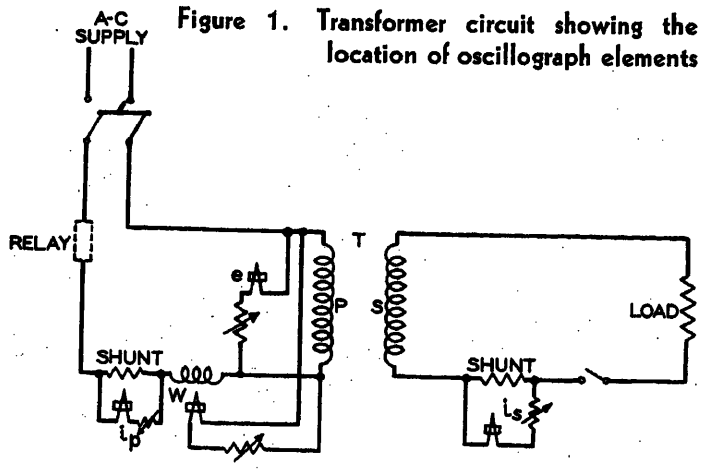
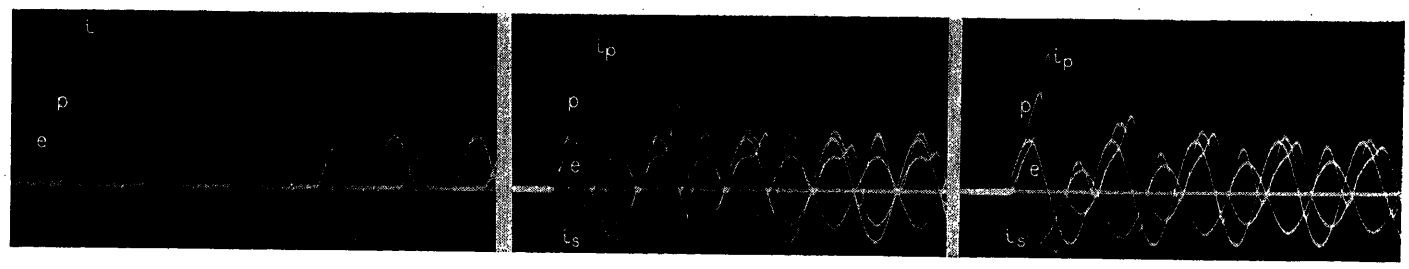



**Figure 1. Transformer circuit showing the location of oscillograph elements**

for each of the 3 load currents assumed and the corrected flux variations. The latter graphs show that the flux is only slightly reduced for the $RC$ load, somewhat more for the $R$ load, and still more for the $RL$ load. The $RL$ current is most effective in decreasing the positive flux values and increasing the negative values due to the d-c component in the secondary current and the resulting increase in

$$\sum Ri_L\Delta t$$

Naturally, this effect decreases as the d-c component dies out. In figure 5 are shown the corresponding magnetizing-current graphs. These values were obtained from the magnetization curve and correspond to the values of flux in figure 4.




**Oscillogram 1. The no-load current and power transient**

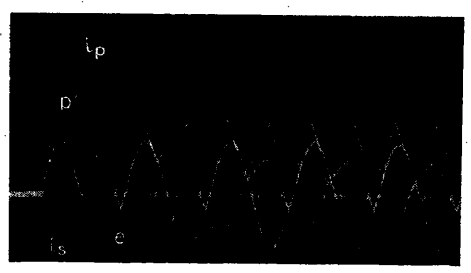
$e$—Applied electromotive force (60 cycle)
$i$—Current $p$—Power
$E$ (effective)—117 volts
Peak $i$—174 amperes Peak $p$—10.5 kw
Steady-state condition: $P$ = 30 watts; $I$ = 0.825 amperes
Transformer rating: 115 volts, 3 kva, 60 cycles

**Oscillogram 2. Current and power delivered to a transformer connected to a unity-power-factor load, and energized at the time the voltage passes through zero**

$e$—Applied electromotive force (60 cycle)
$i_p$—Primary current $p$—Primary power
$i_s$—Secondary current
$E$ (effective)—113.5 volts
Peak $i_p$—160 amperes. Peak $p$—9,700 watts
Steady-state condition: primary power = 2,976 watts; primary current = 26.2 amperes; secondary current = 25.7 amperes; unity load power factor

**Oscillogram 3. Current and power delivered to a transformer connected to a 0.700 lagging-power-factor load, and energized at the instant the supply voltage is zero**

$e$—Applied electromotive force (60 cycle)
$i_p$—Primary current
$p$—Primary power
$i_s$—Secondary current
$E$ (effective)—113 volts
Peak $i_p$—149 amperes
Peak $p$—10.4 kw
Steady-state condition: primary power = 2,160 watts; primary current = 26.6 amperes; secondary current = 25.8 amperes; load power factor = 0.700 lagging; ratio of transformation = 1




**Oscillogram 4. Current and power delivered to a transformer connected to a 0.685 leading - power - factor load, and energized at the time the voltage wave passes through zero**

$e$—Applied electromotive force (60 cycle)
$i_p$—Primary current
$p$—Primary power
$i_s$—Secondary current
$E$ (effective)—115 volts
Peak $i_p$—162 amperes
Peak $p$—6,554 watts
Steady-state condition: primary power = 2,216 watts; primary current = 25.6 amperes; secondary current = 25.8 amperes; load power factor = 0.685 leading

This equation is the same as for the no-load condition with the exception of the $Ri_L\Delta t$ term. Therefore if the flux variation for the no-load transient is decreased by the summation of $Ri_L\Delta t$, from $t = 0$ to $t = t$, the flux variation under load may be found. The current corresponding to this corrected flux will be the magnetizing current for the load condition. Figure 4 shows the summations of $Ri_L\Delta t$

It now merely remains to combine the magnetizing and load component currents to obtain the total primary current. This was done in figure 6. Corresponding values from figures 3 and 5 were combined to give the resultant currents shown. Because of the effect of phase position the $RL$ load peak now exceeds the no-load peak, whereas the $R$ load is somewhat lower and the $RC$ load is much lower, being only a little more than half of the $RL$ peak value.

## Oscillographic Verification

Oscillograms 2, 3, and 4 substantially confirm the anticipated load starting currents of figure 6. In each case the transformer core was demagnetized prior to the energizing of the transformer. Furthermore, in each of these oscillograms the primary circuit was closed on the zero value of the supply voltage, or when $\lambda = 0$. This created the maximum possible disturbance for zero residual flux.

The load was connected to its secondary before the primary circuit was closed.

An inspection of these 3 oscillograms shows that the secondary load current starts with approximately steady-state values. The primary currents in each case, however, contain a large transient component.

A comparison of actual and calculated values of the first loop with *RL* load is shown in figure 7. This shows substantial agreement between actual and predetermined values.

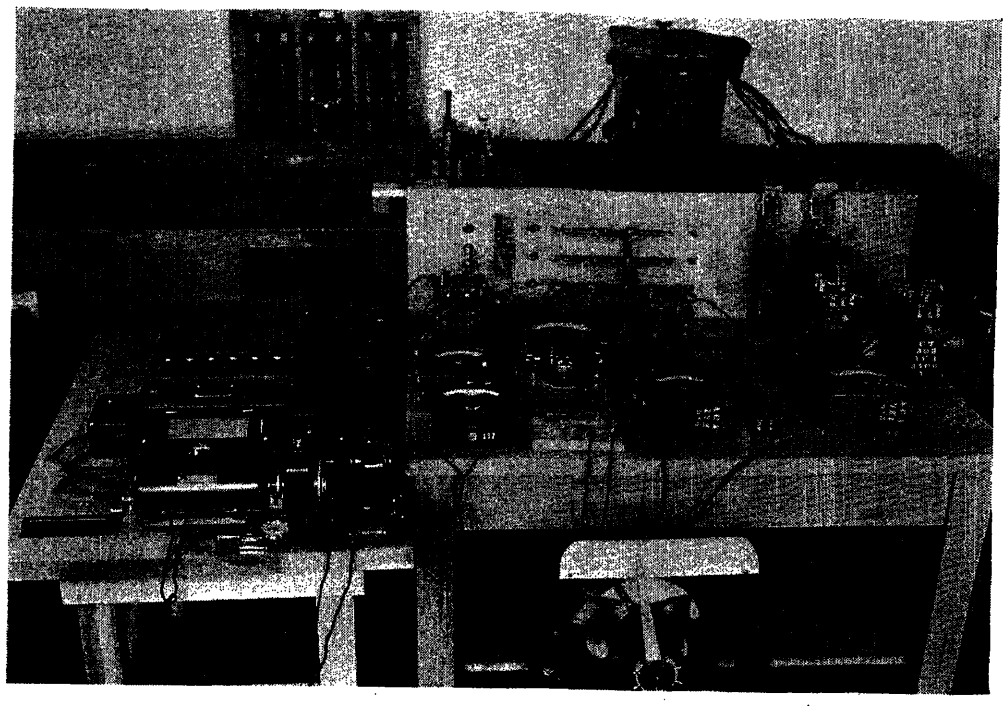


**Figure 2. Transformer, oscillograph, wave point switch, meters, and load used in tests**

## Primary Switching With $\lambda = 90$

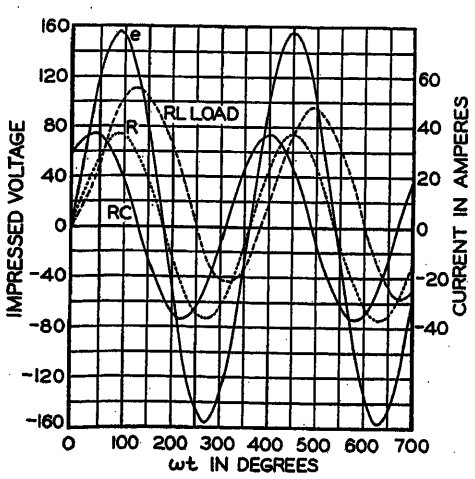
When a transformer is in normal operation its flux is approximately zero when the impressed voltage is at its maximum value. Therefore, a demagnetized transformer connected to the line at the instant of maximum voltage will be under steady-state conditions from the start. Oscillograms 5, 6, and 7 illustrate this fact for unity, lagging, and leading power factors, respectively. Except for the difference in $\lambda$ the conditions are the same as for oscillograms 2, 3, and 4. In the case of *RL* loading the secondary voltage was not exactly at its peak value and therefore a small d-c component is noticeable in the load current which in turn is reflected in the primary current. In the case of leading power factor the load consisted of *R* and *C* in parallel. This permitted the condenser to draw an abnormal current during the first quarter of a cycle.

## Secondary Switching

In taking oscillograms numbers 8 to 13 inclusive, the primary circuit was first closed and the flux allowed to become normal before the secondary load circuit was closed. Any transient appearing in the primary will then be due to disturbances caused in the secondary circuit. Oscillograms numbers 8, 9, and 10 are for unity, lagging, and leading power factors when the secondary switch is closed at $\lambda = 0$, while 11, 12, and 13 are corresponding oscillograms for $\lambda = 90$.

In oscillograms 8 and 11 with resistance loading no transients are expected, and this is confirmed by the rec-

**Figure 4 (right). Actual no-load and predicted load-flux variations**



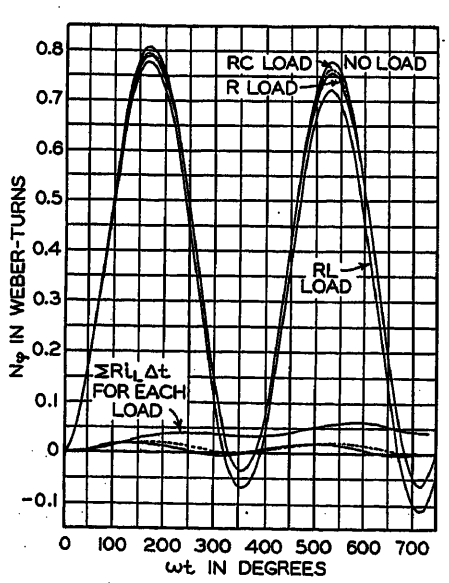




**Figure 5 (below). Magnetizing component of primary current for 3 loads**

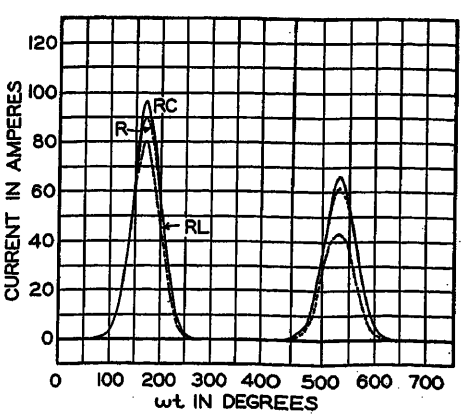
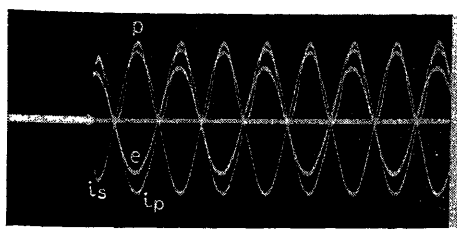
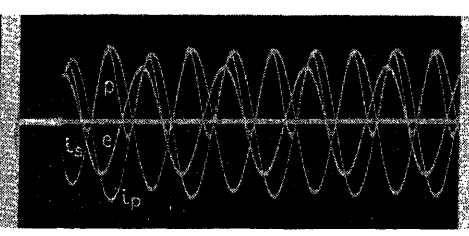


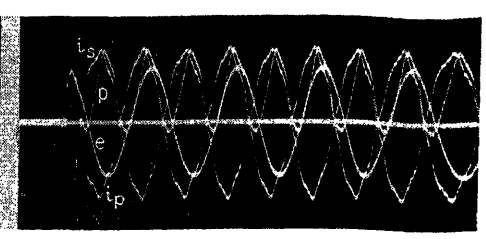

**Figure 3 (left). Assumed primary load components. Effective value approximately 26 amperes. Power factors: unity, 45-degree lagging, and 50-degree leading**



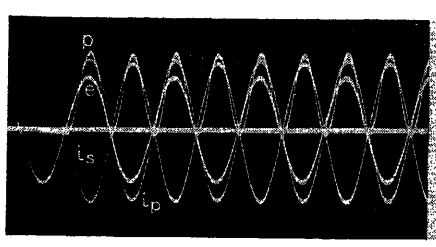

Oscillogram 5. Resistance loading. Primary switching at $\lambda = 90$ degrees; other conditions same as in oscillogram 2



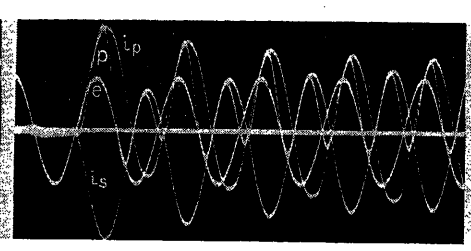

Oscillogram 6. Inductive loading. Primary switching at $\lambda = 90$ degrees; other conditions same as in oscillogram 3



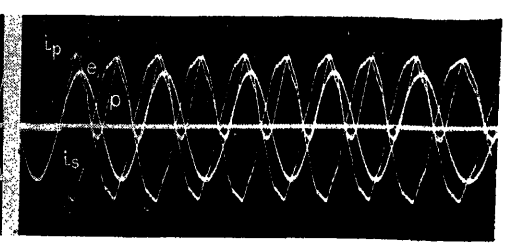

Oscillogram 7. Primary switching at $\lambda = 90$ degrees; other conditions same as in oscillogram 4




Oscillogram 8. Resistance loading. Secondary switching at $\lambda = 0$ degrees; other conditions same as in oscillogram 2




Oscillogram 9. Inductive loading. Secondary switching at $\lambda = 0$ degrees; other conditions same as in oscillogram 3




Oscillogram 10. Capacitive loading Secondary switching at $\lambda = 0$ degrees; other conditions same as in oscillogram 4

ords. In oscillogram 9, however, with $RL$ loading and $\lambda = 0$ a large d-c component is present in the load current which is of course reflected in the primary current. In oscillogram number 13 the condenser draws a large initial current in an attempt to bring its $q/C$ voltage up to the impressed electromotive force. A series $RC$ connection would have partially avoided this difficulty.

## Oscillogram Analysis

In oscillograms like those shown above, where the current and power variations are large and irregular, it is quite difficult to draw satisfactory conclusions. For this reason it was thought desirable to analyze them and make the current, power, and power factor trends more apparent. To this end the "moving average," long used by statisticians, was introduced as a means of ironing out the wide and irregular variations. It was applied in particular to oscillograms 2, 3, and 4.

## The Moving Average Applied to Power

To apply this method of analysis to a power oscillogram, readings of instantaneous values of power were read and tabulated for 15-degree intervals from an enlarged oscillogram as shown in table I, columns 1 and 2. The first value under the heading $\Sigma p$ in column 3 is the sum of the instantaneous power ordinates for the first 360 degrees, and the first value in column 4 is the average

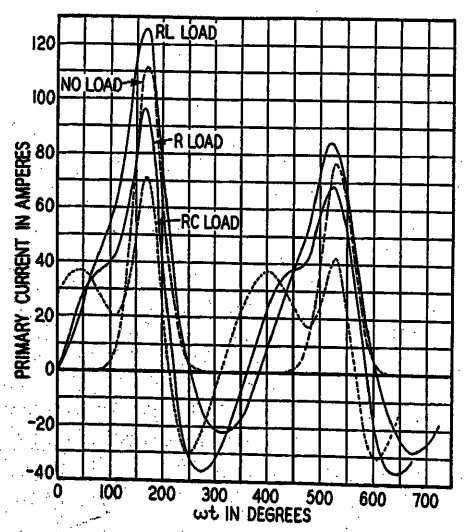



Figure 6. Predetermined total primary currents for 3 assumed loads

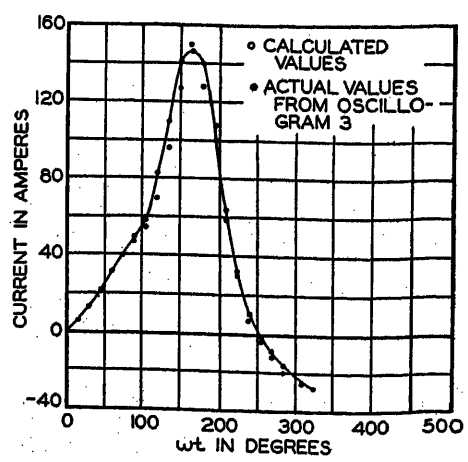



Figure 7. Comparison of actual and calculated values of primary current with RL load

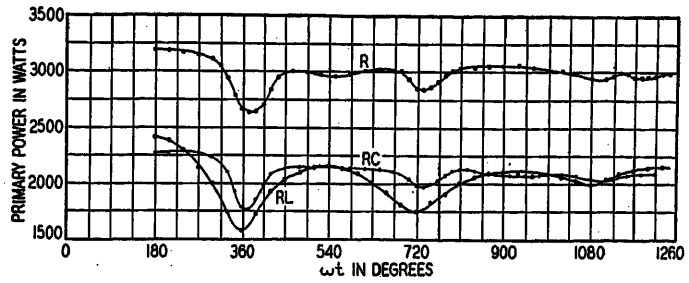



**Figure 8. Trends of average values of primary power corresponding to oscillograms 2, 3, and 4**

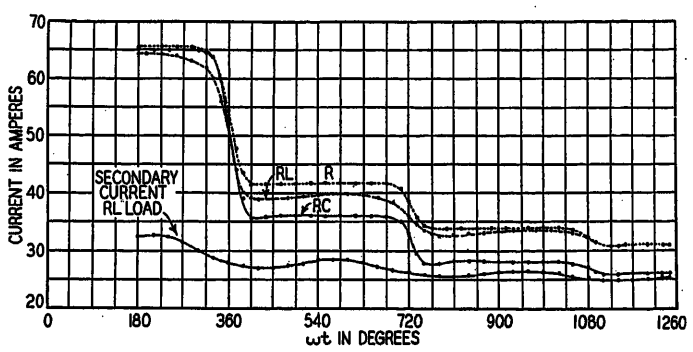



**Figure 9. Trends of the effective values of primary current corresponding to oscillograms 2, 3, and 4**

of these ordinates, and therefore the "average power." It is plotted in figure 8 as the average value of the power at 180 degrees. In like manner succeeding values of average power are obtained by averaging ordinates over a 360-degree span and plotting this value at the midpoint of the span. Figure 8 shows these values for a little over 3 cycles for oscillograms 2, 3, and 4. These graphs show the average power to remain fairly constant throughout the transient period. The *RL* and *RC* are less in value due to reduced values of power factor.

It is interesting to note that the average power during the transient period never goes to values higher than for steady-state values, in spite of the high peaks shown on the oscillogram. These high peak values represent power used in building up a magnetic field which is nearly all returned to the source.

**Table I. Calculations of Average Power and Power Factor**

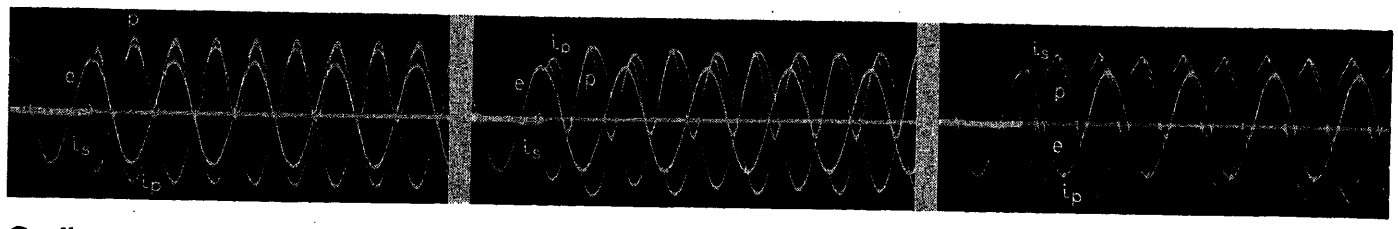
| ωt | p | Σp | Average Power | Power Factor |
|---|---|---|---|---|
| 0 | 0 | | | |
| 15 | — | | | |
| 30 | 560 | | | |
| 45 | 2,160 | | | |
| 60 | 3,840 | | | |
| 75 | 5,350 | | | |
| 90 | 7,580 | | | |
| 105 | 8,740 | | | |
| 120 | 9,850 | | | |
| 135 | 10,400 | | | |
| 150 | 9,480 | | | |
| 165 | 5,700 | ×10 | | |
| 180 (−) | 0 | 5,768 | 2,410 | 0.330 |
| 195 | 5,150 | 5,768 | 2,410 | 0.330 |
| 210 | 6,350 | 5,420 | 2,250 | 0.307 |
| 225 | 5,350 | 5,637 | 2,350 | 0.321 |
| 240 | 2,540 | 5,509 | 2,300 | 0.316 |
| 255 (+) | 470 | 5,332 | 2,210 | 0.304 |
| 270 | 1,500 | 5,150 | 2,150 | 0.297 |
| 285 | 2,670 | 5,973 | 2,080 | 0.290 |
| 300 | 3,150 | 5,789 | 2,000 | 0.281 |
| 315 | 2,810 | 5,524 | 1,890 | 0.268 |
| 330 | 2,140 | 4,194 | 1,750 | 0.257 |
| 345 | 1,110 | 3,884 | 1,620 | 0.254 |
| 360 (−) | 0 | 3,788 | 1,580 | 0.280 |
| 375 | 560 | 3,901 | 1,630 | 0.325 |
| 390 | 190 | 4,163 | 1,730 | 0.380 |
| 405 (+) | 880 | 4,410 | 1,840 | 0.413 |
| 420 | 2,070 | 4,619 | 1,930 | 0.435 |
| 435 | 4,030 | 4,765 | 1,990 | 0.450 |
| 450 | 5,810 | 4,887 | 2,040 | 0.460 |
| 465 | 690 | 4,854 | 2,020 | 0.454 |

## Moving Average Applied to Current

The procedure in finding the current trend is slightly different since the root-mean-square value is required and not the average. Instantaneous values for 15-degree intervals are read from the oscillogram and tabulated as shown in columns 1 and 2 table II. In column 3 the squared values are given. Column 4 is the sum of these squared values for 360 degrees, column 5 gives the average squared value, and column 6 the square root of this value, or the effective value. This value is plotted at the midpoint of the 360-degree span, namely at the 180-degree point. Succeeding values are obtained in the same manner. Values so obtained for oscillograms 2, 3, and 4 are plotted in figure 9 for about 4 cycles. This figure shows the currents to decrease in steps at the rate of one step per cycle. The total reduction is from a value of 65 amperes to the steady-state value of 26 amperes. The *RL* cur-

**Table II. Calculations of Effective Current**

| ωt | i | $i^2$ | Σ$i^2$ | Average $i^2$ | I |
|---|---|---|---|---|---|
| 0 | 0 | 0 | | | |
| 15 | 4.4 | 19 | | | |
| 30 | 12.9 | 167 | | | |
| 45 | 22.2 | 493 | | | |
| 60 | 31.8 | 1,010 | | | |
| 75 | 39.9 | 1,590 | | | |
| 90 | 47.1 | 2,220 | | | |
| 105 | 56.0 | 3,140 | | | |
| 120 | 69.5 | 4,840 | | | |
| 135 | 95.2 | 9,070 | | | |
| 150 | 127 | 16,200 | | | |
| 165 | 149 | 22,200 | | | |
| 180 | 138 | 19,000 | 98,689 | 4,120 | 64.2 |
| 195 | 108 | 11,700 | 98,889 | 4,120 | 64.2 |
| 210 | 58.9 | 3,460 | 98,925 | 4,120 | 64.2 |
| 225 | 30.2 | 910 | 98,758 | 4,120 | 64.2 |
| 240 (−) | 7.2 | 52 | 98,349 | 4,100 | 64.0 |
| 255 | 4.8 | 23 | 97,750 | 4,080 | 63.9 |
| 270 | 12.4 | 154 | 96,968 | 4,050 | 63.6 |
| 285 | 19.5 | 380 | 95,988 | 4,000 | 63.2 |
| 300 | 28.1 | 532 | 94,568 | 3,940 | 62.7 |
| 315 | 24.4 | 595 | 91,968 | 3,840 | 62.0 |
| 330 | 23 | 530 | 86,248 | 3,600 | 60.0 |
| 345 | 20.1 | 404 | 74,888 | 3,120 | 55.9 |
| 360 | 14.5 | 210 | 58,918 | 2,460 | 49.6 |
| 375 | 6.7 | 45 | 46,298 | 1,930 | 44 |
| 390 (+) | 0 | 0 | 38,398 | 1,600 | 40 |
| 405 | 9.16 | 84 | 36,758 | 1,535 | 39.2 |
| 420 | 20.3 | 411 | 36,233 | 1,510 | 38.8 |
| 435 | 28.4 | 808 | 36,181 | 1,510 | 38.8 |
| 450 | 35.2 | 1,240 | 31,251 | 1,515 | 38.9 |
| 465 | 41.5 | 1,720 | 36,403 | 1,520 | 39.0 |



Oscillogram 11. Resistance loading. Secondary switching at $\lambda = 90$ degrees; other conditions same as in oscillogram 2

Oscillogram 12. Inductive loading. Secondary switching at $\lambda = 90$ degrees; other conditions same as in oscillogram 3

Oscillogram 13. Capacitive loading. Secondary switching at $\lambda = 90$ degrees; other conditions same as in oscillogram 4

rent decreases somewhat more rapidly due to the coincident decrease of the secondary current.

## Transient Power Factor

After the effective current and average power are known the power factor can be calculated since the effective voltage is also known. The values of power factor corresponding to the current and power trends are tabulated in table I and plotted in figure 10. These graphs show

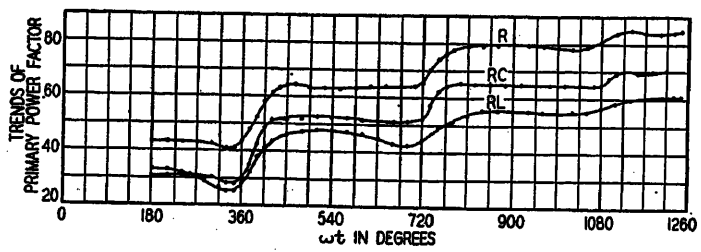



Figure 10. Trends of primary power factor corresponding to oscillograms 2, 3, and 4

that the power factors start with low values and increase in steps simultaneously with the decrease of the currents.

## Conclusions

Some of the more important conclusions which may be drawn from this study can be briefly stated as follows:

1. The finite differences method will give satisfactory results when used to calculate transformer transients.

2. The load power factor has a decided effect upon the initial current and power variations in the case of loaded transformers.

3. The inductive load causes the maximum and the capacitive load the minimum disturbance in the primary current.

4. The effective value of the transient current, as calculated by the method of moving averages over a 360-degree span, decreases in steps.

5. The average power during the transient period, as calculated by the method of moving averages over a 360-degree span, does not vary much from its normal steady-state value.

6. The power factor is very low at the beginning of the transient and increases to its normal value in steps.

7. The magnetizing component of the primary current experiences little transient effect when a load is connected to the secondary.

## References


1. Transient Currents in Transformers, H. M. Turner. Franklin Institute *Journal*, volume 211.

2. Starting Currents of Transformers, T. D. Yensen. University of Illinois Bulletin, No. 55.

3. Switch Makes Contact at Any Point on Wave, R. L. Witzke. *Electrical World*, February 13, 1937.


# Some Effects of Welding on Ship Construction

SHIPBUILDING PRACTICE has been affected more in the last decade by the introduction and general adoption of welding than by any other one innovation, according to James B. Hunter in a paper presented during the spring meeting of The Society of Naval Architects and Marine Engineers at Chester, Pa., June 22, 1937. Design has been modified, particularly because a ship's hull must be assembled without annealing and so-called built-in stresses should be avoided as far as possible. The maximum amount of prefabrication on the ground or in the shop is desirable. Intricate forgings often can be replaced by simple welded parts, and welding is used extensively in parts for major machinery.

Erection and assembly procedure has been greatly modified by the use of welding, primarily because of the omission of holes and flanges for fastening individual members together and also because of the various methods adopted to take care of shrinkage and buckling, particularly on the lighter structures. In assembly, welding in most instances requires greater time because of sequence in order to avoid distortion and the introduction of so-called locked-up stresses. Such sequence usually entails completion of one section before starting work on the adjacent section. The greater amount of erection time directly affects shipyard capacity. Sheet-metal and pipe shops have also been affected greatly by the use of welding.

Different types of vessels require different methods and shop equipment. Welding has advanced recently to a great degree in the building of naval vessels, but in the design of this type the urge to save weight, because of treaty limitations, justifies increased cost, since military characteristics can be provided which would otherwise be impossible Such reasoning, however, cannot be applied to merchant vessels except in very special cases.

# Magnetic Generation of a Group of Harmonics

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## Synopsis

A harmonic generator circuit is described which produces a number of harmonics simultaneously at substantially uniform amplitudes by means of a nonlinear coil. Generators of this type have been used for the supply of carrier currents to multichannel telephone systems, for the synchronization of carrier frequencies in radio transmitters, and for frequency comparison and standardization.

A simple physical picture of the action of the circuit has been derived from an approximate mathematical analysis. The principal rôles of the nonlinear coil may be regarded as fixing the amount of charge, and timing the charge and discharge of a condenser in series with the resistance load. By suitably proportioning the capacity, load resistance, and saturation inductance of the nonlinear coil, the amplitudes of the harmonics may be made to approximate uniformity over a wide frequency range. The sharply peaked current pulse developed by condenser discharge passes through the nonlinear coil in its saturated state and so contributes nothing to the eddy-current loss in the core. In this way the efficiency of frequency transformation is maintained at a comparatively high value for the harmonics in a wide frequency band, even with small core structures. The theory has also been adequate in establishing a basis for design, and in evaluating the effects of extraneous input components.

## I. Outline of Development

THE USE of nonlinear ferromagnetic core coils to generate harmonics started with a simple type of circuit due to Epstein[1] which appeared in 1902. Application of the idea was not made to any great extent until it was elaborated by Joly[2] and by Vallauri[3] in 1911. The frequency multipliers thus developed were limited to doublers and to triplers, polarization being required for the doubler. In these, as well as in subsequent developments, single and polyphase circuits were used, and various arrangements were adopted for the structure of the magnetic core and for the circuit, by which unwanted components were balanced out of the harmonic-output path. Later developments had to do with improvements in detail, and with the generation of higher harmonics in a single stage and in a series of stages. The applications of perhaps greatest importance were to high power, long-wave radiotelegraph transmitters, where the fundamental input was obtained from an alternator. Other applications of the idea of harmonic production by magnetic means have been made in the power and communication fields.[4]

It appears that these circuits were all developed primarily to generate a single harmonic. Comparatively good efficiencies were obtained, values from 60 to 90 per cent being reported for the lower harmonics. The theory of frequency multiplication was investigated by a number of workers, among whom may be mentioned Zenneck[5] and Guillemin.[6] The latter, after analysis which determined the optimum conditions for the generation of any single harmonic, found experimentally that the efficiency of harmonic production decreased as the order of the harmonic increased. He obtained efficiencies of 10 per cent for the ninth harmonic, and 3 per cent for the thirteenth harmonic of 60 cycles.

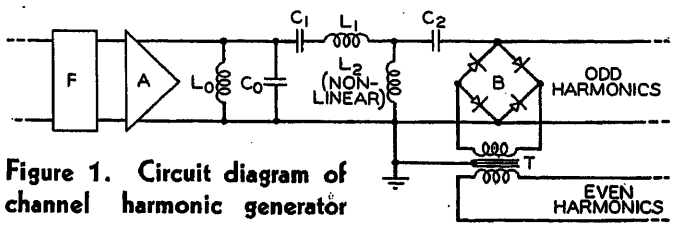



**Figure 1. Circuit diagram of channel harmonic generator**

Where the circuits are properly tuned and the losses low, free oscillations may be developed. The frequencies of these free oscillations may be harmonic, or subharmonic as in the circuit described by Fallou;[7] they may be rational fractional multiples of the fundamental, or incommensurable with the fundamental, as in Heegner's circuit.[8] The amplitudes of these free oscillations are usually critical functions of the circuit parameters and input amplitudes, and where the developed frequencies are not harmonic, they are characterized by the fact that the generated potentials are zero on open circuit. The theory of the effect has been worked out by Hartley.[9] It is presumably this effect which is involved in the generation of even harmonics by means of an initially unpolarized ferromagnetic core, an observation which has been attributed to Osnos.[10]

## II. Circuit Description

The harmonic producer circuit which forms the subject of the present paper differs from those mentioned in that it is designed to generate simultaneously a number of harmonics at approximately the same amplitude.

Harmonics developed in circuits of this type have been used for the supply of carrier currents to various multichannel carrier telephone systems, for synchronizing carriers used in radio transmitters, and for frequency com-

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1. For all numbered references, see list at end of paper.

parison and standardization. Only odd harmonics are generated by the harmonic producer when the core of the nonlinear coil is unpolarized, as is the case here. To generate the required even harmonics, rectification is employed. This is accomplished by means of a well-balanced copper-oxide bridge, which provides the even harmonics in a path conjugate to the path followed by the odd harmonics.

A typical circuit used for the simultaneous generation of a number of odd and even harmonics at approximately

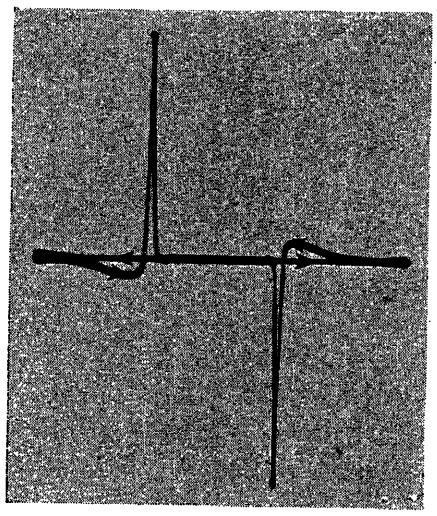


**Figure 2. Cathode-ray oscillogram of output-current wave form with fundamental input current as abscissa**

equal amplitudes is shown schematically in figure 1. Starting with the fundamental frequency input, a sharply selective circuit $F$ is used to remove interfering components, and an amplifier $A$ provides the input to the harmonic generator. The shunt resonant circuit $L_0C_0$ tuned to the fundamental serves primarily to remove the second harmonic generated in the amplifier. The elements $C_1L_1$ are inserted to maintain a sinusoidal current into the harmonic producer proper, as well as to tune out the circuit reactance.

$L_2$ is a small permalloy core coil which is operated at high magnetizing forces well into the saturated region. The circuit including $L_2$, $C_2$, and the load impedance, which is practically resistive to the desired harmonics, is so proportioned that highly peaked current pulses rich in harmonics flow through it. Two such pulses, oppositely directed, are produced during each cycle of the fundamental wave, the duration of each being a small fraction of the fundamental period. The typical output wave shown in figure 2 was obtained by means of a cathode-ray oscillograph, the ordinate representing the current in the load resistance, and the abscissa representing the fundamental current into the coil. The desired odd harmonics are selected by filters connected across the input terminals of the copper-oxide bridge. The even harmonics are obtained by full-wave rectification in the copper-oxide bridge, and are taken off from the conjugate points of the bridge through an isolating transformer to the appropriate filters. Thus the harmonics are produced in 2 groups, with the even harmonics separated from the odds to a degree depending largely upon the balance of the copper-oxide bridge, as well as upon the amount of second harmonic passed on from the amplifier. In this way the required discrimination properties of any filter against adjacent harmonics are reduced to the extent of the balance.

A particular application of the circuit described above to the generation of carriers for multichannel carrier telephone systems uses a fundamental frequency of 4 kilocycles, from which a number of harmonics are developed. Of these the sixteenth to the 27th are used as carriers. A photograph of an experimental model of this carrier supply system (developed by Mr. J. M. West) is shown in figure 3. The top panel includes an electromagnetically driven tuning fork serving as the highly selective circuit $F$, the amplifier $A$, the output stage of which consists of a pair of pentodes in push-pull, and the tuned circuit $L_0C_0$. The next panel includes the elements $L_1C_1$, $L_2$, $C_2$, $B$, and $T$,

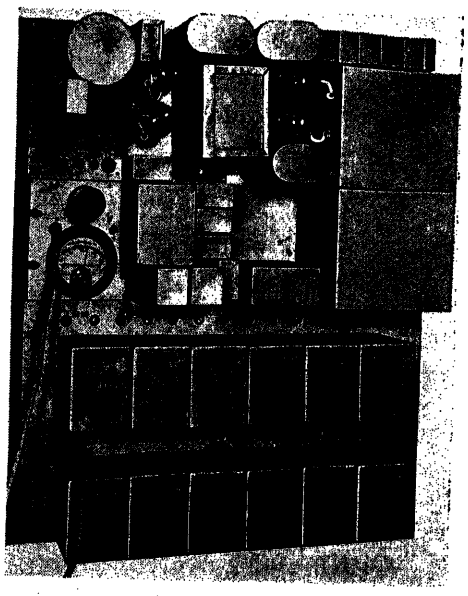


**Figure 3. Carrier supply unit, furnishing 12 harmonics of 4 kilocycles (experimental model)**

together with a thermocouple and meter terminating in a cord and plug for test and maintenance purposes. The last 2 panels include the 12 harmonic filters, with test jacks and potentiometers for close adjustment of the output of each harmonic.

A few of the more interesting performance features are given in figure 4. The harmonic power outputs shown in figure 4*a* represent measurements at the input terminals of the filters. The variation observed is produced by the nonuniform impedance of the filters. When these are corrected, the variations due to the harmonic generator proper are less than $\pm 0.2$ decibels from the sixteenth to the 27th harmonic. Outside this region the amplitudes gradually decrease to the extent of 4 decibels at the third and 35th harmonics, and 11 decibels at the fundamental and the 61st harmonic. The variation of harmonic output with change of amplifier plate potential is given for the 2 harmonics indicated in figure 4*b*. Figure 4*c* shows the 104-kilocycle output as a function of the 4-kilocycle input. Arrows are used to indicate normal operating points. The input amplifier is operated in an overloaded state so that,

beyond a critical input, the fundamental output of the amplifier and the harmonic output corresponding are but little affected by change of input amplitude. With a linear amplifier the harmonic output current would vary roughly as the 0.4 power of the input current.

Another application involving higher frequencies has been made to the generation of the so-called "group" carriers used in conjunction with a coaxial conductor.[11] There only odd harmonics of 24 kilocycles from the ninth to the 45th are required. These are generated at substantially uniform amplitudes. The circuit differs from figure 1 in that the copper-oxide bridge is omitted, and the nonlinear coil is provided with 2 windings to facilitate impedance matching. The performance of an experimental model is similar to that of the generator described above.

In both applications the required harmonics are generated at amplitudes high enough to avoid the necessity for amplification. A notion of the physical size and construction of the nonlinear coils used may be had from the photographs of figure 5.

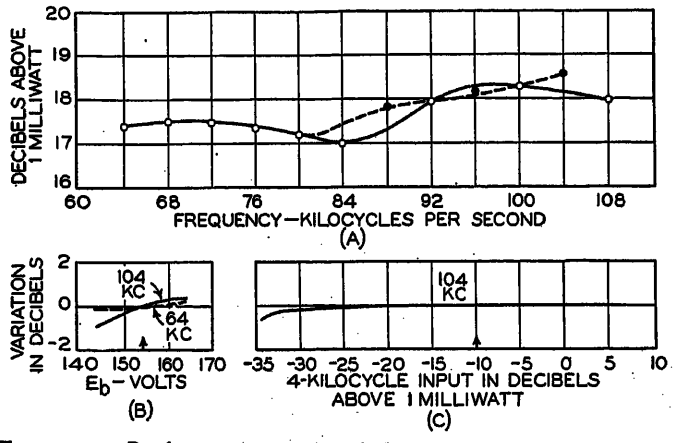



**Figure 4. Performance curves of channel harmonic generator**

*A*—Harmonic outputs

*B*—Variation of sixteenth and 26th harmonics with amplifier plate potential

C—Variation of 26th harmonic with fundamental input

## III. Theory of Operation

The analysis of operation of the harmonic-generating circuit described above meets with difficulties, since a high degree of nonlinearity is involved in working the coil well into its saturated region.

To avoid these difficulties, an expedient is adopted by which the hysteresis loop is replaced by a single-valued characteristic made up of connected linear segments[6] as shown in figure 6*b*. It is then possible to formulate a set of linear differential equations with constant coefficients, one for each linear segment. The solutions are readily arrived at and may be pieced together by imposing appropriate conditions at the junctions, so that a solution for the whole characteristic is thereby obtained. From this solution the wave form of current or voltage associated with any circuit element may be calculated. Resolution of the wave form into components may then be accomplished by an independent Fourier analysis.

The assumed $B$-$H$ characteristic of figure 6*b* is made up of but 3 segments. While it is manifestly a naïve representation of a hysteresis loop, it will be shown by comparison with experiment that the main performance features of harmonic generators may be reproduced by this crude model.

It will be noted on figure 6*b* that the differential permeability of the assumed nonlinear core, a quantity proportional to $dB/dH$, takes on one of 2 values, determined by the absolute value of the magnetizing force. These are designated by $\mu$ in the permeable region and $\mu_s$ in the saturated region. The corresponding inductances are $L_{20}$ and $L_{2s}$, $L_{20}$ being many times greater than $L_2$. The values of current through the coil at which the differential inductance changes are designated $\pm I_0$, corresponding to the magnetizing forces $\pm H_0$. With this simple representation of the nonlinear inductance, the operation of the circuit shown in figure 6*a* will be described over a complete cycle of the fundamental input wave.

The current flowing in the input mesh is made practically sinusoidal by tuning $L_1$, $C_1$. If now we start at the negative peak of the sinusoidal input current of amplitude $I_1$ and frequency $p/2\pi$, the nonlinear coil is worked in the saturated state where its inductance $L_{2s}$ is low. Since the resistance of the winding is small, the potential drop across the coil is correspondingly small. The current $i_2$ which charges the condenser $C_2$, assuming the latter to have zero

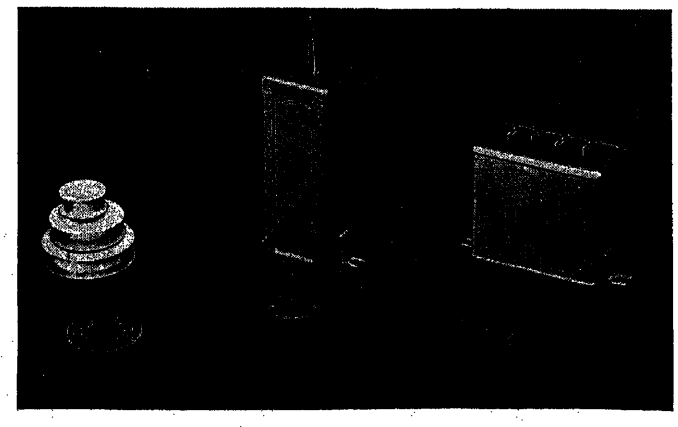
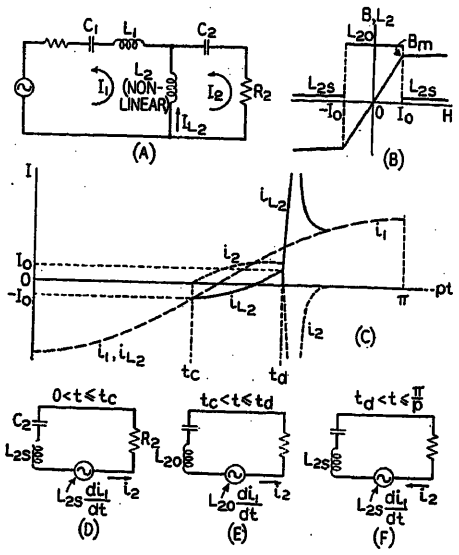


**Figure 5. Construction of experimental nonlinear coils used for harmonic generation, showing core forms, magnetic tape, wound coils, and assembled units**

charge at the start, is therefore negligible as indicated in figure 6*c*. This state of affairs is maintained until the current through $L_2$ reaches the value $-I_0$, at time $t_c$. At this point the inductance of the coil increases suddenly to $L_{20}$ and the voltage across the coil tends to increase. Hence the current $i_2$ increases and $C_2$ is charged much more rapidly than in the preceding interval. Charging continues until the current through the coil increases through $I_0$ at time $t_d$. At that time, the coil inductance returns to




A—Harmonic generator circuit

B—Differential inductance and flux density of assumed nonlinear coil as functions of magnetizing force

C—Variation with time of currents in primary and secondary meshes, and in nonlinear coil

D, E, F—Equivalent circuits of the harmonic generator for the 3 time intervals indicated

**Figure 6. Diagrams illustrating operation of the harmonic generator**

the low saturation value $L_{2s}$, and the potential across the coil decreases. The condenser potential is no longer opposed by the potential drop across the coil and the condenser discharges through $R_2$ and $L_{2s}$; $i_2$ reverses its direction, maintaining the coil in the saturated region. The form and duration of the sharply peaked discharge pulse characteristic of this type of harmonic generator are determined by the values of the elements just mentioned. The resistance, capacity, and saturation inductance effectively in circuit are adjusted to permit the current to rise to a high maximum, to damp the pulse, and to shorten the pulse duration to the point at which the highest harmonic required reaches the desired amplitude. Under the working conditions which will be assumed in the following, this insures that the pulse dies away before the end of the half-cycle as shown in figure 6*c*. At that time the currents and potentials are the same, except for reversals of sign, as those at the start, so that the current wave consists of an alternating succession of these pulses. Equivalent circuits for the 3 respective time intervals of a half-cycle are shown in figures 6*d*, 6*e*, 6*f*. The similarity of the load-current wave form derived above, and that experimentally observed and shown in figure 2, is to be noted.

The course of events described above parallels closely conclusions drawn from the mathematical analysis. This picture attributes to the coil $L_2$ a sort of switching property which permits the condenser $C_2$ in the load circuit to be charged and discharged alternately. The charge starts when the large inductance $L_{20}$ is switched across the primary and secondary meshes, thus permitting energy to flow from the primary circuit into the condenser $C_2$. This corresponds to that part of the wave described above during which the load current slowly rises as the charge accumulates on $C_2$. Discharge starts when the large inductance $L_{20}$ is switched out and the much smaller inductance $L_{2s}$ is switched in. This sharply reduces the voltage across $L_2$, and the condenser is discharged through the load resistance and the saturation inductance. During this interval the secondary circuit is practically isolated from the primary. The switching process is sustained by the alternations of the sinusoidal primary current and is periodic, as we have seen, since similar conditions exist at the start of each pulse. The times at which switching occurs are those at which the current through the coil passes through the critical values ($\pm I_0$) where the inductance changes.

Since the narrow discharge pulse provides the principal contribution to the higher harmonics in which we are interested, and since this charge takes place in the secondary independently of the primary, the elements of the secondary mesh during discharge determine the form of the output spectrum. From this viewpoint we may regard the condenser as the source of energy for these harmonics and hence as a possible location for equivalent harmonic generator electromotive forces. In this light, the discharge circuit becomes a half-section of low-pass filter terminated in resistance $R_2$, with $L_{2s}$ as the series element and $C_2$ as the shunt element.

## IV. Quantitative Results of Analysis

To connect the 3 solutions which hold for the 3 linear regions of the *B-H* characteristic, conditions at the junctions are introduced, which lead to transcendental equations. These may be solved graphically when definite values are assigned to the circuit parameters. From these may be obtained the maximum value $Q_m$ of charge on $C_2$ which is reached at the end of the charging stage.

By plotting a representative group of these final charges over a range of parameters ordinarily encountered, an empirical equation has been deduced for $Q_m$ as follows:

$$Q_m = \sqrt{2}\,\frac{I_1}{p}\left(\frac{pL_{20}}{R_2}\right)^{0.75}(pC_2R_2)^{0.05}\left(\frac{I_0}{I_1}\right)^{0.6} \qquad (1)$$

For the usual operating conditions the narrow peaked discharge part of the current pulse is most important in the determination of the higher harmonics (say beyond the ninth) with which we are concerned here. The charging interval then may be neglected in calculating the higher harmonics. The form of the discharge pulses is determined by the parameters $pC_2R_2$ and $k$, where

$$k = L_{2s}/R_2^2C_2$$

The familiar criterion for oscillation in a series circuit containing inductance, capacity, and resistance may be expressed in terms of $k$. If $k > 1/4$, the discharge is an exponentially decaying oscillation; if $k \leq 1/4$, the discharge is

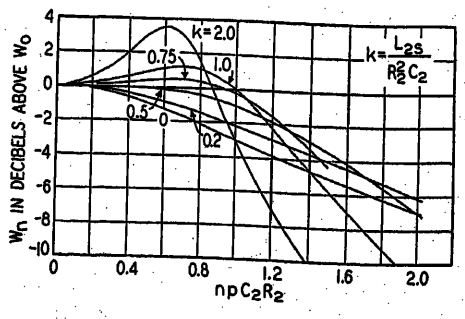



**Figure 7. Harmonic power spectrum plotted from equation 2 as function of $npC_2R_2$ with k as parameter**

an exponentially decaying pulse. This last condition is the one assumed in the description of operation given above.

If the discharge is oscillatory, and if further the second peak is large enough, the current through the coil may become less than $I_0$ during the discharge interval. Thus $L_2$ will return to its larger value, and recharging of the condenser will result. This process may lead to large and undesired variations in the harmonic amplitudes. To maintain the frequency distribution as uniform as possible over the frequency range of interest, the circuit parameters are usually adjusted so that recharging does not occur.

Harmonic analysis shows that the $n$th harmonic amplitude under the above assumptions is given by

$$I(n) = \frac{(2/\pi)\, pQ_m}{\sqrt{1 + (1 - 2k)\,(npC_2R_2)^2 + k^2\,(npC_2R_2)^4}} \qquad (2)$$

where $n$ is odd. This expression neglects the contributions due to the charging stage, which are usually small for harmonics higher than the ninth.

The corresponding harmonic power output is

$$W_n = \frac{I(n)^2 R_2}{2} \frac{W_0}{1 + (1 - 2k)\,(npC_2R_2)^2 + k^2\,(npC_2R_2)^4} \qquad (3)$$

where $W_0$ is a convenient parameter which does not vary with $n$ and hence serves as an indication of the power of the output spectrum. It is related to $W$, the total power delivered to the load resistance, by the equation

$$W_0 = \frac{4}{\pi}\, pC_2R_2W$$

For purposes of calculation $W_0$ may be found from (1) and (2) to be

$$W_0 = \frac{10^{-7}}{\pi^2}\, pB_m\, Ad\, H_1 \left(\frac{H_0}{H_1}\right)^{0.2} (pC_2R_2)^{1.8} \left(\frac{pL_{20}}{R_2}\right)^{0.5} \text{watts} \qquad (4)$$

where

$$L_{20} = \frac{4N^2A\mu 10^{-9}}{d}$$

$$H_1 = 0.4\, N\, I_1/d$$

$$H_0 = 0.4\, N\, I_0/d$$

and $N$ is the number of turns wound on the toroidal core of diameter $d$ centimeters and cross-sectional area $A$ square centimeters.

In figure 7 the power spectrum is shown by plotting $W_n$ in decibels above or below $W_0$ as a function of $npC_2R_2$ for several values of $k$. These curves illustrate the degree of uniformity obtainable in harmonic amplitudes under different conditions. It may be shown from (3) that $W_n$ has a maximum with respect to $n$ when $k$ is greater than 1/2, if

$$npC_2R_2 = \frac{1}{k}\sqrt{k - \frac{1}{2}}$$

and that its value at this point is

$$(W_n)_{max} = W_0k^2/(k - 1/4)$$

A number of relations may be derived from these equations which are useful for design purposes. Thus the form of harmonic distribution is fixed by $k$ and $pC_2R_2$. The power for a given magnetic material worked at a given fundamental magnetizing force then depends solely upon the volume of core material. Finally, the impedance is fixed by the number of turns per unit length of core. If the impedances desired for primary and secondary circuits differ, separate windings may be used for each circuit.

## V. Calculated and Observed Performance

In order to make practical use of the results given above, we need some basis for deriving the assumed parameters of the nonlinear coil from the physical properties of the magnetic materials used in harmonic producers.

The fact that the actual magnetization curve is a loop instead of a single-valued curve as assumed requires increased power input to the circuit to provide for the hysteresis and eddy losses in the core. Other than this, the principal remaining effect of the existence of a loop is a lag in the time at which the pulses occur, an effect which is of no great moment in determining the form or magnitude of the resulting pulses.

The next point requiring consideration is the effect introduced by the assumed abrupt change of slope contrasted to the smooth approach to saturation actually observed. While no rigorous comparisons can be drawn, the effect of the more gradual approach to saturation was approximated analytically by introducing an additional linear segment between the permeable region and each saturated region of the $B$-$H$ characteristic, at a slope intermediate between the two, so as to form a $B$-$H$ characteristic of 5 segments in place of the original 3. The solutions for these 2 characteristics were found to yield negligibly small differences in the amplitudes of the higher harmonics. It was inferred from this result that no substantial change would be introduced by a smooth approach to saturation.

Finally, the actual $B$-$H$ characteristic has a slight curvature in the saturated region, while the analysis considered a small linear variation. A rough approximation for the effect of this curvature, which leads to fair agreement with experiment, consists in taking for $L_{2s}$ the average of the actual slope, from its minimum value reached during the discharge peak down to the point at which the slope is $^1/_{10}$ maximum. To this is added the linear inductance contributed by the dielectric included within the winding.

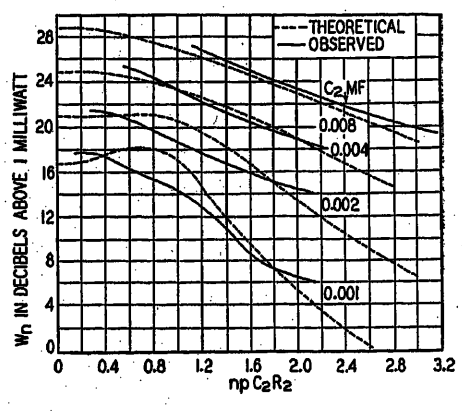



**Figure 8. Comparisons of calculated and measured harmonic distributions, plotted as functions of $npC_2R_2$, with $C_2$ as parameter; fundamental (4-kilocycle) magnetizing force 8.1 oersteds**

To summarize then, the harmonic outputs obtained from the analysis with the assumed $B$-$H$ characteristic may be brought into line with experimental observations by the introduction of quantities obtained from actual $B$-$H$ loops at appropriate frequencies and magnetizing forces. In these the maximum slope found on the loop is taken for $L_{20}$, the average slope over the saturated region is taken for $L_{22}$, and the energy corresponding to the area of the real $B$-$H$ loop must be added to that originally supplied the harmonic generator input.

A comparison between measured and calculated harmonic distributions obtained with a 4-kilocycle fundamental input is shown in figure 8. In this case the harmonic distributions were measured for 4 different values of the secondary condenser $C_2$ as shown by the plotted points. The power output of each harmonic is plotted in terms of the quantity $npC_2R_2$. Calculated values are indicated by dashed lines. It is observed that while the agreement between calculation and experiment is perhaps as good as could be expected for the 2 highest curves, a substantial divergence is noticed in the 2 lowest sets; the forms of the 2 sets are significantly different, and it seems that the divergence might become even greater at larger values of $npC_2R_2$ than those shown. Upon examination of the equations, however, it turns out that the conditions existing for the lowest pair of curves are just those for which recharging occurs, so that the conditions for which the equations were framed hold no longer. The calculated distributions might be expected to be too low for the higher harmonics, since we have taken an average value for the saturation inductance. This means that the peak of the discharge pulse will be sharper than that calculated, with a corresponding effect upon the higher harmonics.

Another comparison between calculated and observed values is shown in figure 9 for a fundamental input of 120 kilocycles with 2 values of resistance load. Fair agreement is observed over the greater part of the frequency range, which extended to 5 megacycles. The distribution curve for the smaller resistance load undulates as the load resistance is reduced, since multiple oscillations and recharging are then promoted, in consequence of which the output power tends to become concentrated in definite bands of harmonics. In general, agreement within a few decibels is found over a wide range of circuit parameters when working into a resistance load, provided that recharging does not occur.

When the resistance termination is replaced by a bank of filters as it is in practice, the resistance termination is approximated over the frequency band covered by the filters. Where the band is wide the results obtained do not differ greatly from those with the pure resistance load, but when only a few harmonics are taken off by filters and the impedances to the other harmonics of large amplitude vary widely over the frequency range, then the wave form of the current pulse is substantially altered, with corresponding effect upon the frequency distribution, and the calculations for a pure resistance termination do not apply.

A difficulty sometimes arises in getting a desired value of fundamental current into the coil. Under certain circuit conditions the current amplitude is found to change rapidly as the input voltage is smoothly varied. This phenomenon has been described by various terms such as Kippeffekt, ferroresonance, and current-hysteresis.[13] If the operating point is located close to one of these discontinuities, the fundamental input and harmonic output may vary widely with small changes in supply potentials and circuit parameters. This troublesome source of variation may be avoided in a number of different ways, of which the simplest is to increase the resistance of the resonant mesh. In the present case this is effectively accomplished without sacrificing efficiency by using pentodes, which have high internal resistances, in the amplifier stage connected to the resonant mesh.

The efficiency of power conversion from fundamental to harmonics may be found from the fundamental power input to the circuit, as derived from measurements on a cathode-ray oscillograph, and from the total harmonic output measured by means of a thermocouple. The maximum efficiency obtainable with the low power circuits described in the second section is in the neighborhood of 75 per cent, and decreases with increasing fundamental frequency because of the increased dissipation due to eddy currents. It should be noted that this figure does not include losses in the primary inductance $L_1$. When only a few harmonics are used, the efficiency of obtaining this useful power naturally drops to a much lower value, which for the particular cases mentioned in the second section, is between 15 and 25 per cent.

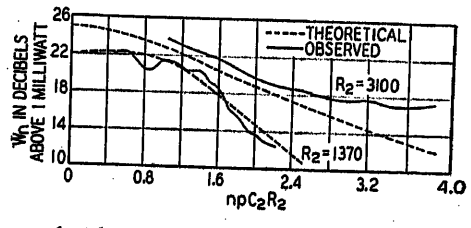



**Figure 9. Comparisons of calculated and measured harmonic distributions, plotted as functions of $npC_2R_2$ with $R_2$ as parameter; fundamental (120 kilocycle) magnetizing force 9.8 oersteds**

## VI. Effect of Extraneous Components

In any practical case the fundamental input to the harmonic producer is accompanied by extraneous components introduced by crosstalk, by modulation, or by an impure source. Thus if the fundamental is derived as a harmonic of a base frequency, small amounts of adjacent harmonics will be present. Or if the amplifiers are a-c operated, side frequencies are produced differing from the fundamental by 60 cycles and its multiples. Extraneous components of this sort in the input modulate the fundamental and produce side frequencies about the harmonics in the output. When the harmonics are used as carriers, the accompanying products must be reduced to a definite level below the fundamental if the quality of the transmitted signal is to be unimpaired. The requirements imposed by this condition can be calculated by simple analy-

sis, the results of which agree rather well with experimental values.

The method of analysis used is to consider the extraneous component at any instant as introducing a bias[14] to the nonlinear coil. The primary effect of a small bias $b$ is to shift the phase of the discharge pulse by $\mp b/H_1$ radians, $H_1$ being the amplitude of the fundamental magnetizing force. The sign of the shift alternates so that intervals between pulses are alternately narrowed and widened.

The effect of this shift on the harmonics produced may be found by straightforward means in which the amplitude of any harmonic is expressed in terms of the bias. Hence when the extraneous component or components vary with time, the sidebands produced may be evaluated when the bias is expressed by the appropriate time function.

If the bias is held constant, the wave is found to include both odd and even harmonics, the amplitudes of which are given by

$$\left.\begin{aligned} I_n &= I(n)\left|\cos nb/H_1\right| \quad (n \text{ odd}) \\ &= I(n)\left|\sin nb/H_1\right| \quad (n \text{ even}) \end{aligned}\right\} \tag{5}$$

$I(n)$ being the harmonic distribution in the absence of bias as given by equation 2.

If the extraneous input component is sinusoidal, we have

$$b = Q \sin (qt + \phi) \tag{6}$$

Substituting this expression for $b$ in the equation for the harmonic components yields odd harmonics of the fundamental, and modulation products with the angular frequencies $mp \pm lq$, which may be grouped as side frequencies about the odd harmonics. The amplitude of the $n$th (odd) harmonic is

$$I_n = I(n)\left|J_0\left(\frac{nQ}{H_1}\right)\right| \tag{7}$$

and the amplitude of the modulation product $mp \pm lq$ is

$$I_{m,\pm l} = I(m)\left|J_l\left(\frac{mQ}{H_1}\right)\right| \qquad (m + l \text{ odd}) \tag{8}$$

where $J_l(x)$ is the Bessel function of order $l$.

Considering the side frequencies about the $n$th harmonic, the largest and nearest of these are $(n + 1)p - q$ and $(n - 1)p + q$, $n$ being odd. The ratio of the amplitudes of either side frequency to the $n$th harmonic is

$$\frac{I_{n\pm1,\mp1}}{I_n} = \left|\frac{J_1[(n \pm 1)Q/H_1]}{J_0(nQ/H_1)}\right| \tag{9}$$

on the assumption that the harmonic distribution in the neighborhood of $n$ is uniform so that $I(n \pm 1) \doteq I(n)$. If the arguments of the Bessel functions are less than 0.4, a good approximation to the right member of equation 9 is $(n \pm 1)Q/2H_1$. Hence with sufficiently small values of interference, the sidebands produced are proportional to the amplitude of the interference, and increase linearly with the order of the harmonic. These relations apply to harmonic generators which produce sharply peaked waves in general, and are not peculiar to the magnetic types.

Neighboring modulation products involving the interfering component $q$ more than once have much smaller amplitudes in normal circumstances than the product considered above. Because of the tuning in the input mesh, interfering components far removed in frequency from the fundamental are greatly reduced and the most troublesome interference is likely to be close in frequency to the fundamental.

It may be noted that where the interference is produced by amplitude modulation of the fundamental, so that 2 interfering components enter the input, the distortion

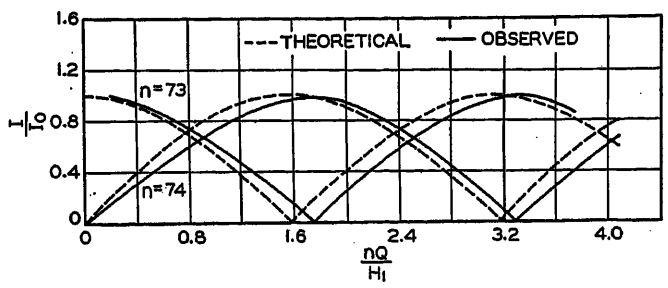



**Figure 10. The 73rd and 74th harmonic amplitudes as functions of direct current flowing through nonlinear coil. Ordinate is ratio of harmonic amplitude, with bias indicated, to that of 73rd harmonic with zero bias; abscissa is harmonic number multiplied by the ratio of bias to fundamental; dashed lines calculated from equation 5, full lines measured; fundamental 4 kilocycles**

produced may be approximated by doubling the amplitudes of the side frequencies produced by one of the interfering components. If the disturbance is the second harmonic of the fundamental, the effect is nearly the same as that for constant bias, and the relations (5) may be used if $b$ is taken as the amplitude of the second harmonic magnetizing force.

To illustrate the effects of d-c bias, figure 10 shows the amplitudes of the 73rd and 74th harmonics of 4 kilocycles as functions of the parameter $nQ/H_1$. The agreement between measured and calculated values indicates that the most important effects of bias have been included in the simple analysis.

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# Transmission Lines at Very High Radio Frequencies

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## Summary

Radiation resistance, although ordinarily neglected, is actually of dominant importance in determining the selectivity factor $Q$ and the input impedance $Z_s$ for both parallel-wire and concentric lines at high radio frequencies, and therefore materially changes the optimum design of the line, whether used as a low-loss inductive or capacitive reactance or to give high selectivity or high impedance as a resonant line. Accurate design equations for maximum selectivity and for maximum impedance are developed in this paper for both parallel-wire and concentric lines, and curves are included showing radiation resistance, selectivity, input impedance, optimum values of spacing, conductor radius, etc. It is shown that for maximum $Q$ the optimum ratio of spacing to wire radius for parallel-wire lines is $D/r = 6.186$, and the ratio of outer conductor radius to inner conductor radius for concentric lines is $b/a = 4.22$, as compared with values of about 3.6 for both ratios when radiation resistance is neglected. For maximum impedance corresponding values are $D/r = 20.96$ and $b/a = 14.3$, as compared with values of 8 and 9.2, respectively, predicted neglecting radiation resistance. Moreover, $Q$ and $Z_s$ are not proportional to $D$ and $b$, as indicated in previous analyses; instead definite values of $D$ and $b$ give maximum $Q$ and slightly larger values give maximum $Z_s$, and even a small departure from the best value produces a large decrease in $Q$ or in $Z_s$. $Q$ and $Z_s$ for optimum design are both *inversely* proportional to the cube root of the frequency for parallel-wire lines and inversely proportional to the 0.4 power of the frequency for concentric lines, whereas previous analyses showed both *increasing* as the square root of the frequency.

## Introduction

RADIO COMMUNICATION in recent years has experienced a greatly increased utilization of the ultrahigh frequencies (those above 30,000,000 cycles), and the near advent of television will undoubtedly make these frequencies among the most valuable and most used in the entire spectrum. At these very high frequencies resonant transmission lines offer advantages in many ways which are not even closely approached by their nearest competitors. For instance the oscillating crystal, almost invariably used at lower frequencies to give radio transmitters a high degree of frequency stability, can be used at ultrahigh frequencies only in conjunction with several stages of frequency multiplication, since the $Q$ of the crystal (the ratio of its inertia reactance to its frictional resistance, and therefore a measure of its frequency stabilizing ability) is inversely proportional to frequency and assumes such a low value at the ultrahigh frequencies as to be practically worthless for frequency stabilization. For instance at 30,000,000 cycles the $Q$ of an $X$-cut quartz crystal is approximately 170, and at 300,000,000 cycles it is only about 17. To obtain values even as high as these requires careful mounting to keep the external work done by the oscillating crystal as small as possible. On the other hand, properly designed resonant transmission lines at these frequencies are extremely selective. For instance at 300,000,000 cycles as short-circuited quarter-wave parallel-wire line (approximately 10 inches long) of number 10 copper wire spaced 0.32 inch between wire axes has a $Q$ of 771. A concentric line of the same length and of optimum design has a $Q$ of 4,560. (The $Q$ of any electrical circuit is defined as

$$Q = \frac{2\pi fL}{R} = \frac{2\pi cL}{\lambda R} = \frac{2\pi L}{\lambda R\sqrt{LC}} = \frac{2\pi Z_0}{\lambda R}$$

where $R$, $L$, and $C$ are respectively resistance, inductance, and capacity per unit length of 2-wire line, $c = 1/\sqrt{LC} = 3 \times 10^{10}$ centimeters per second is the velocity of propagation of an electromagnetic wave in space and, at the ultrahigh frequencies, also the velocity along a wire, $\lambda$ is the wave length in centimeters and equals $c/f$, and $Z_0 = \sqrt{L/C}$ is the characteristic impedance of the line.) Evidently at the ultrahigh frequencies a comparatively tiny resonant line can give frequency stabilization far superior to that obtained by means of a crystal and at a small fraction of the expense. The high $Q$ of such lines also gives them a unique place as voltage step-up devices, the step-up ratio for an open-circuited quarter-waveline equaling $4Q/\pi$. Thus at 300,000,000 cycles, at which frequency the ordinary tuned radio-frequency transformer is of little value, a quarter-wave open-circuited concentric line gives a voltage step-up of 5,810.

Moreover, the high impedance obtainable by the use of resonant lines makes them ideally adapted as coupling elements between stages of vacuum-tube amplifiers at these high frequencies. Approximately a million ohms resistance may readily be obtained by means of a shorted quarter-wave concentric line. The quarter-wave line is also used extensively as an impedance matching device,[1] as a means of holding current at the receiving end of the line constant regardless of large changes in the magnitude and angle of the load impedance,[2] and as an impedance inverting device.[3]

A short-circuited transmission line of less than a quarter wave length acts as a high-quality low-loss inductive re-

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1. For all numbered references, see list at end of paper.

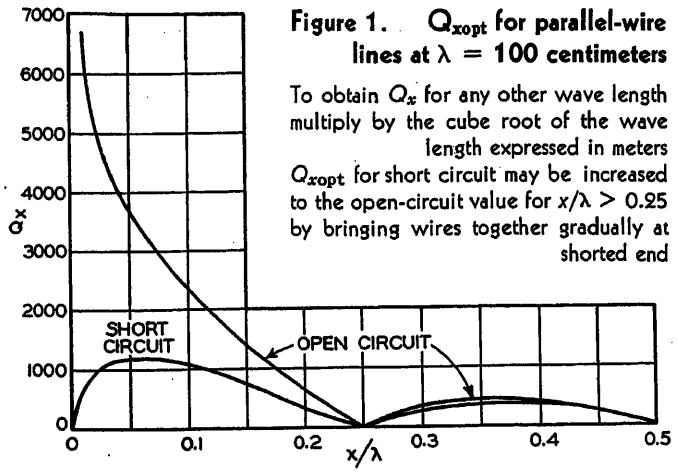



**Figure 1. $Q_{xopt}$ for parallel-wire lines at $\lambda$ = 100 centimeters**

To obtain $Q_x$ for any other wave length multiply by the cube root of the wave length expressed in meters

$Q_{xopt}$ for short circuit may be increased to the open-circuit value for $x/\lambda > 0.25$ by bringing wires together gradually at shorted end

actance with a $Q$ at the ultrahigh frequencies far superior to that of any coil. An open-circuited line of less than a quarter wave length acts as a high $Q$ capacitive reactance. If a capactive reactance which will pass direct current is desired, a short-circuited line of about $^3/_8$ wave length may be used, preferably a concentric line. Transmission lines, especially those of the concentric type, are therefore ideally adapted for use as circuit elements for electric filters and as tuning devices in general at ultrahigh frequencies.

The use of transmission lines as circuit elements at ultrahigh frequencies has been considered in several previous papers, of which Terman's "Resonant Lines in Radio Circuits," published in ELECTRICAL ENGINEERING, July 1934, is the most comprehensive. However, in all of these papers the effect of radiation resistance in altering the effective resistance of both parallel-wire and concentric lines has been neglected. In addition, the effect of proximity of the 2 wires in a parallel-wire line, in altering the constants $L$, $C$, and $R$, and therefore the input impedance and the $Q$ of the line although mentioned in some of the papers, has not been taken into account with rigid mathematical accuracy. The proximity effect is small for the optimum ratio of spacing to wire radius, decreasing $L$ and $Z_0$ by about 1.5 per cent each, increasing $C$ by about 1.5 per cent, and increasing $R$ by about 5.5 per cent. Of course there is no proximity effect in a concentric line. Consideration of these factors, and especially of the radiation resistance, very materially changes the optimum design of the line, whether used as a low-loss inductive or capacitive reactance or to give high selectivity or high impedance as a resonant line.

Specifically the following changes are introduced:

1. When radiation and the proximity effect are neglected, the analysis *seems* to show that both the resonant input impedance $Z_s$ and the resonant $Q$ are directly proportional to the square root of the frequency for both parallel-wire and concentric lines. That is, the analysis appears to show that $Q$ *increases* as frequency increases. However, when radiation resistance and the proximity effect are taken into consideration it is found that for parallel-wire lines $Q$ is *inversely* proportional to the cube root of the frequency, and for concentric lines is inversely proportional to the 0.4 power of the frequency. In other words, $Q$ actually *decreases* as frequency increases for both parallel-wire and concentric lines.

2. When radiation resistance and the proximity effect are neglected, the analysis seems to show that the resonant $Q$ and $Z_s$ are proportional to the spacing for parallel-wire lines, and proportional to the outer diameter for concentric lines, and designers have therefore been urged to use large values of spacing and diameter, respectively. Taking radiation resistance and the proximity effect into account, however, shows that for any frequency and length of line a definite spacing for parallel-wire lines and a definite outer diameter for concentric lines give maximum $Q$, and slightly larger values of spacing and outer diameter, respectively, give maximum values for $Z_s$. Moreover these values, in general, especially for the very high frequencies, are considerably smaller than the values which have been recommended on the basis of the older analysis, and even a small departure from the best value produces a relatively large decrease in $Q$ or in $Z_s$.

3. Disregarding radiation resistance and the proximity effect gives a false optimum value of $D/r = 2.72$ for a parallel-wire line, and $b/a = 3.6$ for a concentric line to give maximum $Q$.
$D$ is spacing between wire axes for parallel wires,
$r$ is wire radius for a parallel-wire line,
$b$ is inner radius of outer tube of a concentric line, and
$a$ is outer radius of inner conductor.
Taking radiation resistance and the proximity effect into account changes these values to

$D/r = 6.186$ for parallel-wire lines
$b/a = 4.22$ for concentric lines
} Optimum values for maximum $Q$ for a line of any length, whether resonant or not

4. Disregarding radiation resistance and the proximity effect, the analysis seems to show that $Q$ is independent of the number of quarter wave lengths of line used and of the line termination. Actually $Q$ is a function of line length and in general is quite different for open-circuit than for short-circuit termination.

5. Disregarding the radiation resistance and the proximity effect gives a false optimum value of $D/r = 8$ for a parallel-wire line, and $b/a = 9.2$ for a concentric line if maximum input impedance is desired. Taking radiation resistance and the proximity effect into account changes these values to

$D/r = 20.96$ for parallel-wire lines
$b/a = 14.3$ for concentric lines
} Optimum ratios for maximum $Z_s$ at resonance

The higher the frequency the more important radiation resistance becomes. For instance, at 300,000,000 cycles the analysis, disregarding radiation resistance and proximity effect, would seem to show that a parallel-wire line, a quarter wave length long and short-circuited, would have a $Q$ of 2,655 if constructed of wires 0.5 inch in diameter

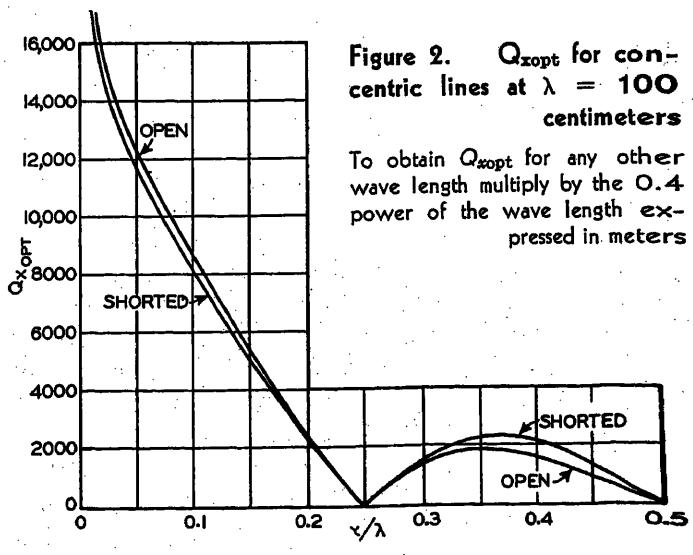



**Figure 2. $Q_{xopt}$ for concentric lines at $\lambda$ = 100 centimeters**

To obtain $Q_{xopt}$ for any other wave length multiply by the 0.4 power of the wave length expressed in meters

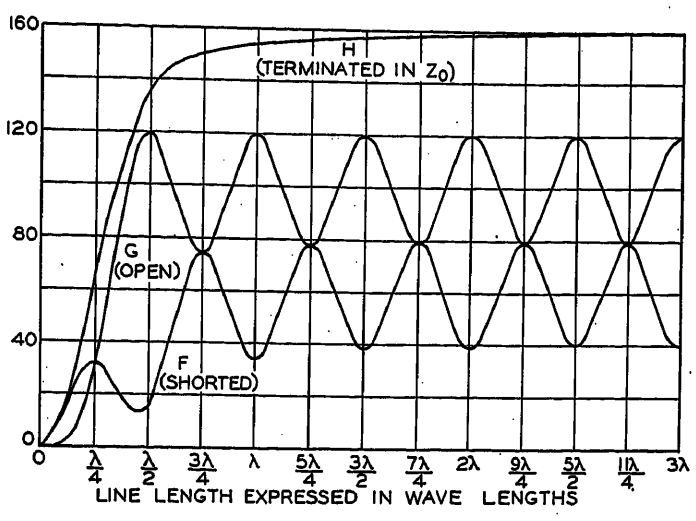



**Figure 3**

Multiply by $(\pi D/\lambda)^2$ to obtain radiation resistance for parallel-wire lines

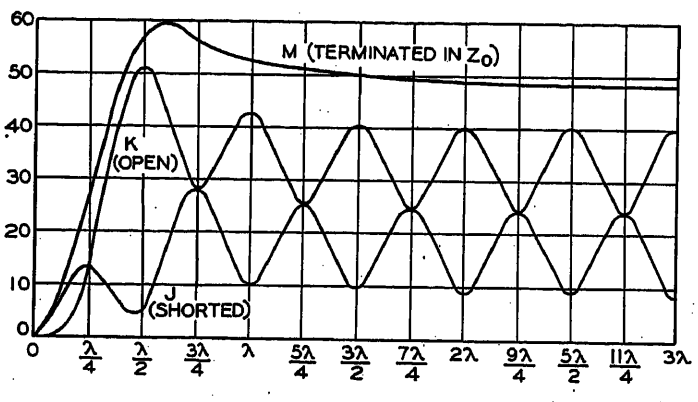



**Figure 4**

Multiply by $(\pi^4/\lambda^4)(b^2 - a^2)^2$ to obtain radiation resistance for concentric line

and spaced 0.68 inch between wire axes. Actually, however, the neglected radiation resistance in this case is almost 8 times as large as all other resistance. The correct value of $Q$ is only 423. If, however, the diameter of the wire is *decreased* to 0.262 centimeter (0.103 inch) and the spacing to 0.812 centimeter (0.319 inch), the optimum values for this frequency, a $Q$ of 771 is obtained. If, instead of using a shorting bar to short the line, the 2 wires are brought together gradually, this $Q$ can be increased to over 1,000. Both diameter and spacing must, however, be increased about 50 per cent over the values given above.

Similarly for a quarter-wave short-circuited concentric line to be operated at 60,000,000 cycles Hansell and Carter (April 1936, IRE *Proceedings*, page 599) recommend values of $b = 30$ centimeters (11.8 inches) and $a = 8.25$ centimeters (3.25 inches). Neglecting radiation resistance they compute that the $Q$ of the line would equal 20,000. Actually here also the effect of the radiation resistance, which was neglected, is approximately 5.6 times as large as that of all other resistance. So, instead of a $Q$ = 20,000, it actually is only 3,420. If the optimum design, considering radiation resistance, had been used, the $b$ and $a$ could have been decreased to 16.95 centimeters and 4.02 centimeters respectively, which would have raised $Q$ for the quarter-wave shorted line to 8,680. Moreover, if a half-wave concentric line, shorted at both ends and fed at any intermediate point on the line, had been used the $Q$ could have been raised to 12,000.

## Fundamental Transmission Line Equations

Whether a transmission line is to be used to carry hundreds of thousands of kilowatts at commercial power frequencies, or fractions of a watt at the audio frequencies as in a telephone line, or power in varying amounts at radio frequencies, the same equations, derived in many textbooks (see Woodruff's "Electric Power Transmission and Distribution") hold accurately, namely

$$\left.\begin{aligned} E_s &= E_r \cosh px + I_r \sinh px \\ I &= I_r \cosh px + \frac{E_r}{Z_0} \sinh px \\ Z_s &= E_s/I_s \end{aligned}\right\} \quad (1)$$

where

$E_r$ and $I_r$ are voltage and current respectively at the receiving or load end of the line,
$E_s$ and $I_s$ are voltage and current at the sending end of the line,
$x$ is length of line (in our work the unit of length is the centimeter),
$p = (\alpha + j\beta)$ is the propagation constant per unit length of line,
$\alpha$ is the attenuation constant per unit length of line,
$\beta$ is the wave length constant per unit length of line,
$Z_0 = \sqrt{Z/Y}$ is the characteristic impedance of the line,
$Z$ is the series impedance per unit length of line,
$Y$ is the admittance between conductors per unit length of line.

At high radio frequencies

$$\alpha = \frac{R}{2}\sqrt{\frac{\bar{C}}{L}} = \frac{R}{2Z_0}$$

$$\beta = \frac{2\pi}{\lambda}$$

where $\lambda$(lambda) is the wave length.

If the wave length is expressed in centimeters, $\lambda = 3 \times 10^{10}/f$, where $f$ is frequency.

## The Line as a Low-Loss Inductive or Capacitive Reactance

For open circuit, $I_r = 0$, so

$$Z_s = \frac{E_r \cosh px}{\frac{E_r}{Z_0} \sinh px} = Z_0 \frac{\cosh \alpha x \cos \beta x + j \sinh \alpha x \sin \beta x}{\sinh \alpha x \cos \beta x + j \cosh \alpha x \sin \beta x}$$

Eliminating the $j$ term from the denominator by multiplying by

$$\frac{\sinh \alpha x \cos \beta x - j \cosh \alpha x \sin \beta x}{\sinh \alpha x \cos \beta x - j \cosh \alpha x \sin \beta x}$$

and collecting terms gives

$$Z_s = Z_0 \frac{(\alpha x - j \cos \beta x \sin \beta x)}{(\alpha x)^2 \cos^2 \beta x + \sin^2 \beta x} \quad (2)$$

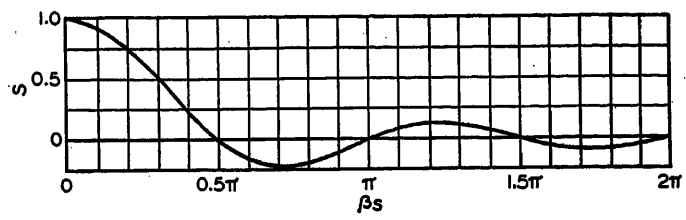



**Figure 5. S versus βs**

$S = (\sin 2\beta s)/2\beta s$

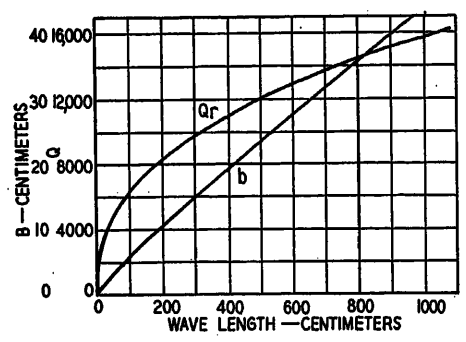



**Figure 6. Optimum $Q_r$ and b versus λ for half-wave concentric line shorted at both ends and fed at any intermediate point**

since for $x$ only a few wave lengths long, $\alpha x$ at the ultra-high frequencies is so small that cosh $\alpha x = 1.0$ and sinh $\alpha x = \alpha x$ (both ordinarily within one part in $10^6$). Except for $x$ *very* close to $n\lambda/2$, where $n$ is any integer, $(\alpha x)^2$ is negligible compared with $\sin^2\beta x$, and

$$Z_s = Z_0\left(\frac{\alpha x}{\sin^2 \beta x} - j \operatorname{ctn} \beta x\right) = Z_0 \operatorname{ctn} \beta x\left(\frac{Rx}{Z_0 \sin 2\beta x} - j\,1.0\right) \tag{3}$$

Evidently such a line acts as a condenser with a $Q_x = (Z_0 \sin 2\beta x)/Rx$.

*Note:* We differentiate throughout the paper between the $Q$ of a line acting as an inductive or capacitive reactance, which we designate $Q_x$, and the $Q$ of the resonant line, which we designate $Q_r$. In general, the $2Q$'s have very different values.

*Example:* For a parallel-wire line, for $\lambda = 100$ centimeters ($f$ = 300,000,000 cycles), and $x = \lambda/20 = 5$ centimeters, with optimum radius of wire and spacing for minimum loss,

$Z_0$ = 215.2 ohms
$Z_s$ = 661 (0.000266 − $j$ 1.0)
$Q_x$ = 3,750 (from curve in figure 1)

Similarly for short circuit

$$Z_s = Z_0 \frac{\alpha x + j \sin \beta x \cos \beta x}{\cos^2 \beta x + (\alpha x)^2 \sin^2 \beta x} \tag{4}$$

Except for $x$ *very* close to $(2n + 1)\lambda/4$, $(\alpha x)^2$ is negligible compared with $\cos^2 \beta x$, so

$$Z_s = Z_0\left(\frac{\alpha x}{\cos^2 \beta x} + j \tan \beta x\right) = Z_0 \tan \beta x\left(\frac{Rx}{Z_0 \sin^2 \beta x} + j\ 1.0\right) \tag{5}$$

Thus a short-circuited line, less than a quarter wave length long, acts as an inductive reactance with a $Q_x = (Z_0 \sin 2\beta x)/Rx$.

*Example:* For a parallel-wire line, for $\lambda = 100$ centimeters, and $x = 5$ centimeters, if line is designed for minimum loss, then

$Z_0$ = 215.2 ohms
$Z_s$ = 69.9 (0.000867 + $j$ 1.0)
$Q_x$ = 1,154 (from curve in figure 1)

*Example:* For a concentric line, and same λ and $x$ as above,

$Z_0$ = 86.4 ohms
$Z_s$ = 28 (0.0000865 + $j$ 1.0)
$Q_x$ = 11,550 (from curve in figure 2)

Compare this $Q_x$ with a $Q$ of about 17 for a quartz crystal at this frequency.

## Equations for Resonant Lines

When an open-circuited line is *very* nearly any multiple of a half wave length long, equation 2 is evidently a poor expression for $Z_s$, since neither $(\alpha x)^2 \cos^2\beta x$ nor $\sin^2\beta x$ is negligible compared with the other. In this case it is better to express the input impedance as

$$Z_s = Z_0 \frac{\cosh^2 \alpha x \cos^2 \beta x + \sinh^2 \alpha x \sin^2 \beta x}{\cosh \alpha x \sinh \alpha x + j \sin \beta x \cos \beta x} = \frac{Z_0}{\alpha x} \frac{1}{1 + j \dfrac{\sin \beta x \cos \beta x}{\alpha x}}$$

since cosh $\alpha x = 1$ and sinh $\alpha x = \alpha x$ (within one part in $10^6$) and for $\beta x$ *very* close to $n\pi$, $\cos^2 \beta x = 1$ (very nearly), and $\sinh^2 \alpha x \sin^2 \beta x$ is considerably less than $10^{-6}$, so is negligible compared with 1.0. Moreover for $\beta x$ very close to $\beta_r x = n\pi$,

$$\cos \beta x = (-1)^n \text{ and } \sin \beta x = (-1)^n \frac{x\pi}{\lambda}\left(\frac{f}{f_r} - \frac{f_r}{f}\right)$$

So

$$Z_s = \frac{Z_0}{\alpha x} \frac{1}{1 + j \dfrac{\pi}{\alpha\lambda}\left(\dfrac{f}{f_r} - \dfrac{f_r}{f}\right)} = \frac{2Z_0^2}{Rx} \frac{1}{1 + j \dfrac{2\pi Z_0}{R\lambda}\left(\dfrac{f}{f_r} - \dfrac{f_r}{f}\right)} \tag{6}$$

where $f_r$ is the frequency which would make the line *exactly* a multiple of a half wave length long, and $f$ is the frequency under consideration, differing only slightly from $f_r$, as would be the case if the line were used for frequency control. An open-circuited line very nearly any multiple of a half wave length long evidently acts as a *parallel* resonant circuit, with a $Z_s$ at resonance $= 2Z_0^2/Rx$ and a $Q_r = 2\pi Z_0/R\lambda$.

Similarly when the open-circuited line is very nearly any *odd* multiple of a quarter wave length long, equation 2 may be readily transformed to

$$Z_s = \frac{Rx}{2}\left[1 + j \frac{2\pi Z_0}{R\lambda}\left(\frac{f}{f_r} - \frac{f_r}{f}\right)\right] \tag{7}$$

Thus an open-circuited line very nearly any odd multiple of a quarter wave length long acts exactly as a *series* resonant circuit, with a $Q_r$ of exactly the same value as for equation 6.

Equation 6 holds not only for an open-circuited line very nearly any multiple of a half wave length long, but

also for a short-circuited line very nearly any odd multiple of a quarter wave length long. Similarly equation 7 holds not only for an open-circuited line very nearly any odd multiple of a quarter wave length long, but also for a short-circuited line very nearly any multiple of a half wave length long.

## Transmission Line Constants

At commercial power frequencies with wide spacing between wires, for a parallel-wire line

$$L = \left(\mu + 4 \ln \frac{D}{r}\right) 10^{-9} \text{ henrys per centimeter length of 2-wire line}$$

$$C = \frac{1}{\left(4 \ln \frac{D}{r}\right) 9 \times 10^{11}} \text{ farads per centimeter line to line}$$

$$R = R_{d-c} = \frac{2\rho 10^{-9}}{\pi r^2}$$ ohms per centimeter length of 2-wire line, where $r$ is wire radius and $\rho$ (rho) is resistivity (1,724 for copper of 100 per cent conductivity and slightly larger for commercial copper)

To take account of the proximity effect if the wires are close together and of skin effect at high radio frequencies, these equations are changed to

$$L = \left\{\sqrt{\frac{2\rho}{\pi r^2 \omega \left[1 - \left(\frac{2r}{D}\right)^2\right]}} + 4 \ln \left[\frac{D}{2r} + \sqrt{\left(\frac{D}{2r}\right)^2 - 1}\right]\right\} 10^{-9}$$

henrys per centimeter length of 2-wire line, assuming that wire is not of magnetic material

$$C = \frac{1}{\left\{4 \ln \left[\frac{D}{2r} + \sqrt{\left(\frac{D}{2r}\right)^2 - 1}\right]\right\} 9 \times 10^{11}}$$ farads per centimeter, line to line

$$R' = \frac{\sqrt{2\rho f}\, 10^{-9}}{r \sqrt{1 - \left(\frac{2r}{D}\right)^2}}$$ ohms per centimeter length of 2-wire line, *excluding effect of radiation resistance*

For a copper line,

$$R' = \frac{84\sqrt{f}\, 10^{-9}}{r \sqrt{1 - \left(\frac{2r}{D}\right)^2}} = \frac{0.01455}{\sqrt{\lambda r} \sqrt{1 - \left(\frac{2r}{D}\right)^2}} \quad (8)$$

$$R = R' + \frac{2 R_{rad}}{x(1 \doteq S)} \quad (9)$$

where $R_{rad}$ is radiation resistance of the line, a function of frequency, line length, and line termination. $S$ is discussed in detail later. It equals zero for a line any multiple of a quarter or half wave length long.

The first term in the equation for $L$ is negligible for very high frequencies, so the equation for inductance may be written

$$L = \left\{4 \ln \left[\frac{D}{2r} + \sqrt{\left(\frac{D}{2r}\right)^2 - 1}\right]\right\} 10^{-9}$$ (Accurate within 1 part in 1,200 at 300,000,000 cycles)

Then

$$Z_0 = \sqrt{Z/Y} = \sqrt{L/C} = 120 \ln \left[\frac{D}{2r} + \sqrt{\left(\frac{D}{2r}\right)^2 - 1}\right]$$

ohms for a *parallel-wire* line (10)

For a *concentric* line at high radio frequencies

$L = (2 \ln b/a)\, 10^{-9}$ henrys per centimeter length of line (both conductors)

$$C = \frac{1}{(2 \ln b/a)\, 9 \times 10^{11}}$$ farads per centimeter length of line (between conductors, for air dielectric)

$$R' = 42\sqrt{f}\, 10^{-9} \left(\frac{1}{a} + \frac{1}{b}\right) = \frac{0.007275}{b\sqrt{\lambda}} \left(\frac{b}{a} + 1\right)$$

ohms per centimeter of line (11)

$$R = R' + \frac{2 R_{rad}}{x(1 \doteq S)} \quad (12)$$

$$Z_0 = 60 \ln b/a \quad (13)$$

## Radiation Resistance of Parallel-Wire Lines

The radiation resistance of a line is defined as equal to the power radiated in watts divided by the square of the current in amperes at a point on the line where the current has a maximum value. For an open-circuited line a quarter wave length long, such a maximum current point or current loop is at the sending end; for a short-circuited quarter-wave line it is found at the receiving end. In general current loops are found at all odd quarter-wave points, measured from the open end, on open-circuited lines; they are found at all half-wave points, measured from the shorted end, on short-circuited lines. A line terminated in its characteristic impedance of course has no standing waves, so the current has the same effective value at all points (neglecting the very small loss along the line). Therefore $R_{rad}$ for a line terminated in its characteristic impedance is simply the power radiated divided by the square of the current.

The following equations, derived by the author, have been used in computing the data from which the curves for $F$, $G$, and $H$ in figure 3 were plotted.

$$R_{rad} = 120 \left(\frac{\pi D}{\lambda}\right)^2 \left[\frac{1}{3} - \frac{2}{Y^2} + \left(\frac{1}{3} + \frac{1}{Y^2}\right) \sin^2 Y + \frac{1}{Y^3} \sin 2Y\right] = \left(\frac{\pi D}{\lambda}\right)^2 F \quad (14)$$

for a short-circuited line. This does not include the radiation resistance of the shorting bar, which alone equals $80(\pi D/\lambda)^2$. Total radiation resistance of a shorted line if a shorting bar is used, is $(\pi D/\lambda)^2(80 + F)$.

We have for convenience written $Y$ for $\beta x$ in all of the radiation resistance formulas. For an open-circuited line the equation becomes

$$R_{rad} = 120 \left(\frac{\pi D}{\lambda}\right)^2 \left[1 - \left(\frac{1}{3} + \frac{1}{Y^2}\right) \sin^2 Y\right] = \left(\frac{\pi D}{\lambda}\right)^2 G \quad (15)$$

For a line terminated in its characteristic impedance the equation becomes

$$R_{rad} = 120 \left(\frac{\pi D}{\lambda}\right)^2 \left[\frac{4}{3} - \frac{2}{Y^2} + \frac{\sin 2Y}{Y^3}\right] = \left(\frac{\pi D}{\lambda}\right)^2 H \quad (16)$$

Note that $R_{rad}$ for the line terminated in its characteristic impedance equals the sum of $R_{rad}$ for open circuit and $R_{rad}$ for short circuit. (The derivation of these equations

and also those for the radiation resistance of concentric lines is contained in a paper by the author, entitled "Radiation Resistance of Parallel-Wire and Concentric Lines," accepted for presentation at the IRE convention to be held at Spokane, Wash., this fall. It is hoped that it will appear in an early issue of the *Proceedings* of the Institute of Radio Engineers.)

## Radiation Resistance for Concentric Lines

For short circuit

$$R_{rad} = 120\frac{\pi^4}{\lambda^4}\left[b^2 - a^2\right]^2\left[\frac{1}{15} + \frac{1}{Y^2} + \left(\frac{2}{15} + \frac{9}{Y^4}\right)\sin^2 Y - \frac{12}{Y^4} - \left(\frac{1}{Y^3} - \frac{6}{Y^5}\right)\sin 2Y\right] \quad (17)$$

$$= \frac{\pi^4}{\lambda^4}(b^2 - a^2)^2 J$$

Note that this is the total radiation resistance for this case, since the shorting disk for a concentric line does not radiate.

For open circuit

$$R_{rad} = 120\frac{\pi^4}{\lambda^4}(b^2 - a^2)^2\left[\frac{1}{3} + \frac{1}{Y^2} - \left(\frac{2}{15} + \frac{3}{Y^4}\right)\sin^2 Y + \frac{\sin 2Y}{Y^3}\right] = \frac{\pi^4}{\lambda^4}(b^2 - a^2)^2 K \quad (18)$$

As in the case of the parallel-wire line, so also for concentric lines the radiation resistance for the line terminated in its characteristic impedance is the sum of the radiation resistance of the open-circuited and short-circuited lines. It may be expressed

$$R_{rad}\text{ (for } Z_0 \text{ termination)} = \frac{\pi^4}{\lambda^4}(b^2 - a^2)^2 M \quad (19)$$

Curves for $J$, $K$, and $M$ versus $x$ are plotted in figure 4. A slight correction factor, depending on the values of $b/\lambda$ and $a/\lambda$, and very slightly on line length, has been neglected in these formulas. For optimum values of $b$ and $a$, the correction factor is less than 1 per cent. It has, however, been taken into account in computing and plotting the values of $J$, $K$, and $M$.

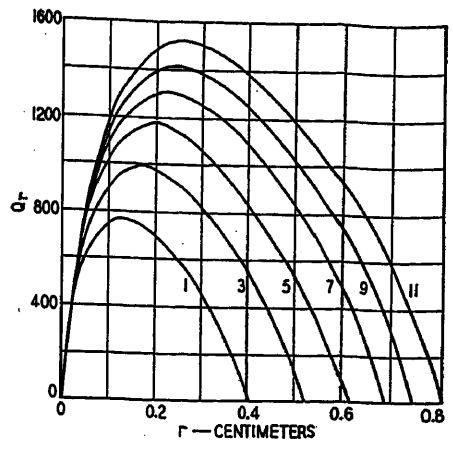
## Total Resistance of Line at High Radio Frequencies

The power lost in a line evidently equals the sum of the $I^2R$ loss and the power radiated (for leakage loss negligible, as is practically always justified in a radio-frequency line). For a line with standing waves, $I = I_0 \cos \beta s$ if the line is shorted, and $I = I_0 \sin \beta s$ if the line is open-circuited, $s$ being distance in centimeters measured from the receiving end and $I_0$ being the root-mean-square current at a current loop. Then for a shorted line

$$\text{power} = I_0^2 R_{rad\,(shorted)} + R'\int_0^x I_0^2 \cos^2 \beta s\, ds = I_0^2\frac{x(1+S)}{2}\left[R' + \frac{2R_{rad\,(shorted)}}{x(1+S)}\right]$$

**Figure 7. Parallel line, short circuit**

$Q_r$ versus $r$
$\lambda = 100$ centimeters
$D = D_{opt}$
Curve numbers refer to number of quarter wave lengths




where $S = (\sin 2\beta x)/2\beta x$. See figure 5 for a curve of $S$ versus $\beta x$. Therefore the equivalent resistance per centimeter length for a short-circuited line is

$$R = R' + \frac{2R_{rad\,(shorted)}}{x(1+S)}$$

For an open-circuited line the equivalent resistance per centimeter length comes out

$$R = R' + \frac{2R_{rad\,(open)}}{x(1-S)}$$

For $x$ any multiple of a quarter or half wave length, sine $2\beta x = 0$, so $S = 0$. So for both open and shorted lines at all multiples of a quarter or half wave length from the receiving end, $R = R' + 2R_{rad}/x$, the appropriate $R_{rad}$ being used in each case. For a line terminated in its characteristic impedance, $R = R' + R_{rad}/x$.

## Design of Resonant Parallel-Wire Lines for Maximum Selectivity (Maximum Q)

Equations 6 and 7 show that the $Q$ for lines at or very near their resonant frequencies is $Q_r = 2\pi Z_0/R\lambda$. Putting into this equation the values of $Z_0$ and $R$ for parallel-wire lines from equations 8, 9, 10, 14, and 15 gives

$$Q_r = \frac{240\,\pi \ln\left[\frac{D}{2r} + \sqrt{\left(\frac{D}{2r}\right)^2 - 1}\right]}{\frac{0.01455\sqrt{\lambda}}{r\sqrt{1 - \left(\frac{2r}{D}\right)^2}} + \frac{2\lambda}{x}\left(\frac{\pi D}{\lambda}\right)^2\left(\frac{80+F}{1+S}\text{ or }\frac{G}{1-S}\right)}$$

Use $(80 + F)/(1 + S)$ for shorted line, and $G/(1 - S)$ for an open line.

This expression has its maximum value when

$$\frac{0.01455\sqrt{\lambda}}{r\sqrt{1 - \left(\frac{2r}{D}\right)^2}} = \frac{4\lambda}{x}\left(\frac{\pi D}{\lambda}\right)^2\left(\frac{80+F}{1+S}\text{ or }\frac{G}{1-S}\right) \quad (20)$$

and

$$\ln\left[\frac{D}{2r} + \sqrt{\left(\frac{D}{2r}\right)^2 - 1}\right] = \frac{1.5\sqrt{1 - \left(\frac{2r}{D}\right)^2}}{1 - 2\left(\frac{2r}{D}\right)^2} \quad (21)$$

From 21 value of $D/r$ to give maximum $Q$ is

$$(D/r)_{opt} = 6.186 \tag{22}$$

Placing this value into 20 and solving for $D$ gives

$$D_{opt} = \frac{0.134\,\lambda^{5/6}}{\sqrt[3]{\frac{\lambda}{x}\left(\frac{80+F}{1+S} \text{ or } \frac{G}{1-S}\right)}} \tag{23}$$

This expression for optimum $D$ holds for both optimum $Q_r$ and $Q_x$. For any value of $x/\lambda$, the appropriate value of $F$ or $G$ may be taken from curves of figures 3 and the value of $S$ from figure 5. For instance, for a quarter-wave short-circuited line, $80 + F = 111.37$, $S = 0$, so $D_{opt} = 0.0172\,\lambda^{5/6}$.

Putting the optimum value of $D$ into the expression for $Q_r$ gives

$$Q_{r_{opt}} = \frac{1270\,\lambda^{1/3}}{\sqrt[3]{\frac{\lambda}{x}\left(\frac{80+F}{1+S} \text{ or } \frac{G}{1-S}\right)}} = \frac{9480}{\sqrt{\lambda}} D_{opt} \tag{24}$$

For a shorted quarter-wave parallel-wire line,

$$Q_{r_{opt}} = 166\,\lambda^{1/3} \tag{25}$$

For an open-circuited half-wave parallel-wire line,

$$Q_{r_{opt}} = 162\,\lambda^{1/3} \tag{26}$$

Since for the shorted quarter-wave line, 71.8 per cent of the radiation resistance is due to the shorting bar, the $Q_r$ may be substantially increased (by almost 50 per cent) if the wires are brought together gradually, thus eliminating the necessity for a shorting bar. Note, however, that this also changes slightly the value of $Z_0$ to be used in the equation for $Q_r$ and increases by 50 per cent the optimum $D$ to be used.

Note that the expression for $Q_{r_{opt}}$ which we have given holds accurately only for lines close to resonant lengths (any multiple of a quarter or half wave length), the only lengths for which $Q_r$ is of any importance. However, from this expression for $Q_r$, the value of $Q_x$ for a line of any length may be accurately determined. $Q_{x_{opt}} = Q_{r_{opt}} (\sin 2\beta x)/\beta x$ for both parallel-wire and concentric lines. Also $Q_x$ for any frequency may be easily computed from the curves of figures 1 and 2.

## Design of Resonant Concentric Lines for Maximum Selectivity

$$Q_r = \frac{2\pi Z_0}{R\lambda} = \frac{120\pi \ln b/a}{R'\lambda + \frac{2\lambda}{x}\frac{R_{rad}}{1 \pm S}}$$

$$= \frac{120\pi \ln b/a}{\frac{0.007275\sqrt{\lambda}}{b}\left(\frac{b}{a}+1\right) + \frac{2\lambda}{x}\frac{\pi^4}{\lambda^4}(b^2-a^2)^2\left(\frac{J}{1+S}\text{or}\frac{K}{1-S}\right)} \tag{27}$$

Solving for optimum $b/a$ and optimum $b$ gives

$$b/a_{opt} = 4.22 \tag{28}$$

$$b_{opt} = \frac{0.14051\,\lambda^{0.9}}{\sqrt[5]{\frac{\lambda}{x}\left(\frac{J}{1+S} \text{ or } \frac{K}{1-S}\right)}} \tag{29}$$

Use $J/1 + S$ for short circuit, use $K/1 - S$ for open circuit, obtaining values of $J$ and $K$ from curves of figure 4.

Putting these values into the expression for $Q_r$ gives

$$Q_{r_{opt}} = \frac{120\,\pi \ln 4.22}{1.25\,R'\lambda} = \frac{1{,}607\,\lambda^{0.4}}{\sqrt[5]{\frac{\lambda}{x}\left(\frac{J}{1+S} \text{ or } \frac{K}{1-S}\right)}}$$

$$= \frac{11{,}420}{\sqrt{\lambda}}\, b_{opt} \tag{30}$$

For a shorted quarter-wave concentric line, $J = 13.37$ and $S = 0$, so

$$b_{opt} = 0.0634\,\lambda^{0.6} \tag{31}$$

$$Q_{r_{opt}} = 725\,\lambda^{0.4} \tag{32}$$

For a half-wave concentric line shorted at both ends and fed at any intermediate point, $K = 5.43$ and $S = 0$, so

$$b_{opt} = 0.0873\,\lambda^{0.9} \tag{33}$$

$$Q_{r_{opt}} = 997\,\lambda^{0.4} \tag{34}$$

$Q_{r_{opt}}$ and $b_{opt}$ are plotted as functions of wave length in figure 6. The $Q_{r_{opt}}$ could be increased by using a longer line shorted at both ends. For instance $Q_{r_{opt}} = 1{,}310\,\lambda^{0.4}$ for $x = 3\,\lambda$. For a high $Q_r$ always use a concentric line, some multiple of a half wave length long, shorted at both ends and fed at the particular intermediate point which gives the desired input impedance.

Curves in figures 9 and 10 show how $Q_r$ decreases when $a$ is varied, in one case holding $b$ constant, in the other case holding the ratio $b/a$ constant. Figures 7 and 8 show the corresponding curves for parallel-wire lines.

## Design of Parallel-Wire Lines for Maximum Input Impedance

Equation 6 shows that any open-circuited line some multiple of a half wave length long, and also any short-circuited line some odd multiple of a quarter wave length long, has an input impedance

$$Z_{s_r} = \frac{2\,Z_0^2}{Rx} \quad \text{(True for both parallel-wire and concentric lines)}$$

Using the values of $Z_0$ and $R$ from equations 8, 9, 10, 14, and 15 gives

$$Z_{s_r} = \frac{28{,}800 \ln^2\left[\frac{D}{r} + \sqrt{\left(\frac{D}{2r}\right)^2 - 1}\right]}{\frac{0.01455\,x}{\sqrt{\lambda}\,r\sqrt{1-\left(\frac{2r}{D}\right)^2}} + 2\left(\frac{\pi D}{\lambda}\right)^2((80+F) \text{ or } G)} \tag{35}$$

Differentiating 35 with respect to $D$, and also with respect to $r$, and solving the resulting equations simultaneously, shows that 35 takes a maximum value when

$$D/r = 20.96 \tag{36}$$

and

$$D = \frac{0.198\,\lambda^{5/6}}{\sqrt[3]{\frac{\lambda}{x}((80+F) \text{ or } G)}} \tag{37}$$

When these values are used,

$$Z_{s_{opt}} = \frac{114{,}600\ \lambda^{1/3}}{\frac{x}{\lambda}\sqrt[3]{\frac{\lambda}{x}}\ ((80 + F) \text{ or } G)} \tag{38}$$

This value is evidently a maximum for the smallest parallel resonant value of $x/\lambda$, which is $^1/_4$ for the shorted line and $^1/_2$ for the open-circuited line.

For the quarter-wave shorted parallel-wire line $F = 31.37$, so

$$D_{opt} = 0.0259\ \lambda^{5/6} \text{ and } Z_{s_{opt}} = 60{,}150\ \lambda^{1/3} \tag{39}$$

For the half-wave open-circuited line, $G = 120$, so

$$D_{opt} = 0.0318\ \lambda^{5/6} \text{ and } Z_{s_{opt}} = 36{,}900\ \lambda^{1/3} \tag{40}$$

Evidently to obtain the highest possible impedance the quarter-wave line should be drawn together gradually at the shorted end, so as to eliminate the necessity for a shorting bar. In the case $z_0$ will be decreased somewhat, which tends to decrease the numerator of 39. However, the denominator is decreased so much more that the value of $Z_{s_{opt}}$ is increased approximately 33 per cent, giving

$$Z_{s_{opt}} \cong 80{,}000\ \lambda^{1/3} \tag{41}$$

For this case

$$D_{opt} = 0.0389\ \lambda^{5/6} \tag{42}$$

and $(D/r)_{opt}$ remains 20.96.

Evidently high impedances may be obtained in this way, for instance 371,000 ohms at $\lambda = 100$ centimeters ($f = 300{,}000{,}000$ cycles), and 800,000 ohms at $\lambda = 1{,}000$ centimeters.

## Design of Concentric Lines for Maximum Impedance

From equations 11, 12, 13, 17, and 18

$$Z_{s_r} = \frac{2Z_0^2}{Rx} = \frac{7{,}200 \ln^2 b/a}{\frac{0.007275}{\sqrt{\lambda}}\frac{x}{b}\left(\frac{b}{a}+1\right) + 2\frac{\pi^4}{\lambda^4}(b^2 - a^2)^2(J \text{ or } K)}$$

$$= \frac{7{,}200 \ln^2 b/a}{\frac{A}{b}\left(\frac{b}{a}+1\right) + B\,(b^2 - a^2)^2} \tag{43}$$

This is a maximum when

$$\frac{A}{b}\left(\frac{b}{a}+1\right) = 4\,B\,(b^2 - a^2)^2 \tag{44}$$

and

$$\ln b/a = \frac{2.5[(b/a)^2 - 1]}{(b/a)^2 - (b/a) + 1} \tag{45}$$

Solving 45 gives

$$(b/a)_{opt} = 14.3 \tag{46}$$

Putting this value into 44 gives

$$b_{opt} = \frac{0.1705\ \lambda^{0.9}}{\sqrt[5]{\frac{\lambda}{x}}\ (J \text{ or } K)} \tag{47}$$

and

$$Z_{s_{r_{opt}}} = \frac{62{,}600\ \lambda^{0.4}}{\frac{x}{\lambda}\sqrt[5]{\frac{\lambda}{x}}\ (J \text{ or } K)} \tag{48}$$

For a shorted quarter-wave line, $J = 13.37$, so

$$b_{opt} = 0.077\ \lambda^{0.9} \tag{49}$$

$$Z_{s_{r_{opt}}} = 113{,}000\ \lambda^{0.4} \tag{50}$$

For a half-wave line shorted at both ends and fed at an intermediate point on the line, $K = 5.43$, so

$$b_{opt} = 0.106\ \lambda^{0.9} \tag{51}$$

$$Z_{s_{r_{opt}}} = 77{,}750\ \lambda^{0.4} \tag{52}$$

Evidently the quarter-wave shorted concentric line should be used if an enormous impedance (a pure resistance) is desired. Such a line represents an impedance of 713,000 ohms at a wave length of 100 centimeters, an impedance of 1,793,000 ohms at a wave length of 1,000 centimeters, and correspondingly higher impedances for longer wave lengths (lower frequencies).

## Design for Low Loss When Line Is Terminated in Its Characteristic Impedance

For both the transmission and reception of high-radio-frequency waves, either parallel-wire or concentric lines may be used to connect the antenna to the transmitter or receiver. In airplanes and in police cars, equipped for 2-way ultrashort-wave radio communication, such transmission lines may be only a fraction of a wave length long. At commercial radio transmitting or receiving stations the transmission lines may be many wave lengths long. In any case it is important to terminate the line at both ends in an impedance equal in magnitude and phase to the characteristic impedance of the line, so as to prevent the formation of standing waves on the line. When a line is so terminated, the transmission line equations reduce to

$$E_s = E_r\,\epsilon^{px} = E_r\,\epsilon^{\alpha x}.\epsilon^{j\beta x}$$
$$I_s = I_r\epsilon^{px} = I_r\epsilon^{\alpha x}.\epsilon^{j\beta x}$$
$$Z_s = Z_r = Z_0$$
$$P_r = P_s\epsilon^{-2\alpha x}$$

($P_r$ and $P_s$ stand for power at receiving and sending ends of the line, respectively)

and the power loss expressed in decibels is

$$N_{db} = 8.686\ (\alpha x) = 8.686\frac{Rx}{2Z_0} = 8.686\frac{\pi x}{\lambda}\frac{R\lambda}{2\pi Z_0} = \frac{8.686\pi x}{\lambda Q_r}$$

the value of $Q_r$ being equal to $2\pi Z_0/R\lambda$, just as for open or short-circuited lines. Evidently the loss is a minimum when $Q_r$ is a maximum.

For parallel-wire lines, from equation 23, noting that $H/2$ is to be substituted for $(80 + F/1 + S)$ or $(G/1 - S)$,

$$D_{opt} = \frac{0.134\ \lambda^{5/6}}{\sqrt[3]{\frac{\lambda}{x}\frac{H}{2}}} \tag{53}$$

This was a good form in which to leave the equation in the case of open or short-circuited lines, in which $x$ was al-

most invariably either $\lambda/4$ or $\lambda/2$; however, it is better in the case of lines terminated in their characteristic impedance, where $x$ is ordinarily not an exact multiple of a quarter or half wave length, to express $D_{opt}$ as

$$D_{opt} = 0.169\,\lambda^{0.8}\sqrt[3]{\frac{x}{H}} \qquad (54)$$

$(D/r)_{opt} = 6.186$, as was found also for $Q_{r_{opt}}$.

Loss when optimum design is used is ($N_{db}$ stands for number of decibels loss)

$$N_{db} = 0.01705\,\frac{x}{\lambda}\sqrt[3]{\frac{H}{x}} \qquad (55)$$

*Example:* For $\lambda = 100$ centimeters and $x = 4\lambda$

$D_{opt} = 2.29$ centimeters
$r_{opt} = 0.37$ centimeter
$N_{db} = 0.0502$ decibel

Of this loss, exactly one third represents power radiated from the line. To see how much the loss is increased if optimum design is not used, refer to curves in figures 7 and 8. Although this line is 4 wave lengths long, whereas the longest line for which curves are drawn is 11 quarter wave lengths long, note that practically the same relations hold for all the curves. Therefore the error involved in using curve 11 in either figure 7 or figure 8 is negligible. Since the loss is inversely proportional to $Q_r$, evidently

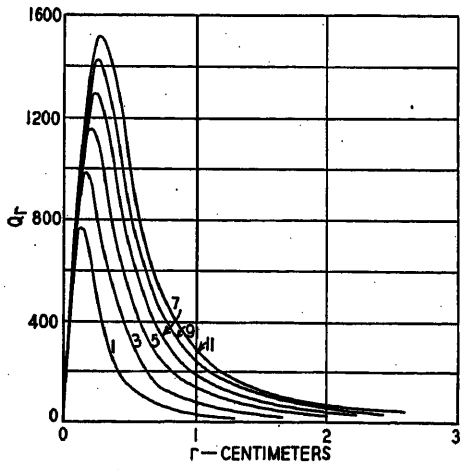



**Figure 8. Parallel line, short circuit**

$\lambda = 100$ centimeters
$Q_r$ versus $r$
$D/r = D/r_{optimum}$
Curve numbers refer to number of quarter wave lengths

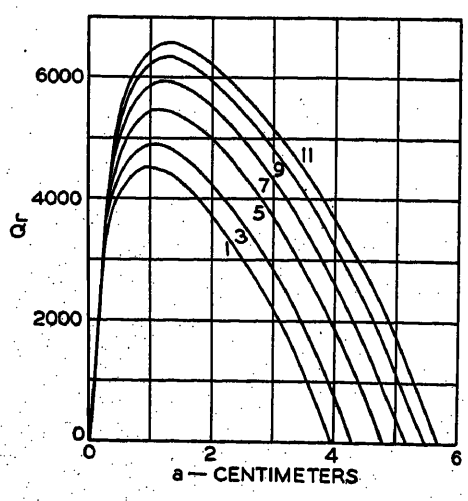
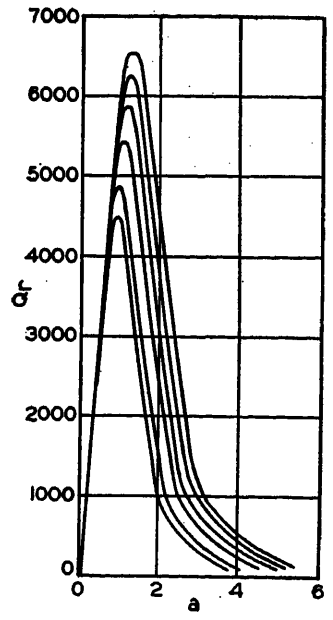



**Figure 9. Concentric lines, shorted**

$\lambda = 100$ centimeters
$b = b_{opt}$
$Q_r$ versus $a$

**Figure 10. Concentric line, short circuit**

$\lambda = 100$ centimeters
$Q_r$ versus $a$
$b/a = (b/a)_{opt}$




the curves showing $Q_r$ can be used to compute the variation in loss as the design is changed from the optimum one.

*Example:* How much would the loss be increased if $r$ were made $^1/_4$ of its optimum value, holding $D = D_{opt} = 2.29$ as just computed? Using curve 11 in figure 7, we see that $Q_{r_{opt}} = 1{,}530$ at $r = 0.255$ centimeter. At $r = 0.255/4 = 0.06375$, $Q_r = 955$. But $1{,}530/955 = 1.605$. So the loss has been increased by 60.5 per cent.

*Example:* How much would the loss be increased if $D/r$ remained $(D/r)_{opt}$, but both $D$ and $r$ were made 4 times their optimum values? In this case use curve 11 of figure 8. $Q_r = 1{,}530$ at $r = 0.255$ centimeter. At $r = 4 \times 0.255 = 1.02$ centimeters, $Q_r = 280$. Since $1{,}530/280 = 5.46$, evidently the loss has been increased from 0.0502 decibel (the loss for optimum design) to $5.46 \times 0.0502 = 0.274$ decibel. In this case it is interesting to note that 97 per cent of the total loss is due to radiation from the line, whereas for the optimum design only one third the loss was due to radiation.

For a concentric line, from equation 29, substituting $M/2$ for $(J/1 + S)$ or $(K/1 - S)$,

$$b_{opt} = \frac{0.14051\,\lambda^{0.9}}{\sqrt[5]{\frac{\lambda}{x}\,\frac{M}{2}}} = \frac{0.1615\,\lambda^{0.7}}{\sqrt[5]{\frac{M}{x}}} \qquad (56)$$

$\left(\frac{b}{a}\right)_{opt} = 4.22$ (same as for maximum $Q_r$), and $N_{db} =$

$$0.0148\,\frac{x}{\lambda}\sqrt[5]{\frac{M}{x\lambda}} \qquad (57)$$

For concentric lines, the loss due to radiation is one fifth of the total loss, if the line is designed for maximum $Q_r$ (or minimum loss). From the curves in figure 9 and figure 10 one may readily determine how much the loss is increased if the optimum design is not followed. Since for concentric lines the total loss is so small, it will often be advantageous to build the line with considerably less than the optimum dimensions, in the interest of over-all economy.

It is of interest to note that a concentric line, terminated

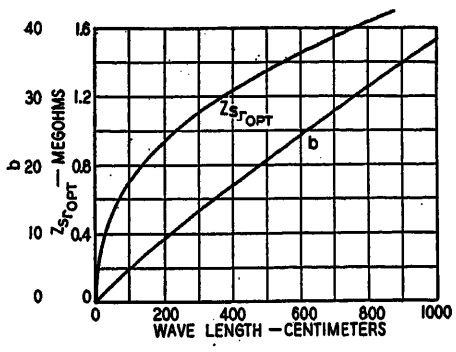



**Figure 11. Optimum $Z_{sr}$ and b versus λ for quarter-wave shorted concentric line**

in its characteristic impedance, has a maximum value of radiation resistance, and therefore radiates maximum power, when it is 0.6 of a wave length long. Note that $M = 59.5$ for this value of $x$, decreasing gradually as the line length increases until for all lengths above about 4 wave lengths its value is about 47.5. For parallel-wire lines also, as shown by the curve for $H$ in figure 3, if the line is at least 3 or 4 wave lengths long, further increase in length has no effect on the radiation resistance. So a line radiates the same amount of power whether it is 3 or 4 wave lengths long or 3,000 or 4,000 wave lengths long, if it is terminated in its characteristic impedance.

Note also that the radiation from an open-circuited concentric line cannot be decreased by partially closing the end. This follows immediately from the fact that the shorting disk used to short a shorted concentric line does not radiate. Since such a disk does not radiate power itself, it cannot prevent the radiation of power through it from the current in the line. Moreover, a line supposed to be open-circuited should never have the end partially closed with metal, since the presence of such metal greatly increases the capacity at the end, and in effect terminates the line with a low value of capacity reactance, instead of the desired open circuit.

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# Radiotelephone Noise Reduction

(*Continued from page 974*)

such a control terminal. Speech entering the terminal from the left goes through the upper branch of the circuit, with volume regulating means and privacy apparatus, to the radio transmitter. Speech received from the distant terminal enters at the lower right from the radio receiver and proceeds through the privacy apparatus, the noise reducer, receiving regulating network and amplifier to the 2-wire line. Outgoing speech operates the transmitting path and disables the receiving path. Incoming speech operates the receiving amplifier detector, which disables the transmitting amplifier detector, thus preventing singing and reradiation of received waves.

Without the noise reducer the receiving relay may be operated by noise in the receiving path and such operation to an excessive extent will interfere with outgoing speech. To avoid this effect, it is customary to reduce its sensitivity so that noise may not operate it. This results in the weaker speech parts also failing to operate the receiving relay. This weak speech and noise returned to the transmitting path through the land-line connection may be strong enough to operate the transmitting relays and thus cut off incoming speech. This is avoided by reducing the volume to the land line. Therefore, any device which reduces noise in the receiving path in the absence of speech effects an improvement not only in the switching operation but also in the received volume. By placing the noise reducer in the receiving path false operation is diminished and volume increases of 5 to 15 decibels are realized. The noise reducer is applied to the receiving side of the terminal beyond the privacy apparatus so that it does not introduce any distortion in the privacy portion of the circuit. It is placed ahead of the receiving amplifier detector, thereby reducing noise between words which might affect the operation of this relay apparatus.

## Summary

The noise reducer, which is a voice-controlled variolosser with limited and controllable action, has been provided for use on short-wave radiotelephone circuits and has proved to be a valuable and relatively inexpensive means of securing noise reduction. Improved reception is obtained for many of the transmission conditions experienced on such circuits. This results in better intelligibility to the subscriber, greater margin in the operation of 2-way radiotelephone circuits, and a reduction of difficulties in the wire plant caused by connection to noisy radio circuits.

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# The Vodas

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## Introduction

THE INTERCONNECTION of ordinary telephone systems by means of long radiotelephone links presents some unique and interesting technical problems. Since radio noise is often severe as compared with that in wire lines, radio transmitter power capacity is relatively large and expensive, and it is in general economical to control the speech volumes so that the radio transmitter will be fully loaded and thus the effect of noise minimized for a given transmitter power rating. This volume control, to be fully effective, calls for voice-operated switching devices to suppress echoes and singing.

This paper describes the measures which have been developed for use at radio-wire junctions in the United States. They are based upon an arrangement called a "vodas." This word, devised to fill a need for verbal economy, is formed from the initial letters of the words "*v*oice-*o*perated *d*evice *a*nti-*s*inging"; and thus implies not only a suppressor of feedback or singing, but also automatic operation by voice waves.

The general principles and applications of the vodas have been discussed from time to time in various papers listed at the end of this text. The present paper goes somewhat more into detail regarding the transmission performance of the vodas, including a description of an improved form of circuit which discriminates between line noise and the syllabic characteristics of speech.

## Historical

The 2-way problem in telephony began with the invention of the telephone itself, and was the subject of considerable pioneering activity during the latter part of the nineteenth century. The invention of the amplifier brought about new problems when applied in a repeater for 2-way operation. Even before a practical repeater had been devised, inventors visualized controlling the direction of transmission through amplifiers in a line by relays controlled from switches associated with the subscribers' instruments, an idea which is in use today on airplanes and small boats and in special circuits where this type of 2-way operation is practicable. It is also used by amateur radiotelephone operators. But for public telephone service more rapid and automatic control of 2-way conversation is preferable.

To control the direction of transmission in a manner that would meet public convenience invention progressed through the early part of the twentieth century toward devices for switching the speech paths automatically by voice waves. During this period, long-distance radiotelephony was first demonstrated to be practical on a one-way basis.

From that time until the first trans-Atlantic radiotelephone circuit was placed in service on January 7, 1927, antisinging voice-operated devices underwent a process of development aimed at meeting the requirements of 2-way radiotelephone service. The vodas was one result. Since 1927, improvements have been made in cheapening and simplifying the equipment and in making a vodas that will operate better on speech and not so frequently on noise. It has also been possible to arrange a vodas so as to permit using the same privacy apparatus for both directions of transmission, thereby saving the cost of duplicate apparatus.

## The Radiotelephone Problem

The conditions encountered when joining 2-wire 2-way circuits by radio links are illustrated in figure 1 in which *a* shows a connection between 2 subscribers *W* and *E* while *b* shows the paths of direct transmission and echo when *E* talks. In addition to the talker and listener echoes which arise in such a connection, singing can occur around the closed circuit *CAFGDBC* if the amplification is great enough. Also, when the same frequency band is used to transmit in both directions, 2 cross-transmission paths *AB* and *DF* are set up, and echoes and singing can take place around the end paths *ABC* and *DFG*. Any echoes or singing are of course primarily due to reflections of energy at points of impedance irregularities in the 2-wire plant, including the subscribers' telephones themselves.

In wire circuits, simple hybrid coils and echo suppressors[2] are usually adequate to prevent such effects because the gains are not increased to provide for loading the cir-

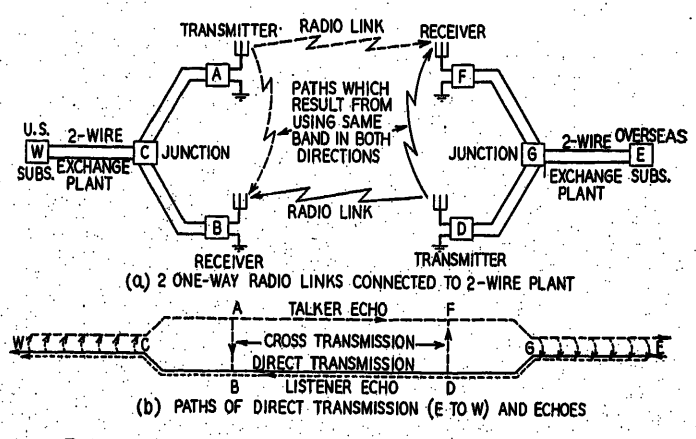



**Figure 1. Echoes in a radiotelephone connection**

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2. For all numbered references, see list at end of paper.

cuit with energy when speech is weak, and also because the cross-transmission paths are absent. In long radio circuits, however, singing may result from the adjustments of amplification made to load the radio transmitter in case of weak speech and thus override noise, even though separate frequency bands are used in the 2 directions. Moreover, it is desired that the users of the service have as good transmission over the entire connection including these radio links as that to which they are accustomed in their own wire telephone systems and even better transmission may be desired owing to differences in the language habits of the subscribers. Consequently, the overall transmission efficiencies of intercontinental radio circuits are sometimes better than those of the best land lines in the areas to be interconnected.

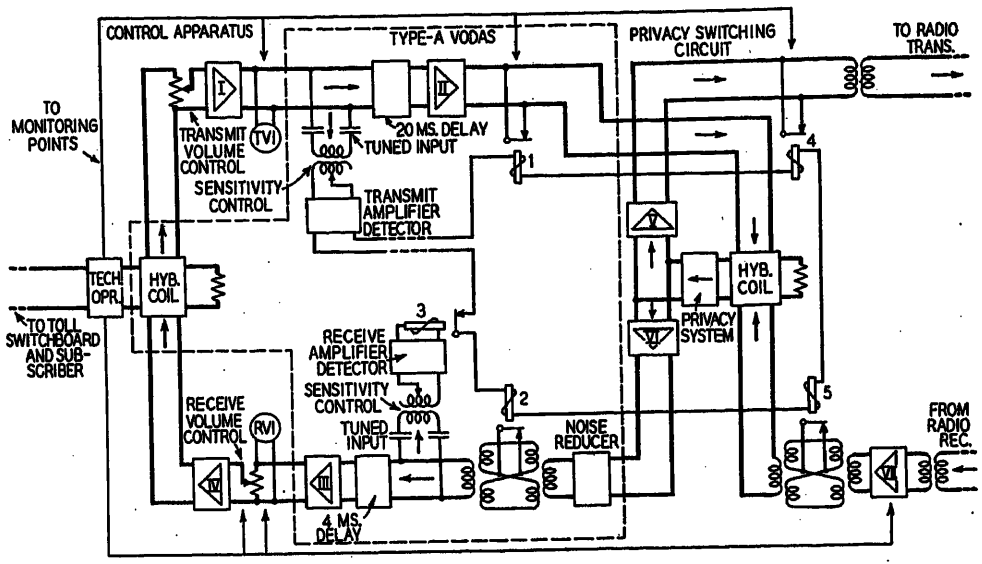



**Figure 2. Schematic of type-A control terminal**

## Fundamentals of Vodas Operation

A voice-operated device to suppress singing effects can be designed to have 3 possible arrangements:

1. The terminal can normally be blocked in one direction and connected through in the other.
2. Both directions of transmission can normally be blocked and activated in either but not both directions by the voice waves.
3. The circuit can remain activated in the last direction of speech and blocked in the other direction.

Where there is no noise on the transmission system under consideration any of these 3 arrangements will give satisfactory operation as there is then nothing to prevent making the voice-operated devices as sensitive as may be necessary to obtain full operation on weak as well as on strong voice waves. If there is any noise on the system which tends to operate the device it is necessary to make it less sensitive to avoid false operation. A point may be reached where the sensitivity is so low that the weakest parts of speech will not cause operation, and the weak consonants will be lost. The reduction in articulation has been found to be proportional to the time occupied by these lost or "clipped" sounds.[9]

If the device is located at a point in the circuit where the signal-to-noise ratio coming from one direction is poorer than that coming from the opposite direction it is obvious that a considerable advantage will be gained by using arrangement 1, since the device may be pointed in the direction in which the normally blocked path is exposed to the better signal-to-noise ratio and the normally activated path is exposed to the poorer signal-to-noise ratio. The vodas is, of course, arranged so that the normally blocked (transmitting) side is exposed to the land lines which are usually quieter than the radio links. In the receiving side, the device can be less sensitive because there is no need for having it completely operated under control of the voice waves. All that is necessary is to have this side sensitive enough to operate in response to comparatively large voice or noise waves which might otherwise, after reflection and passage into the outbound path, result in false operation of the more sensitive side associated with this path.

In the vodas the principle of balance is used to keep the

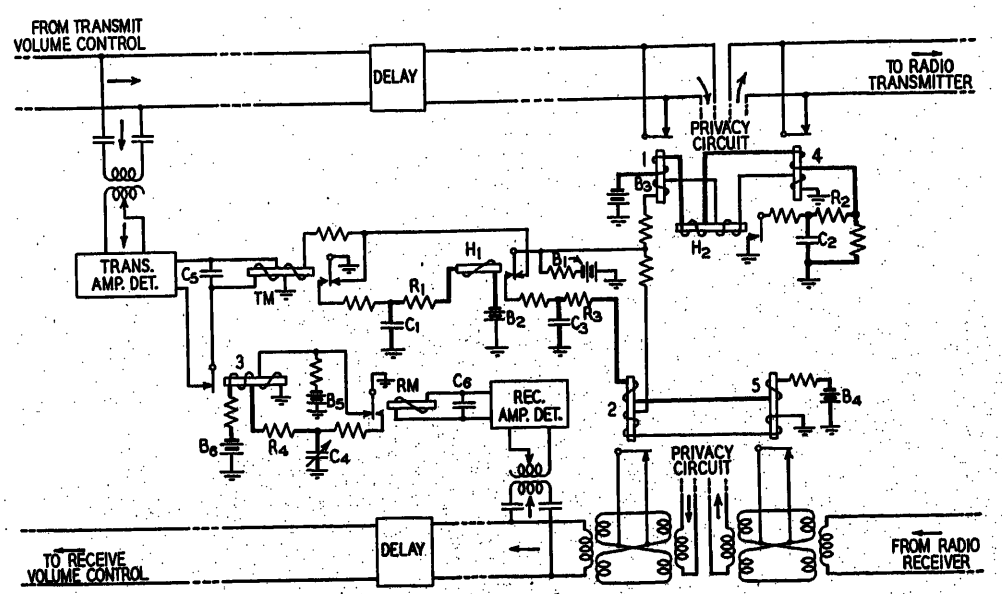



**Figure 3. Vodas relay circuits**

reflected currents small and thus allow the sensitivity of the normally activated device to be further reduced if necessary. Where a high degree of balance is not obtained and when noise from the radio limits the sensitivity of the receiving device it is sometimes necessary, particularly for weak outgoing volumes, to reduce the incoming volume so as to prevent echoes from operating the normally blocked transmitting side.

This echo limitation is primarily due to noise in the radio link, reflections from the 2-wire plant and weak volumes from the subscribers. It is difficult to produce any large improvement in talker volumes and balance; so it would appear that the solution of the difficulty would probably come from the direction of improving radio transmission. Some benefit has also been obtained by reducing the effect of radio noise on the vodas with special devices of which the "compandor"[17,18] and the "codan"[19,20] are examples. More recently, use has been made of a new voice-controlled device called a "noise reducer,"[21,22] which reduces the received noise between speech sounds.

## Vodas Design—Type-A Control Terminal

Figure 2 shows a schematic diagram of a vodas arranged to use the same privacy device for both transmitting and receiving. The vodas apparatus together with the volume-control devices and technical operator's circuits go to make up what is called a type-*A* control terminal. This is the type used on trans-Atlantic and other long routes. Since the operation of this arrangement has been described before,[18] it will not be repeated here.

The diagram of the relay circuit in figure 3 shows how various time actions are obtained. Relays 1, 2, 4, and 5 are operated from battery $B_1$ when the ground contact of relay $TM$ is opened. Thus the travel time of any relay armature is not a factor in securing fast initial operation. When the armature of relay $TM$ reaches its left-hand contact, relay $H_1$ operates and delays release of the relay train even if $TM$ is at once restored to normal. $H_1$ is delayed in releasing by the time required to charge condenser $C_1$. The final release of relays 1 and 4 is then controlled by the time constant of an auxiliary circuit involving relay $H_2$ and condenser $C_2$, while that of relays 2 and 5, which is made later so as to suppress delayed echoes, is controlled by the circuit charging $C_3$. On the receiving side, condenser $C_4$ is adjustable so as to permit the technical operator to select the shortest release time for suppressing the delayed echoes in a given land-line extension.

The vodas control terminal of the *A* type[8] used at New York consists of a line of technical operating positions

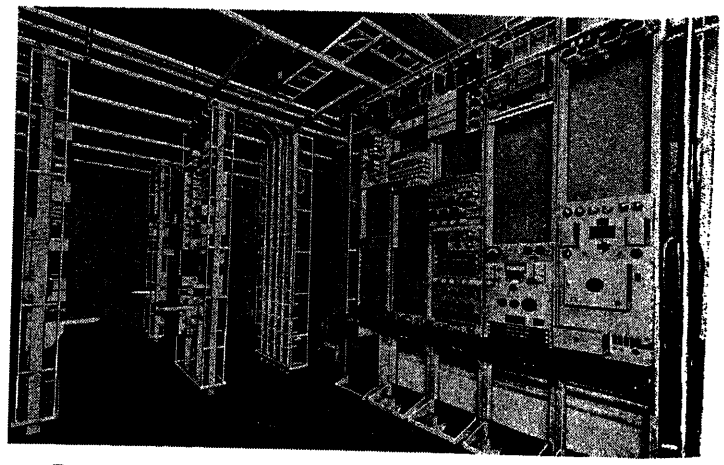


Figure 4. Type-A control terminal at San Francisco

with cross connections to other lines of equipment containing the delay units, repeaters, vodas amplifier-detectors, and privacy apparatus. Figure 4 shows an arrangement of a single terminal at San Francisco. The control bay is placed between 2 line-testing bays on the left and 2 transmission-testing bays on the right of the operating lineup. The distributing frame is in the center of the picture; and repeaters, ringers, and privacy apparatus are shown at its left. At the extreme left is the vodas bay.

## Syllabic Vodas—Type-B Control Terminal

The desire for a cheaper control terminal than the type *A* led to the development of a second type, known as type *B*, in which the vodas employs the same fundamental principles. In this vodas added protection against false operation from line noise is secured by the use of a new principle in voice-operated devices, called "syllabic" operation.

It is observed that in many types of noise a large component of the long-time average power is steady. Speech, however, comes as a series of wave combinations of relatively short duration. These facts suggested a device

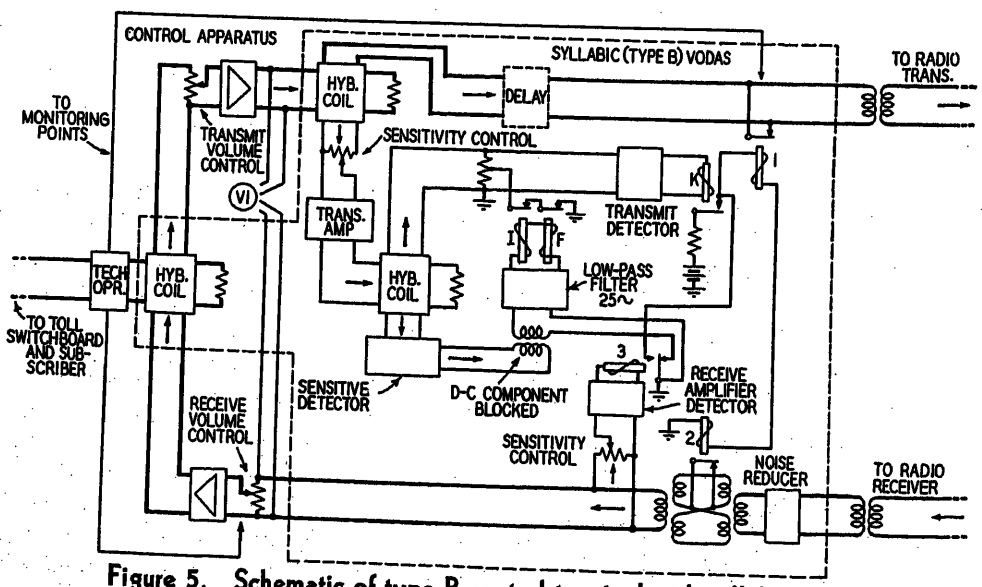



Figure 5. Schematic of type-B control terminal with syllabic vodas

which distinguishes between the rates of variation of the envelopes of the impressed waves. This is accomplished by a filter in the detector circuit which passes the intermodulated components of speech in the syllabic range, but suppresses those of line noise which are above or below this range.

Figure 5 shows a schematic diagram of the application of this device to a type-*B* control terminal. The privacy switching circuits are omitted from this drawing, as are also the circuits for delaying the release of the relays. In comparing this drawing with figure 2, it will be seen that relays 1, 2, and 3 perform the same functions, but the transmitting branch of the vodas consists of 2 portions, one a sensitive detector with a syllabic frequency filter, which on operation increases the sensitivity of the second portion.

Considering the action of figure 5 on transmitted speech, the output of the sensitive detector of the syllabic device is a complex function of the applied wave having intermodulated components in the range passed by the tuned input circuit, together with a d-c component and various low-frequency components set up by the syllabic nature of the speech. There are also various components of any noise waves which may be present including a d-c component. The first step in getting rid of the noise is to pass the detector output through a repeating coil which blocks the d-c component of both the speech and noise, but passes frequencies above about $^1/_2$ cycle per second. The resulting waves enter the low-pass filter, the output of which contains frequencies between $^1/_2$ and 25 cycles per second which "syllabic range" is between the d-c component of zero frequency and the fundamental frequency of the line noise. These syllabic-frequency currents cause momentary operations of relays *I* and *F*. Relay *I* operates when a speech wave is commencing and relay *F*, which is poled oppositely, operates while the impulse is dying out, thus sending current out of the filter in the opposite direction. Operation of either *I* or *F* effectively inserts gain ahead of the upper detector, thereby increasing the sensitivity of relay *K*, when speech is present. Even if the noise is strong enough to operate relay *K* over the upper branch when the gain is inserted, the release of relay *F* at the end of a speech sound will remove the gain and permit *K* to fall back. Thus, it is possible to work relay *K* more sensitively on weak speech than would be possible without the syllabic device.

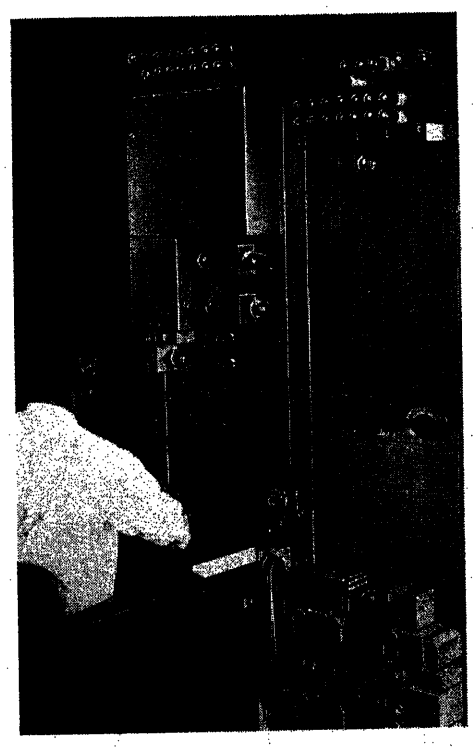
Figure 6 shows a photograph of a *B*-type terminal in ship-to-shore service at Forked River, N. J. The vodas and volume control apparatus are in the left-hand cabinet. The right-hand cabinet contains privacy apparatus, a signaling oscillator, and a vodas relay test panel.

## Performance

In any system employing voice-operated devices it is necessary for the time actions to provide for to-and-fro conversation with a minimum of difficulty when the subscribers desire to reverse the direction. The electromagnetic relays used in the vodas have advantages over other types of switching arrangements which have been proposed in that they (1) operate and release at definite current values; (2) have fast operating and constant releasing times; (3) have their windings and their contacts electrically separated, thus simplifying the circuits; and (4) operate in circuits having low impedances.

The operating times of the 2 types of vodas are shown in figure 7 as a function of the strength of suddenly applied single-frequency sine waves in the voice range. These measurements were made with a capacity bridge.[5] The sensitivities of the 2 types were adjusted so that observers noted an equivalent amount of clipping. The type-*A* vodas was provided with a 20-millisecond delay circuit, the type *B* had no delay. For the type-*A* vodas, the operating time is quite small and constant just above the threshold of operation.

For weak inputs the operating time of the syllabic device is determined by relay *I* and the filter, as shown in



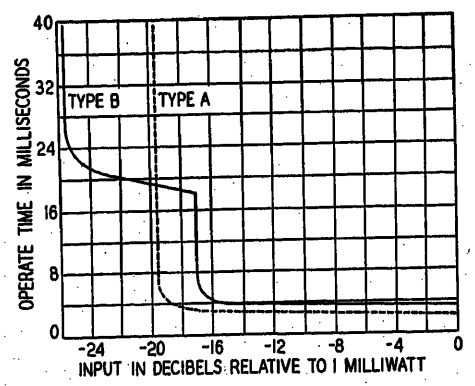



**Figure 7 (above). Vodas operating times with sine waves suddenly applied**

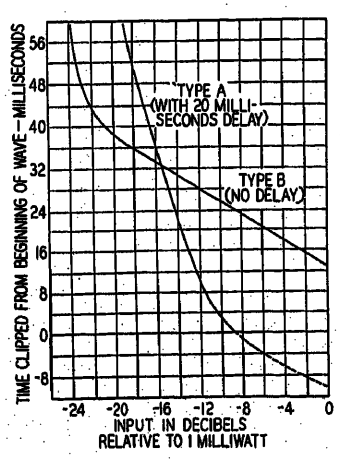



**Figure 8 (right). Operation on a 5-cycle-per-second sine wave**

**Figure 6 (left). Technical operator at Forked River, N. J., using a type-B control terminal to establish a circuit between a steamship and a shore telephone operator**

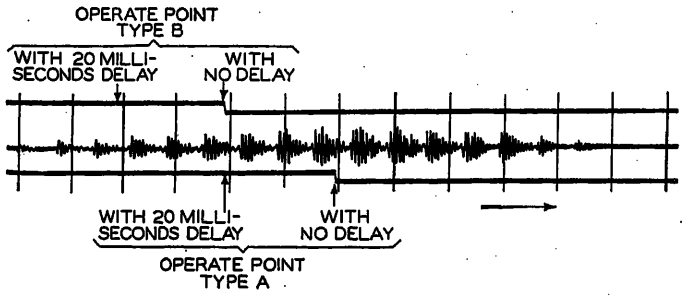



**Figure 9. Oscillogram of the word "six," illustrating clipping and its reduction by a delay circuit in the transmission path**

figure 7. As the suddenly-applied input is increased, a point is reached where the less sensitive detector operates relay *K*, reducing the operating time from around 20 milliseconds to values comparable with those of the type *A*.

The operation was also tested on waves formed by applying simultaneously 2 sine waves of equal amplitude but slightly different frequencies. These waves were recorded on an oscillograph together with a d-c indication of the operation of each of the vodas relays, with the sensitivities adjusted the same as for figure 7. The time from the beginning of a beat wave (null point) to the time of operation was measured from these oscillograms and plotted against various values of total applied voltages. Figure 8 shows the results for a 5-cycle-per-second difference between the 2 frequencies. Negative values of time indicate that the path was cleared before the beginning of the wave, and these occur only with the type-*A* vodas due to the delay circuit. The curves for frequency differences of less than 5 cycles per second show more clipping and greater differences between the devices, while those for greater frequency differences show less time clipped and less difference between the 2 types of vodas. In the case of weak waves it is evident that the syllabic will give less clipping because the energy of the wave does not rise to the value required to operate the type-*A* device until after the syllabic device has operated; and for very weak waves, the type *A* does not operate at all. In the case of strong waves, the type-*A* vodas is better due to its delay circuit. However, since the clipped time is greater on weak sounds than on strong ones, the 2 types give performances on speech which are judged to be equivalent.

A comparison of operation of the 2 types of vodas on a speech wave is shown in figure 9. Reading from left to right the middle trace of this oscillogram shows the wave recorded by saying the word "six" over a telephone circuit transmitting a band of frequencies from about 800 to 2,000 cycles per second, which is the range normally effective in operating the vodas. The upper trace shows the point at which the syllabic type-*B* device operated and the lower trace shows the point at which the type-*A* device operated. Since the speech wave shown was used to operate both devices, the reduction of clipping by the delay circuit in the type-*A* vodas was not recorded. However, the effect of a transmission delay of 20 milliseconds is shown by subtracting 20 milliseconds from the point at which operation occurred. This is indicated on the oscillogram for both devices. It is concluded that on this wave the syllabic device without a delay circuit would give about the same clipping as the type-*A* vodas with its delay circuit. Figure 8 indicates that the type *A* would be better for stronger speech and the type *B* would be better for weaker speech. The advantage of a delay circuit is either case is evident.

It is evident from this analysis that the reason for using delay circuits is not primarily because the relays are slow in operating. When the sensitivity is limited by noise, clipping of initial consonants can occur with infinitesimal operating times. One way of reducing the clipping is to use long releasing times so that the relays remain operated between syllables. This has the disadvantage of making it harder for the opposite talker to break in. To avoid this difficulty, the relays in the vodas are given releasing times that permit the distant speech to break in about 1/6 second after a United States talker ceases to speak.

One advantage of delay circuits is to reduce the clipping of initial consonants and thus permit using short releasing times, thereby making it possible to reverse the circuit more readily. In addition, delay circuits permit using a lower relay sensitivity which has 2 advantages: First, more noise can be tolerated without causing false operation; second, more received volume can be delivered without the echoes causing false operation of the normally blocked transmitting side.

The advantage of artificial delay of various amounts has been determined using different types of normally blocked arrangements to find the relation between the delay and the sensitivity required to produce given amounts of clipping of initial sounds. The results are shown for a

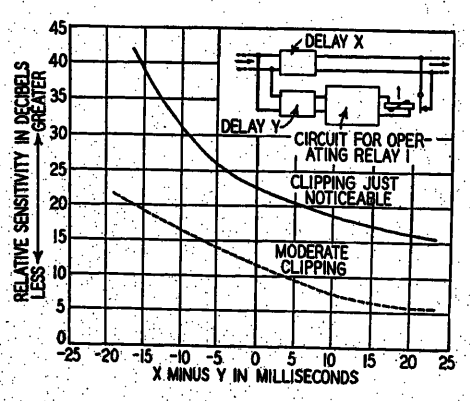
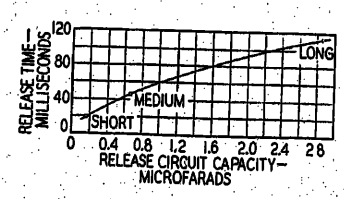



**Figure 10 (left). Typical delay versus sensitivity for certain clipping effects**

**Figure 11 (below). Release time versus capacity**



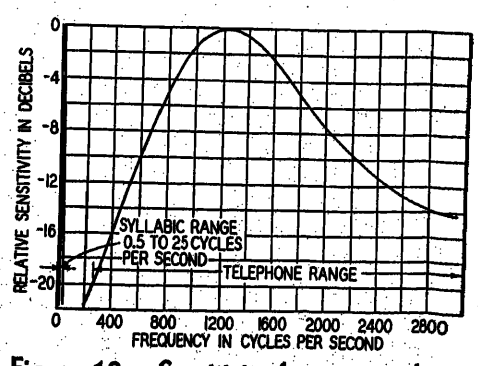




**Figure 12. Sensitivity-frequency characteristics of the vodas**

type-*A* vodas in figure 10. The curves for the syllabic device are similar. The setup was arranged so that various delays could be inserted in either the transmission circuit (delay *X*) or the relay circuit (delay *Y*). The left ends of the curves indicate that when delay *Y* is used, that is, when the net operating time of the relay is great, a point will be reached where no reasonable increase in sensitivity is sufficient to prevent intolerable clipping. The value of 20 milliseconds of delay *X* as compared to zero is equivalent to an increase of about 5 decibels in sensitivity for a given amount of noticeable clipping.

A reasonable release time is of value in preventing clipping, as it causes the relays to remain operated not only for trailing weak endings of sounds, but also when the energy is temporarily reduced by intermediate consonants which may be comparable with noise. Delayed release is also important when it is required to maintain the blocked condition while delayed echoes are being dissipated. For these echoes, the hangover or release times should be constant for various applied voltages. In the vodas, the change in release time over a wide range of inputs is less than one per cent. Adjustments are made by varying the condensers and resistances of the auxiliary circuits shown in figure 3. Typical values obtained by this method are indicated in figure 11.

The vodas amplifier-detectors have broadly tuned input circuits to exclude by frequency discrimination many of the frequencies induced by power sources and those which are unnecessary for speech operation. The sensitivity-frequency characteristic is shown on figure 12. This figure also shows the relatively narrow frequency range passed by the repeating coil and syllabic frequency filter of the type-*B* vodas.

## Operating Attendance

To insure proper operation of a vodas a technical operator[3] is in attendance. He is provided with circuits which enable him to talk and monitor on the circuit as indicated in figures 2 and 5. His duties include adjusting the sensitivity of the receiving relays for the particular value of radio noise existing and adjusting the transmitting and receiving speech volumes by the aid of potentiometers and volume indicators. He selects the proper hangover time and co-ordinates the operation of the circuit as a whole with the distant end. At times, he may be required to increase the sensitivity of the transmitting side of the vodas in the case of talkers with poor ability to operate relays or to decrease the sensitivity when weak volumes are supplied from land lines with more than the usual amount of noise.

## Summary

The vodas is used in radiotelephony to switch the voice paths rapidly to and fro, and thus prevent echoes and singing that would otherwise occur at unpredictable times. It is also used to save privacy apparatus by permitting the use of the same apparatus for both directions of transmission. The performance characteristics of the electromagnetic relays used in the vodas are very suitable in that they have small operating and constant releasing times.

Improved performance of the voice-operated relays in the presence of line noise can be secured by the use of a syllabic type of vodas which discriminates between the characteristic voltage-time envelopes of the noise and speech waves. Laboratory and field tests indicate that this device even without delay circuits, gives slightly better performance on most conditions than the original vodas with delay. When provided with a transmitting delay circuit, the syllabic device is decidedly better than the older vodas.

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# Capacitance Control of Voltage Distribution in Multibreak Breakers

By R. C. VAN SICKLE
MEMBER AIEE

## Summary

This paper discusses the need for good distribution of the voltage among the interrupters of a high-voltage multibreak circuit breaker and the results which have been obtained using capacitances.

## Introduction

THE DEVELOPMENT of high-speed circuit breakers capable of interrupting short circuits on 287-kv systems in not over 3 cycles, 0.05 second, has called attention to the importance of the distribution of voltage among a number of interrupters in series. To obtain such high speed of operation all parts must work promptly, quickly, and effectively. Obtaining adequate contact separation to interrupt the circuit and to withstand the restored voltages is accomplished by using a number of interrupters connected in series and operated simultaneously. This construction depends on a division of duty between the individual breaks, each interrupter being loaded with its share so that the interrupting capacity of the pole unit is approximately equal to the sum of the capacities of the units. Uniform distribution of duty is most desirable but it can only be approximated because short circuits of various kinds may occur on either side and the distorting forces cannot be neutralized for all conditions. This paper discusses the problem and capacitance shields which satisfactorily distribute the duty among the interrupters in multibreak circuit breakers.

## Factors Determining Voltage Distribution

The distribution of voltages should be suitable during the arcing period, during the extinction of the arc, and after the circuit is interrupted. During the first of these periods all circuit breakers have good voltage distribution. The similar conditions existing in the series gaps of a multibreaker should result in them having approximately equal arc voltages since arcs of equal length carrying equal currents in the same medium under the same conditions have equal voltages.

After the arcs are extinguished and normal voltage has appeared across the breaker, the voltage distribution is determined by the capacitance relationships of the various parts. If all capacitances except those across the gaps could be eliminated, there would be only a simple series circuit composed of equal capacitances. If a voltage were applied across them it would divide equally between the various gaps and this division would be unaffected by the relative potential of the ground. Unfortunately the conditions are not this simple and capacitances to ground and to other parts not at the same potential form a network of circuits so that the voltage distribution is distorted and may depart widely from uniformity. Moreover, different types of short circuits will produce different degrees of distortion. For convenience this distribution will be referred to hereafter in this paper as the static voltage distribution.

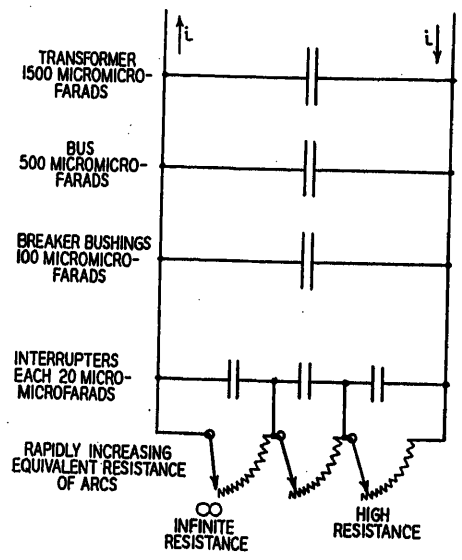



**Figure 1. A diagram representing a multibreak circuit breaker at the instant one arc is extinguished**

Between the 2 periods already discussed is an important transient period during which the arc space is changing rapidly from a good conductor to a good insulator and during which the voltage distribution is determined first by the arc resistance and later by the electrostatic capacitances of the parts and the relative potentials of the terminals.

When the breaker first starts to open, the current is carried by a continuous metallic path formed by the terminals, contacts, and connecting members. The separation of the contacts introduces arcs which conduct the current and which are acted upon by deionizing agents. As the current approaches zero at the end of a half-cycle, the deionization proceeds more rapidly than ionization

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1. For all numbered references, see list at end of paper.

and conductivity decreases. The conductivity becomes zero at about the time the current reaches zero and the arc does not restrike if the dielectric strength of the arc space is greater than the applied voltage.

The change of the arc space from a conductor to an insulator is not an instantaneous process but consumes an appreciable time interval, up to a few hundred microseconds. This time interval is a variable in an oil circuit breaker because of the conditions which exist between the arc terminals. The space is filled with a nonhomogeneous mixture of gases, oil vapor, and probably drops of oil, all of which are in rapid turbulent motion. A number of independent interrupters carrying currents of the same magnitude will not interrupt in exactly the same manner at exactly the same time. However, if the same current is passed through a series of interrupters operated simultaneously the operation of one unit may influence the operation of the others and effect a synchronization of their action.

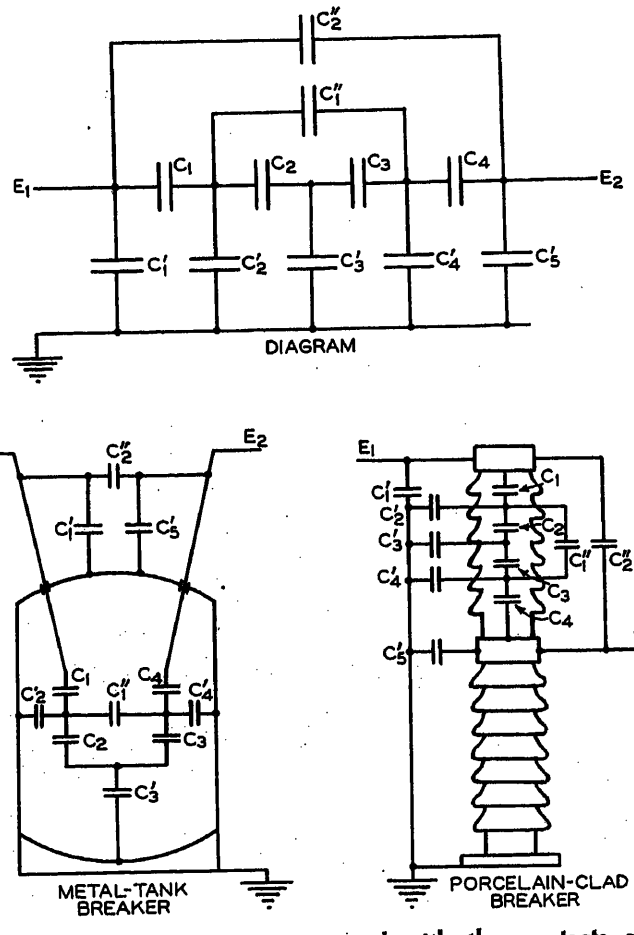



**Figure 2. Capacitances associated with the contacts and terminals of 4-break circuit breakers and typical of all multi-break breakers**

In a breaker without modern interrupting devices, the deionizing activity is relatively weak and the conductivity of the arc space changes relatively slowly. Consequently, the conductivity may be sufficiently high at the current zero to allow the restored voltage to reverse the current and build it up to a few amperes for a short interval before the interruption is finally completed. Since the rate of change of conductivity is relatively low, the differences between series interrupters is so small that this type of performance tends to divide the potential between interrupters equally even though the capacitances would produce a very uneven distribution.[1]

More effective interrupters have a higher rate of deionization and the change from a conducting arc to an insulating space is more rapid. Additional phenomena associated with the capacitances of the circuit assist in keeping the voltage divided between interrupters. These interrupters may deionize the space so rapidly that the dielectric strength required for interruption is obtained at current zero or even before the normal current zero. Oscillograms of circuit-breaker operations in which unstable arc conditions resulted in the arc being extinguished before the normal current zero have been discussed before the Institute.[2,3] This is the other extreme in breaker operation and in this case also the interrupters distribute the voltage among themselves. However, the resistances of the arc spaces will not do it since the resistances become infinite, but the capacitance currents and impedances become important and take over the function. The capacitances not only control the voltage distribution after the arcs are extinguished but also assist in sychronizing the deionization. Exact knowledge of this phenomena is lacking and the following is offered as a possible explanation.

The extreme in this type of operation is characterized by a very rapid increase in effective resistance of the arc as the current approaches zero. It is so great that the arc may become unstable and be suddenly extinguished from a current of about 10 amperes or less.[3] The conditions existing at such an instant may be represented by the diagram in figure 1. The small capacitances are chosen to represent a circuit having a high rate of voltage recovery.

When in the last few microseconds of a half-cycle of current one interrupter is able suddenly to produce infinite resistance between its contacts, the current flowing through the interrupter is diverted into the various ca-

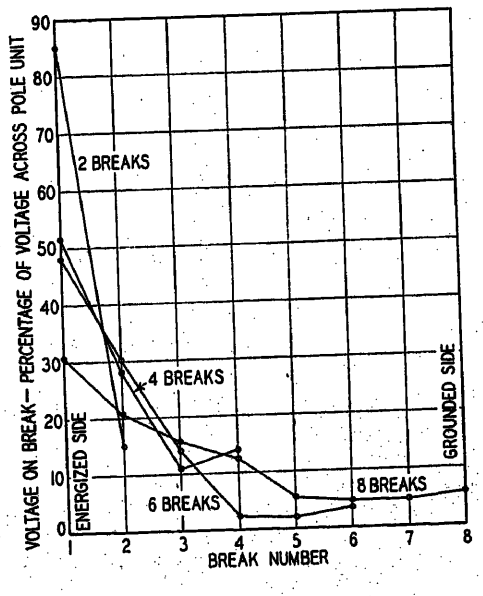



**Figure 3. Voltage distribution in multi-break oil circuit breakers having metal tanks and no shielding devices. The data are for 2, 4, 6, and 8 breaks with one terminal energized and the other grounded**

pacitances, $c$, in parallel with it. This current raises the voltage across the pole unit, starting at a maximum rate, $de/dt$, which depends on the magnitude, $i$, of the current flowing at the instant of arc rupture

$$\frac{de}{dt} = \frac{i}{c}$$

Because the capacitance of the interrupter is small compared to the other capacitances, the current flowing into it is almost negligible. In the case shown in figure 1 it would be only

$$i \times \frac{\text{20 micromicrofarads}}{\text{1,500 + 500 + 100 + 20 micromicrofarads}}$$

or about 0.01 $i$. Therefore the current through the other series interrupters would decrease rapidly from $i$ to 0.01 $i$ as their capacitances were discharged through the residual ionization in the arc spaces. However, all of these interrupters are similar and have about the same characteristics. Oscillograms show that at least one has been able to force its current to zero with more than its share of voltage across it. Therefore, it seems reasonable that the reduced energy input into the other interrupters would result in rapid increases in their effective resistances and that the voltages across them would not completely collapse. Since the change from finite to infinite resistance could hardly be instantaneous in the arc path of even the first interrupter, it appears probable that when one starts

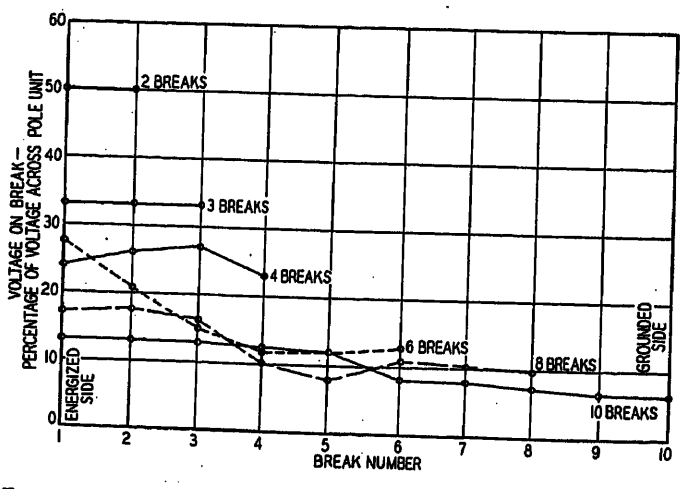



**Figure 4. Voltage distribution in multibreak oil circuit breakers having metal tanks and shielding devices. The data are for 2, 3, 4, 6, 8, and 10 breaks with one terminal energized and the other grounded and when compared with figure 3 show the improvement obtained by shielding**

to choke the current the others assist and the voltages across them are approximately equal.

The larger the capacitances across the interrupters or the more closely they are coupled to large capacitances such as shields, the less will be the voltage collapsing effect of small inequalities in the rates of deionization and the more uniform will be the voltage distribution at the time all units become nonconducting. After the arc spaces become deionized, the capacitances determine the

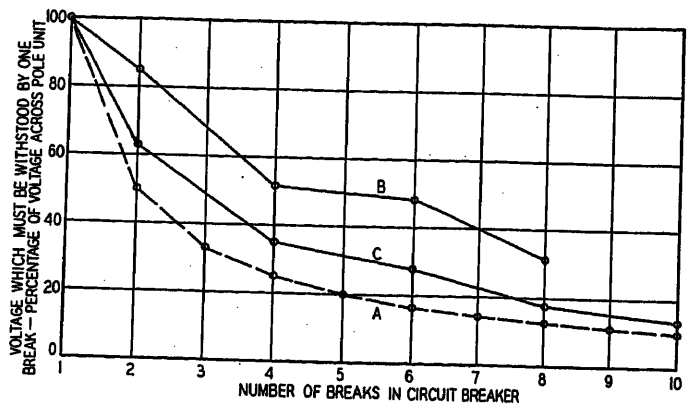



**Figure 5. Shielding reduces the maximum voltage which can appear across any one break**

Curve *A*—Minimum possible (assuming uniform distribution of voltage)
Curve *B*—Measured without shielding
Curve *C*—Measured with shields

subsequent changes in the voltage across each interrupter.

Since the static voltage distribution is of importance in itself and is also a determining factor in the voltage distribution during interruption and since it is much more readily determined, it is taken as a criterion of the electrical stresses applied on the various breaks in a multibreak circuit breaker.

## Voltage Distribution in Breakers

The static voltage distribution depends upon the capacitances of the various parts of the breaker with respect to each other and with respect to ground and upon the voltages applied to the terminals of the breaker. A network representing a 4-break circuit breaker is shown in figure 2. Obviously still more capacitances are present and could be shown but generally they are relatively unimportant. This network shows that fundamentally the problem is the same in either a metal-tank breaker or in a porcelain breaker. The relative capacitances to ground are greater in a grounded metal-tank breaker but satisfactory distribution may be obtained in either case by adequate shielding means.

The relative potentials applied to the terminals of the breaker affect the distribution since some of the capacitances are to ground and their effect will depend on the potentials of the terminals. The distribution of the voltage between breaks is independent of the magnitude of the voltage between terminals, because none of the circuit constants change with voltage. Moreover, it is independent of frequency since all of the components of the circuit are capacitances and react in the same manner to changes in frequency. This is particularly important in connection with the voltage recovery transient. Grounding of the neutral of the system directly or through impedances and the location of the principal impedances determine the voltage applied across a pole unit but need not be discussed here since the voltage distribution in the breaker depends only on the relative potentials of the 2 terminals with respect to ground.

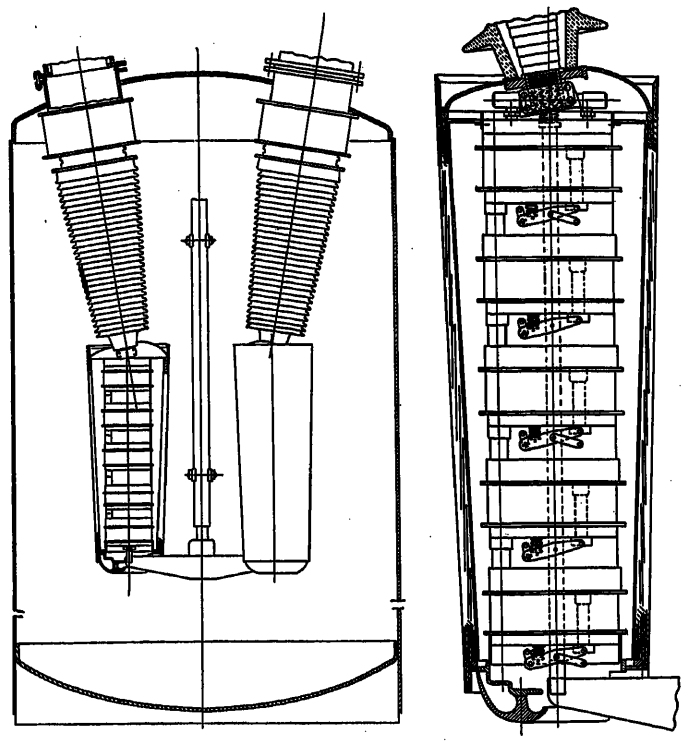


**Figure 6. Shields used in a 287-kv oil circuit breaker**

The best distribution is obtained usually with the connection corresponding to the opening of line-to-line voltage across a single pole because the recovery voltage after current zero impresses equal and opposite potentials on the terminals. The ground potential being midway between the terminal potentials results in a symmetrical distribution of voltage between interrupters and usually a minimum of distortion. A corresponding connection has been used in high-power laboratories for applying 264 kv across a pole unit. The testing transformers were insulated for only 132 kv to ground but by connecting the primaries of 2 of them to the same phase and the secondaries in series with the midpoint grounded 264 kv was obtained between terminals of the breaker.

A more usual condition is a line grounded on one side of the breaker. This is simulated by grounding one terminal of the breaker and energizing the other.

A 3-phase ungrounded short circuit would apply, to the first pole to interrupt, potentials of phase voltage on one terminal and minus half of phase voltage on the other. This is a condition which is between the 2 others with respect to the voltage distribution but it is important because of the magnitude of the voltage between terminals, 87 per cent of line-to-line voltage.

The magnitudes of the voltages impressed on the pole unit will be determined by the system and by the nature of the short circuit. The maximum voltage on any interrupter is determined for the various conditions by the impressed voltages on the pole unit and the corresponding voltage distributions.

The 3 important conditions for voltage distribution are given in table I in terms of the relative test potentials applied to the terminals of the pole unit. It should be noted that $E$ is the total test voltage between terminals and has no relation to the magnitude of the voltages impressed by the corresponding short circuits.

The poorest distribution is obtained with a grounded short circuit near the breaker terminal so this will be used as the basis of comparision to show the need for shielding and its effectiveness.

The voltage distribution in metal-tank breakers having various numbers of breaks and no special provisions to insure proper voltage distribution are given in figure 3. The data are taken from tests on 2-, 4-, 6-, and 8-break circuit breakers of experimental designs. The variations in the arrangements of contacts cause the curves to be of slightly different nature and account for the irregularities in the spacing of the curves at any particular break. The significant point is the inherent unequal distribution of voltage between interrupters in a multibreak circuit breaker having no special shielding provisions. The interrupter next to the bushing having potential is required to withstand more than twice the average voltage for the 4-, 6-, and 8-break circuit breakers. These data show that increasing the number of breaks without taking steps to insure proper voltage distribution does not result in reducing the voltage per gap approximately in proportion to the number of gaps. In fact, the most of the gaps take very little voltage and are actually a liability since they will produce just as much arc energy during the arcing period as the gap which has to withstand the most voltage at the interruption.

The voltage distribution can be modified and made to approach the ideal by the use of capacitances which reduce or eliminate the effect of those causing distortion. Improved distribution obtained with capacitance shields is shown in figure 4. The 2- and 3-break circuit breakers were single pole experimental types and were intended for operation with one side grounded. Consequently, the shielding was designed for this condition only and uniform distribution was obtained. The 6 - and 8-break breakers are the same ones that were tested unshielded and the data are directly comparable. They were designed for

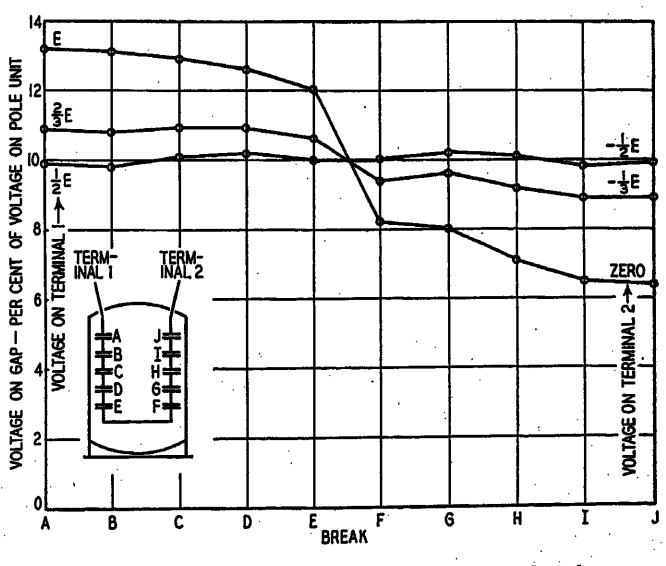



**Figure 7. Voltage distribution in a shielded 10-break circuit breaker under 3 conditions of applied voltage**

**Table I**

| Condition | Potential of the Terminals $E_1$ | $E_2$ |
|---|---|---|
| 1. A grounded short circuit near the breaker terminal | $E$ | Ground |
| 2. First phase to clear on an ungrounded 3-phase short circuit on a grounded system | $+\frac{1}{2}E$ | $-\frac{1}{2}E$ |
| 3. An ungrounded, line-to-line, single-phase short circuit through a single pole. (A test condition) | $+\frac{1}{2}E$ | $-\frac{1}{2}E$ |

Note: $E$ is the voltage across the pole unit and will not have the same value for each of the conditions given above.

grounding on either side so the shielding was symmetrical and the results approached but did not reach uniform distribution. The 6-break assembly is slightly under-shielded. In the 8-break assembly the fourth and fifth interrupters were slightly different from the others and not quite as effective. Consequently, the shielding was designed so that these 2 interrupters would get less voltage than the others. How well this was controlled is shown by the curves.

The advantages gained by shielding are clearly shown in figure 5. The ordinates are the maximum voltage on any one interrupter in percentage of the voltage applied across the pole unit.

Curve *A* indicates the percentage for uniform distribution in breakers, having from one to 10 interrupters. Curve *B* indicates the percentage as measured in some unshielded circuit breakers. Curve *C* indicates the percentage as measured in shielded breakers and shows a big improvement due to shielding. This figure shows that for a given service, about the same interrupting ability is required of the interrupters for the unshielded 8-break circuit breaker, as for the suitably shielded 4-break circuit breaker. The shielded breaker having half the number of interrupters, has half the total arc length and half the arc energy. The use of shielding in the 8-break circuit breaker permits the use of interrupters of about half the voltage interrupting ability and therefore, approximately half the arc length, half the arc duration, and an even smaller fraction of the arc energy.

## Devices Used for Controlling Voltage Distribution

The shielding devices which have produced the results already discussed are of new design. One recently developed for 287-kv breakers and described in a paper before the Institute[4] is shown in figure 6. It consists of a conical tube wound from treated paper and foil. Its construction is similar to that of a condenser bushing but differs in the location and length of the foil layers since the potential is applied between the ends of the shield instead of between the inside and the outside. The shield has an approximately uniform potential gradient from one end to the other on both the inside and outside surfaces. The interrupters located at uniform intervals inside it share the voltage equally among them. Each contact is shielded from ground and has a large capacitance to a layer of foil which has approximately the same potential as the contact. Two shields are used in a pole unit, each shield containing half of the interrupters. The large capacitances of the shields minimize the distorting effect of the capacitance to ground of the moving contact and connected metal parts. This divides the voltage between the 2 halves of the pole unit and the 2 shields divide these portions among the individual grids.

The results obtained with this shield are shown in figure 7 which gives the results of measurements under the 3 conditions of table I and shows the relations between them.

A similar shield was used during experimental work on 4 interrupters. The maximum voltage which could be interrupted was about 88 kv although individually the units could interrupt 30 kv. The electrical field inside the shield was then measured, figure 8, and found to give a voltage distribution of 24, 26, 33, and 17 per cent which indicated that one of the 4 units was being stressed to about 33 per cent of 88 kv or 29 kv. Subsequently an assembly of 4 35-kv interrupters having a voltage distribution of 24, 26, 27, and 23 per cent was tested and found to interrupt 132 kv successfully. The voltage on one unit should have been about 27 per cent of 132 kv or 35.6 kv.

**Table II. Voltage Limitations of Interrupter Assemblies Having Good Voltage Distribution**

| Number of Units in Series | Voltage Limitation (Kilovolts) | Voltage on One Interrupter Per Cent | Kilovolts |
|---|---|---|---|
| 1 | 35 to 40 | 100 | 35 to 40 |
| 2 | 65 to 75 | 50 | 32.5 to 37.5 |
| 3 | 100 to 115 | 33.3 | 33.3 to 38.3 |
| 4 | 132 or more | 27 | 35.6 or more |

The 35-kv interrupters were tested also in 2 and 3 unit assemblies with uniform distribution and the results substantiated the voltage distribution measurements as shown by the data in table II.

These series of tests demonstrated clearly the value of the static voltage distribution as a criterion of the voltage conditions existing during interruption.

## Methods of Measuring Voltage Distribution

The measurement of the voltage distribution in oil circuit breakers presents some interesting problems because of the presence of oil, the variation in the breakdown of gaps in oil, the difficulty or impossibility of locating shielded leads in equipotential surfaces, and the difficulty of making observations of phenomena below the oil surface or within the shields. A modification of the sphere gap method was selected. Gas discharge tubes replaced the sphere gaps and special viewing or detecting means were used in the determination of the breakdown. One assembly of 4 interrupters prepared for test but not yet covered by the shield, is shown in figure 9. Two small neon discharge tubes *A* having a breakdown voltage of about 60 volts are mounted adjacent to the metal assem-

blies between gaps. One lead from each tube is connected to the adjacent metal parts and the other, a flexible insulated lead is connected to a piece of metal fastened to a heavy cord. The cord passes vertically through metal guides along the assembly, the upper end goes directly to the manhole at the top of the breaker, and the lower end passes around the lower end of the shield and thence upward to the manhole. After the breaker is filled with oil, the lead can be pulled into contact with a guide, thereby connecting the tube across either the gap above the tube or the gap below the tube (as shown in the illustration). By stopping the cord midway between the end positions the flexible lead is held adjacent to the metal parts where it will exert practically no disturbing effect while measurements are being made with the other tube. This facilitates testing as it reduces the amount of oil handling.

The light from the small tube would be invisible through the oil, so a glass tube, which is sealed at the bottom and

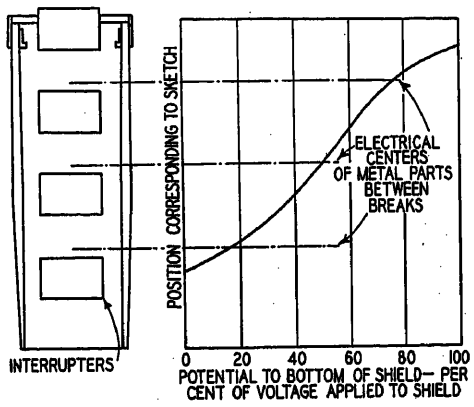



**Figure 8 (above). The electrical field inside a shield used in an experimental 4-break circuit breaker**

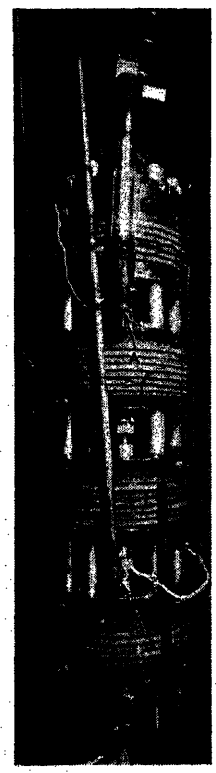


**Figure 9 (right). An assembly of interrupters with equipment for voltage distribution measurements mounted on it**

mounted directly above the discharge tube, is used to transmit the light upward to a point above the surface of the oil, where it is deflected by a prism to the manhole.

The test apparatus has little influence on the voltage distribution. The glass, Micarta, string, and air displace a small amount of oil and change slightly the dielectric, but the effect is negligible. The discharge tubes themselves have little capacitance and the leads are as short as possible and are located where they cause a minimum of error. Consequently the capacitance added to the capacitance of an interrupter by connecting the tube across it is relatively small and approximately constant, and a correction for it is easily made.

Voltage is applied by means of 2 variable-voltage potential test sets having a range of zero to 30 kv and connected to a common source of voltage, so that the secondary voltages are 180 degrees out of phase.

For tests with one terminal grounded, the procedure is as follows. By manipulation of the cords, a tube is connected across the gap under test. Potential is then applied to a terminal and increased until the voltage appearing across the gap under test is sufficient to cause the tube to break down and glow. The applied potential is recorded and 2 or 3 additional readings made as a check to be sure that the observer noticed the first breakdown. The percentage of the voltage appearing across the gap can then be obtained by dividing the breakdown voltage of the tube by the applied voltage and multiplying by 100 per cent. The leads to the terminals of the breaker are then reversed which in effect prepares for the test on the corresponding gap on the other side of the breaker. In this way only one assembly of interrupters needs to be fitted with tubes for test. After all the gaps have been tested, the percentages are added but, due to the increase in the capacitance across each gap when the tubes are connected for measurements, the sum is not 100 per cent. Since the effect of the apparatus has been about the same on each gap a constant multiplying factor is used in raising each percentage so the sum equals 100 per cent.

For tests with both terminals energized the procedure is similar but care must be taken that the potentials applied to the terminals are always in the correct ratio.

The consistency of the results and their agreement with

**Table III. Voltage Distribution on 10-Break Oil Circuit Breaker Equipped With Shields Around Contacts**

Data From Witness Test

| Grid | Voltage Applied (Volts) Term. I | Term. II | Average | Tube Breakdown Volts | Voltage on Gap (Per Cent) Reading | Corrected | Calculated |
|---|---|---|---|---|---|---|---|
| A | 446, 445, 445 | Ground | 445.3 | 51.75 | 11.6 | 13.2 | 12.9 |
| B | 452, 452, 452 | Ground | 452.0 | 51.75 | 11.44 | 13.1 | 13.2 |
| C | 517, 514, 516 | Ground | 515.6 | 58.3 | 11.28 | 12.9 | 13.0 |
| D | 531, 530, 528 | Ground | 529.6 | 58.3 | 11.05 | 12.6 | 12.3 |
| E | 536, 535, 534 | Ground | 535 | 56.0 | 10.5 | 12.0 | 11.6 |
| E (F) | Ground | 786, 784, 784 | 785.3 | 56.0 | 7.17 | 8.2 | 7.6 |
| D (G) | Ground | 830, 830, 830 | 830 | 58.3 | 6.99 | 8.0 | 7.6 |
| C (H) | Ground | 924, 922, 922 | 922.6 | 58.3 | 6.2 | 7.1 | 7.6 |
| B (I) | Ground | 888, 888, 888 | 888 | 51.75 | 5.72 | 6.5 | 7.4 |
| A (J) | Ground | 920, 920, 920 | 920 | 51.75 | 5.63 | 6.4 | 6.8 |
| | | | | Total | 87.58 | 100 | 100 |

calculations made before the shields were built are shown by the typical data presented in table III.

The results of tests made with tubes having breakdown voltages of 60 volts were checked by similar tests with tubes having a breakdown of about 30 kv. The tubes were larger and were inserted in the spaces between interrupters. This made viewing from above still more difficult so a choke coil was inserted in the lead to one terminal and one of the 60-volt discharge tubes was connected across it. This lead was grounded and the other connected to a high potential testing transformer. The voltage was raised until the 30-kv tube broke down. The discharge caused the 60-volt tube to glow. Data taken in this manner with one terminal energized and the other grounded gave the same voltage distribution as the data taken with the lower-voltage tubes. The other conditions were not tested with the high-voltage tube because of the greater difficulty in the manipulation of the higher potentials and the close agreement with the data more easily obtained at lower voltages.

## Conclusions

The efficiency of multibreak circuit breakers depends on the distribution of the voltage between the interrupters.

The presence of grounded parts near the interrupters and the capacitances between interrupters tend to distort the voltage distribution and to decrease the efficiency of the breaker.

Voltage distribution in multibreak circuit breakers can be controlled by capacitance shielding, so that each interrupter does its share under all short-circuit conditions.

Interrupting tests justify the use of static voltage distribution as a criterion of the voltage distribution during an interruption.

The distribution can be calculated and measured.

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2. Arc Extinction Phenomena in High Voltage Circuit Breakers, R. C. Van Sickle and W. E. Berkey. AIEE Transactions, volume 52, 1933, pages 850–60.

3. Breaker Performance Studied by Cathode Ray Oscillograms, R. C. Van Sickle. Electrical Engineering (AIEE Transactions), 1935.

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# Polyphase Rectifier Metering

IN PRESENTING a paper "The Metering of Mercury-Arc Rectifier Supplies and Outputs" at a recent meeting of The Institution of Electrical Engineers in London, England, C. Dannatt (A'29) research engineer for the Metropolitan-Vickers Electrical Company, Manchester, described in detail both the theoretical and practical problems involved in accurate metering of polyphase mercury-arc rectifier input and output quantities. In this 12-page paper, containing 11 illustrations and 8 tables, Mr. Dannatt stressed the essential that an accurate meter for rectifier inputs must be so constructed that its calibration is independent of frequency. The rigorousness of this requirement decreases, however, if the number of rectifier phases is increased, or if the wave form of the voltage applied to the rectifier transformer is improved. Table IV, which is reproduced from the paper, shows the variation in metering errors as the number of phases is changed.

**Table IV**

| | 3-Phase Rectifier* | | 6-Phase Rectifier** | |
|---|---|---|---|---|
| | True Values | Meter Values | True Values | Meter Values |
| Power factor | 0.71 | 0.89 | 0.89 | 0.94 |
| Reactive kilovolt-amperes | 71 | 37.2 | 45.6 | 33.1 |
| Total kilovolt-amperes | 100 | 79.5 | 100 | 94.8 |
| Distortion power ($P_D$) | 60.5 | | 31.3 | |

* With a ratio of line reactance to transformer reactance of 0.85.
** With a ratio of line reactance to transformer reactance of 0.91.

A mathematical series describing the energy associated with current and voltage of distorted wave forms consists of a steady term and a series of pulsating terms, so that a meter used to measure energy must maintain its accuracy at frequencies as high as the component frequencies of the composite wave form. The proportion of pulsating energy to total energy decreases rapidly with an increase in the number of phases; consequently, serious difficulty in metering rectifier input is most likely to occur in rectifiers of low numbers of phases.

Except for known bad performance with respect to changes in frequency, the ordinary induction type of meter has so many advantages that its inherent errors were investigated very carefully to determine whether they were of sufficient importance to nullify the advantages of this type of meter for measuring rectifier input. The conclusion from the tests was that the error of a modern well-designed induction meter connected to rectifier supplies is not likely to exceed one per cent for a 3-phase connection, or 0.5 per cent for a 6-phase connection, provided that the meter is adjusted to register correctly with sinusoidal current and voltage.

The satisfactory performance of the induction meter encouraged the author to try other types of meters that may be used on either alternating current or direct current, and that consequently are less dependent on frequency than the induction meter in calibration. The Thomson motor type of meter is in this category, and was found to be sufficiently independent of frequency to make it an accurate instrument for rectifier power-input measurements, if no shunt is used across the field coils.

This type of meter is said to be satisfactory also for measuring the d-c output of polyphase rectifiers; satisfactory accuracy depends chiefly upon reducing the ripple component of the output, but appreciable inaccuracy of the meter may result from its use on 2- or 3-phase circuits with very little smoothing of the d-c output.

# Discussions

## Of AIEE Papers—as Recommended for Publication by Technical Committees

ON THIS and the following 16 pages appear discussions submitted for publication, and approved by the technical committees, on papers presented at the sessions on tensor analysis, synchronous machinery, and protective devices at the 1937 AIEE winter convention, New York, N. Y., January 25–29, and on one paper not presented at an AIEE meeting. Authors' closures, where they have been submitted, will be found at the end of the discussion of their respective papers.

Members anywhere are encouraged to submit written discussion of any paper published in ELECTRICAL ENGINEERING, which discussion will be reviewed by the proper technical committee and considered for possible publication in a subsequent issue. Discussions of papers scheduled for presentation at any AIEE meeting or convention will be closed 2 weeks after presentation. Discussions should be (1) concise; (2) restricted to the subject of the paper or papers under consideration; and (3) typewritten and submitted in triplicate to C. S. Rich, secretary, technical program committee, AIEE headquarters, 33 West 39th Street, New York, N. Y.

## A Single-Element Polyphase Directional Relay

**Discussion and author's closure of a paper by A. J. McConnell published in the January 1937 issue, pages 77–80, and presented for oral discussion at the protective devices session of the winter convention, New York, N. Y., January 27, 1937.**

**G. W. Gerell** (Union Electric Light and Power Company, St. Louis, Mo.): Mr. McConnell's paper brings to mind certain difficulties which our company has been experiencing with single-phase power directional relays. On rather too frequent occasions reverse power relays have operated during faults behind the relay. In most cases these incorrect operations occurred during single-phase ground faults. Invariably the relay operating falsely was not connected to the faulted phase. It should be noted that these operations have always taken place on systems grounded solidly at 2 or more points. A typical circuit arrangement would consist of 2 33-kv circuits supplying power to a substation. The circuits would be energized from the 13,800-volt power plant bus through 13.8/33 kv delta-wye grounded transformer. At the substation end the circuits would be bussed at 33 kv. The reverse power relays are located on the line oil switches at the substation end. No incorrect operations have been recorded on a number of other circuits, arranged in a similar manner, but bussed at the substation end through 33/4.5 kv transformer banks on the low-tension side.

Extremely low power factors, causing a reversal of torque in the relay may account for these operations, but I am more inclined to believe that they are caused by the relatively high currents flowing in the ungrounded conductors during a one-phase-to-ground fault. The *net* power flow at the point where the false operations occur, is of course, in such a direction to prevent incorrect operation, but in the ungrounded phases it is not necessarily so.

A polyphase relay, measuring net power in a 3-phase circuit, as Mr. McConnell has described, should effectively prevent operations so frequently experienced with the single-phase type of directional relays.

The phenomena reported here, occurs more generally on systems solidly grounded at several points, and such being the case, the question naturally arising is—why are the single-phase relays invariably applied to such systems. Polyphase directional relays were available, I believe, even before the advent of the single-phase type. Moderately high-speed polyphase relays have been available, at least during the last 6 or 7 years. For some reason or the other, they have been applied less frequently as time goes on.

Concerning a method of preventing incorrect operations on existing installations of the single-phase relays it is suggested that setting the over-current element of the directional relay for a pick-up in excess of the calculated value of current flowing in the ungrounded phases may constitute a solution, provided the setting is practical.

**J. H. Neher** (Philadelphia Electric Company, Philadelphia, Pa.): The increased use of pilot protective systems, of either the carrier current or metallic pilot-wire types, has brought about the need for a polyphase directional relay capable of high-speed and positive-contact operations. Mr. McConnell is to be congratulated on the development of such a relay which at the same time fulfills the demand for a rugged general purpose polyphase directional relay comparable in cost to, but occupying considerably less space than the present forms of such relays.

When voltage restraint is added to a directional element the resultant combination may be described as a directional distance fault detector, the range of which is a function of the angle of departure from the angle of maximum torque in the directional circuit and which is a maximum when this angle of departure is zero. In certain relay arrangements it is desirable to make use of this property such as for instance in the case of the starting unit of a reactance type distance relay.

Under such conditions it is desirable that the range of the relay be substantially the same for both 3-phase and phase-to-phase faults. The maximum range of a single-phase directional element with voltage restraint for a phase-to-phase fault is about 86 per cent of the range for a 3-phase fault, while in the case of a polyphase element with the quadrature connections, the range for a phase-to-phase fault is only 50 per cent of that for a 3-phase fault.

It appears that the connections shown in figure 2 will also have a maximum range of 50 per cent in the case of a phase-to-phase fault. As Mr. McConnell has pointed out, however, the construction of this new element is such that a number of other connections may be utilized, and possibly one can be found which will result in ranges for the 2 types of faults which are more nearly equal.

**E. W. Kimbark** (Massachusetts Institute of Technology, Cambridge): The correct working of practically every protective relay scheme, from simple overcurrent protection to carrier-current relaying, depends on directional relays, either of the single-phase type or of the polyphase type. Therefore it is important to know with accuracy what conditions limit the correct operation of such relays; and it would be desirable to have a complete mathematical analysis of their performance, like the analysis of distance relays which has been so ably achieved by Messrs. Lewis and Tippett. The paper by Mr. McConnell makes a good start at such an analysis for the polyphase type of directional relay, particularly by expressing the relay torque for each of 2 different connections in terms of the flow of positive- and negative-sequence power in the protected line, thereby enabling us to see that each of these 2 components of power contributes a suitable component of torque.

The directions of flow of vector power due to a short circuit on a 3-phase network are as follows in terms of symmetrical components: positive-sequence power flows toward the fault; while negative-sequence and zero-sequence power (if one or both are produced by the type of fault in question) flow away from the fault. The relative magnitudes of the positive-, negative-, and zero-sequence powers at a relay location depend on the type of fault, on the division of power of each sequence between the 2 ends of the faulted line, and on the distance between the fault and the relay.

(The relations derived in appendixes I *B* and II *B* of the paper for a dead phase-to-phase fault are exact only if the relay is close to the fault and only if the line is open at the far end, or if the positive- and negative-sequence powers divide between the two ends of the line in the same ratio.) Although the power at a relay location may consist of 1, 2, or 3 sequence components, mixed in various proportions, nevertheless the flow of each component is in the direction stated above; and any component which is present, or a combination of 2 or 3 of them, may be used to indicate the direction of the fault location. If all 3 components are used, the relay torque may be expressed by

$$\text{real part of } [k_1E_1\bar{I}_1\angle\theta_1 + k_2E_2\bar{I}_2\angle\theta_2 + k_0E_0\bar{I}_0\angle\theta_0] = k_1E_1I_1\cos(\phi_1+\theta_1) + k_2E_2I_2\cos(\phi_2+\theta_2) + k_0E_0I_0\cos(\phi_0+\theta_0) \quad (1)$$

(See end of discussion for notation used.) It is desirable that $\theta_2$ and $\theta_0$ should differ by approximately 180 degrees from $\theta_1$ so that the sign of each of the 3 terms of the expression will be the same when negative-sequence and zero-sequence power are flowing in the direction opposite to that of the positive-sequence power (that is, when $\phi_2$ and $\phi_0$ are approximately 180 degrees from $\phi_1$). This is on the assumption that the power factor is approximately the same for each sequence; it may differ somewhat for different sequences, and the positive-sequence power factor may vary with the type of fault. Since the positive- and negative-sequence torque terms are ordinarily obtained, not from a positive-sequence element and a negative-sequence element, but from several elements working on phase currents and voltages, $k_1$ and $k_2$ are necessarily equal, while $\theta_1$ and $\theta_2$ depend on $\theta$ (defined below) and on the relay connections.

The torque of each single-phase directional element is given by the

$$\text{real part of } k\,\bar{E}\,\bar{I}\angle\theta = kEI\cos(\phi+\theta) \quad (2)$$

and the combined torque of several single-phase elements of identical construction, or of an equivalent polyphase element, is given by

$$\text{real part of } k\angle\theta\sum\bar{E}\bar{I} \quad (3)$$

The factor

$$\sum\bar{E}\bar{I}$$

for various connections of 3 single-phase elements, using either *Y* (line-to-neutral) or Δ (line-to-line) voltages and either *Y* or Δ currents, may be expressed as follows:

$$\bar{E}_a\bar{I}_a + \bar{E}_b\bar{I}_b + \bar{E}_c\bar{I}_c = 3(\bar{E}_0\bar{I}_0 + \bar{E}_1\bar{I}_1 + \bar{E}_2\bar{I}_2) \quad (4)$$

$$\bar{E}_a\bar{I}_b + \bar{E}_b\bar{I}_c + \bar{E}_c\bar{I}_a = 3(\bar{E}_0\bar{I}_0 + \bar{E}_1\bar{I}_1\angle120 + \bar{E}_2\bar{I}_2\angle240) \quad (5)$$

$$\bar{E}_a\bar{I}_c + \bar{E}_b\bar{I}_a + \bar{E}_c\bar{I}_b = 3(\bar{E}_0\bar{I}_0 + \bar{E}_1\bar{I}_1\angle240 + \bar{E}_2\bar{I}_2\angle120) \quad (6)$$

$$\bar{E}_a\bar{I}_A + \bar{E}_b\bar{I}_B + \bar{E}_c\bar{I}_C = 3\sqrt{3}(\bar{E}_1\bar{I}_1\angle270 + \bar{E}_2\bar{I}_2\angle90) \quad (7)$$

$$\bar{E}_a\bar{I}_B + \bar{E}_b\bar{I}_C + \bar{E}_c\bar{I}_A = 3\sqrt{3}(\bar{E}_1\bar{I}_1\angle30 + \bar{E}_2\bar{I}_2\angle330) \quad (8)$$

$$\bar{E}_a\bar{I}_C + \bar{E}_b\bar{I}_A + \bar{E}_c\bar{I}_B = 3\sqrt{3}(\bar{E}_1\bar{I}_1\angle150 + \bar{E}_2\bar{I}_2\angle210) \quad (9)$$

$$\bar{E}_A\bar{I}_a + \bar{E}_B\bar{I}_b + \bar{E}_C\bar{I}_c = 3\sqrt{3}(\bar{E}_1\bar{I}_1\angle90 + \bar{E}_2\bar{I}_2\angle270) \quad (10)$$

$$\bar{E}_A\bar{I}_b + \bar{E}_B\bar{I}_c + \bar{E}_C\bar{I}_a = 3\sqrt{3}(\bar{E}_1\bar{I}_1\angle210 + \bar{E}_2\bar{I}_2\angle150) \quad (11)$$

$$\bar{E}_A\bar{I}_c + \bar{E}_B\bar{I}_a + \bar{E}_C\bar{I}_b = 3\sqrt{3}(\bar{E}_1\bar{I}_1\angle330 + \bar{E}_2\bar{I}_2\angle30) \quad (12)$$

$$\bar{E}_A\bar{I}_A + \bar{E}_B\bar{I}_B + \bar{E}_C\bar{I}_C = 9(\bar{E}_1\bar{I}_1 + \bar{E}_2\bar{I}_2) \quad (13)$$

$$\bar{E}_A\bar{I}_B + \bar{E}_B\bar{I}_C + \bar{E}_C\bar{I}_A = 9(\bar{E}_1\bar{I}_1\angle120 + \bar{E}_2\bar{I}_2\angle240) \quad (14)$$

$$\bar{E}_A\bar{I}_C + \bar{E}_B\bar{I}_A + \bar{E}_C\bar{I}_B = 9(\bar{E}_1\bar{I}_1\angle240 + \bar{E}_2\bar{I}_2\angle120) \quad (15)$$

The following 2-element combination is also of interest:

$$\bar{E}_A\bar{I}_C - \bar{E}_C\bar{I}_A = 3\sqrt{3}(\bar{E}_1\bar{I}_1\angle270 + \bar{E}_2\bar{I}_2\angle90) \quad (16)$$

Equations 7, 10, and 16 are for the 90-degree connection (equation 10 representing its usual form); equations 5 and 14 are for the 60-degree connection, which is equivalent to the one recommended in the paper for the new polyphase relay; and equations 9 and 12 are for the 30-degree connection (equation 12 the usual form.) A comparison of the expressions just mentioned, substituted in (3), with equation 1, yields the following values of $\theta_1$ and $\theta_2$:

| Connection | $\theta_1$ | $\theta_2$ |
|---|---|---|
| 90-degree | $\theta - 90$ | $\theta + 90$ |
| 60-degree | $\theta - 60$ | $\theta + 90$ |
| 30-degree | $\theta - 30$ | $\theta + 30$ |

By way of comparison, assume that for each connection the positive-sequence torque is made a maximum at 30 degrees lag ($\theta_1 = -30$). This assumption determines a different value of $\theta$ for each connection, and the value of $\theta$ determines the values of $\theta_2$ and of $\theta_2 - 180$:

| Connection | $\theta_1$ | $\theta$ | $\theta_2$ | $\theta_2-180$ |
|---|---|---|---|---|
| 90-degree | −30 | 60 | 150 | − 30 |
| 60-degree | −30 | 30 | 90 | − 60 |
| 30-degree | −30 | 0 | 30 | −150 |

The values of $(\theta_2 - 180)$ are the phase angles of the negative-sequence current with respect to the negative-sequence voltage for maximum torque, considering that the negative-sequence vector power is substantially opposite in direction to the positive-sequence; thus, the 90-degree connection gives maximum torque at 30-degree lag (equal to the lag at which the positive-sequence power gives maximum torque); the 60-degree connection at the greater lag of 90 degrees; and the 30-degree connection at the still greater lag of 150 degrees. Since so great a lag would never be obtained, the negative-sequence torque would be relatively low in the 30-degree connection, and possibly even reversed in direction. For this reason the 90-degree and 60-degree connections appear preferable to the 30-degree connection, even though the latter would probably operate correctly.

The connections just discussed give no zero-sequence torque, with the exception of the form of 60-degree connection represented by equation 5. For this case $k_0 = k_1$, and $\theta_0 = \theta + 180$. Assuming as before that $\theta_1 = -30$, there results $\theta_0 - 180 = 30$; maximum zero-sequence torque is obtained with current leading by 30 degrees. This is not the best relation that could be imagined, because the zero-sequence current will frequently lag by a considerable angle, giving a low or even reversed torque, though probably seldom strong enough to overweigh the positive- and negative-sequence torques. If desired, the zero-sequence torque can be eliminated by connecting the relay voltage windings in *Y* with no neutral connection. A more reliable and flexible way of introducing a zero-sequence torque is to use an electrically separate mechanically coupled zero-sequence element as described in the paper; by this means $k_0$ and $\theta_0$ can be given any desired values. It would be interesting to know the value of $k_0/k_1$ for the relay described as having a "strong ground-fault element."

The negative-sequence phase angle $(180+\phi_2)$ depends on the impedance from the relay to the generators, including lines, transformers, and generators, and will probably range from 60 to 90 degrees. The zero-sequence phase angle $(180+\phi_0)$ depends on the impedance from the relay to grounding points, including lines, transformers, and grounding impedance, and may range almost from 0 to 90 degrees. The positive-sequence phase angle depends on the negative- and zero-sequence phase angles at the fault, on the fault resistance, and on the line impedance from relay to fault. In the case of a 3-phase fault only the last 2 items come into play. A 3-phase fault near the relay, is, of course, a critical condition for the relay on account of the low voltage on all phases; hence the relay should be designed for maximum torque at a phase angle near the line impedance angle or somewhat more leading so that the arc resistance will have more effect.

Another critical condition for a polyphase directional relay is a single line-to-ground fault in which the fault current is limited by fault resistance or by system grounding impedance to a value comparable with normal load current; because the positive-sequence power flow during fault conditions is determined not only by the fault current but also by the normal load current; and for this reason it is possible for a directional relay actuated by positive-sequence power at the receiving end of a faulted line to give the wrong directional indication. This fact suggests the discarding of positive-sequence power for directional discrimination; however, it must be retained in order that the relay act during a 3-phase fault.

Having never seen a quantitative statement of the conditions under which load current may cause incorrect operation of a polyphase directional relay, I offer a criterion which is admittedly crude. It is

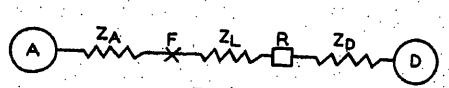



Figure 1

assumed that the power system beyond each end of the protected line may be represented by an equivalent electromotive force in series with an equivalent impedance. In figure 1, *F* represents the point of fault, *R* the relay location, *A* and *D* the equivalent electromotive forces, $Z_A$ and $Z_D$ the equivalent impedances, and $Z_L$ the line impedance. Figure 2 is an approximate vector diagram

of positive-sequence voltages. $AG$ and $DG$ are the equivalent electromotive forces at the sending and receiving ends, respectively, and are assumed to be unaltered by the presence of a fault. $F_1G$ is the voltage at the point of fault before occurrence of the fault and $R_1G$ is the voltage at the relay under the same conditions. $F_2G$ and $R_2G$ represent the voltages at the same points during a mild fault, and $F_3G$ and $R_3G$ the same during a more severe fault. $AF_1R_1D$ is a straight line on the assumption that

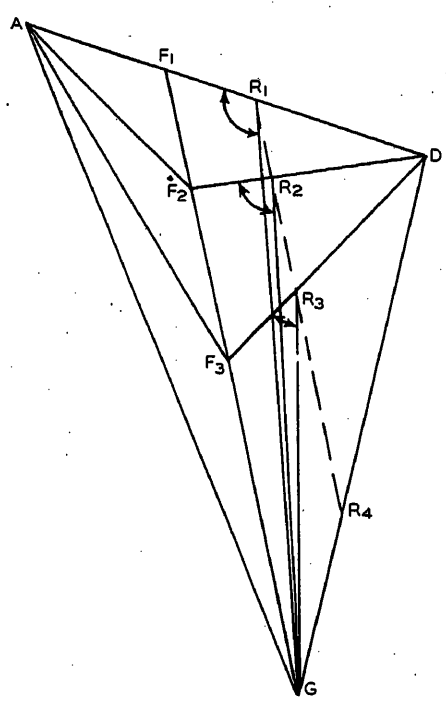



Figure 2

impedances $Z_A$, $Z_L$, and $Z_D$ have the same angle. $F_1F_2F_3G$ is a straight line on the assumption that the positive-, negative-, and zero-sequence impedances of the system have the same angle. $F_1R_1$, $F_2R_2$, and $F_3R_3$ are the respective positive-sequence line drops from the fault to the relay, and the positive-sequence line currents are proportional to them and lag behind them by angle $\lambda$. The positive-sequence torque on relay $R$ is proportional to $E_1I_1 \cos(\phi_1 + \theta_1) = R_1GXR_1FX \cos(\angle GRF + \lambda + \theta_1)$. If we assume for simplicity that the relay has maximum torque at an angle equal to the line impedance angle (i.e., $\theta_1 = -\lambda$), the torque is proportional to $R_1GXR_1FX \cos \angle GRF$. Angle $GRF$ has value $GR_1F_1$ with no fault present, $GR_2F_2$ or $GR_3F_3$ for faults of increasing severity, and finally $GR_4G$ or zero angle for a dead 3-phase fault. The relay torque changes sign when angle $GRF$ passes through 90 degrees. This occurs when the reduction $F_1F_2$ in positive-sequence voltage at the point of fault is about equal to the arithmetical voltage drop from $F$ to $D$ under normal load conditions. If the latter does not exceed 20 per cent, any fault except a line-to-ground fault would give sufficient reduction in voltage to give a relay torque in the correct direction; and a line-to-ground fault would probably do likewise unless the fault current were limited by fault resistance or system grounding impedance. Although several assumptions have been made that are not strictly correct, it appears reasonably certain that a line-to-line fault will always give correct operation. This conclusion has been reached on the basis of the positive-sequence torque alone. The negative-sequence power provides an additional torque acting in the right direction.

NOTATION

The notation used in this discussion is like that in the paper with the following additions:

$$I_A = I_c - I_b$$
$$I_B = I_a - I_c$$
$$I_C = I_b - I_a$$

$I_A$, $I_B$, $I_C$ will be called "delta currents," and may be obtained by a delta connection of the secondary windings of the current transformers.

$\phi$ = angle by which the current of a single relay element lags behind the voltage of same element.

$\phi_0$ = angle by which $I_0$ lags $E_0$.

$-\theta$ = value of $\phi$ at which relay has maximum torque.

$-\theta_0$, $-\theta_1$, $-\theta_2$ = values of $\phi_0$, $\phi_1$, $\phi_2$, respectively, at which relay has maximum torque.

$\lambda$ = angle of line impedance.

$k$, $k_0$, $k_1$, $k_2$ = constants in torque equations.

**W. R. Brownlee** (Tennessee Electric Power Company, Chattanooga): The author has chosen a very clear method of indicating the performance of the new polyphase relay in terms of fundamental system impedances. The low energy requirements and small inertia of moving parts are a most welcome contribution toward accurate high-speed relaying.

The difference of 30 degrees in phase angle between a 3-phase fault and a dead single phase-to-phase fault is indeed an advantage. In addition to the fact that a single-phase line-to-line short circuit causes a phase angle difference depending on the impedance back to and including the generator, this same system and generator impedance is available to produce voltage at the relay terminals considerably in excess of the voltage on the faulted phase at the relay. This method of securing positive directional action for single-phase short circuits has been used in the connections of various impedance relays, usually 3 single-phase units.

One of the chief uses for the new relay element should be the 3-phase directional element combined with a voltage restraint element to provide a directional fault detector. The need for such a device with greatly improved accuracy and speed has been felt for many years, particularly in connection with lines and systems where the short-circuit current under certain generating conditions may be actually less than load current under other conditions. In order to meet this requirement a fault detector should have a nonlinear characteristic so that the current required to operate the unit varies with the voltage at some power higher than the first. Such a fault detector was incorporated as early as 1930 in the Brown Boveri reactance type relay. Shortly thereafter the General Electric Company placed in service a single phase *directional* fault detector incorporated in their type $GAX$ reactance relay using voltage amplification by means of a circuit which was made resonant at low voltages only, by the application of a "thyrite" resistor. This equipment produced a characteristic curve of operating current versus voltage which was most highly useful in solving applications of high load current and low short circuit current.

It appears from the final equations that the new relay if provided with a voltage restraining element would have a straight line characteristic of operating current against voltage (for a balanced 3-phase condition) and even if the sensitivity has been increased it is disappointing that the nonlinear characteristic curve was not applied to the new relay. Perhaps further developments will make it possible to secure such a characteristic with the new relay without adding too much complication or expense.

This criticism is by no means intended to minimize the unquestionable achievement of the G. E. Company in developing the new cup type relay but to point out that the operating man is in urgent need of a much better directional fault detector relay than has been available in the past for taking care of 3-phase short circuits on transmission lines.

**A. J. McConnell:** Mr. Neher is correct in stating that with directional connections as in figure 2 and with a voltage restraining element connected to measure a value proportional to the area of the voltage triangle, the maximum range of the relay for a phase-to-phase fault is 50 per cent of that for a 3-phase fault. If the relay is designed to have the desired range for a phase-to-phase fault, it is sure to operate on a 3-phase fault at the same location. The limiting factor is that the greater reach on the 3-phase condition must not cause operation during normal load conditions.

The starting unit of the $GAX$ reactance relay mentioned by Mr. Brownlee had a nonlinear characteristic principally in order to increase the torque and speed at low voltage without overheating at normal voltage. The author believes that such expedients are seldom necessary with the induction cylinder relay because of the high torque level and low inertia.

The first system described by Mr. Gerell is definitely one in which single-phase directional relays are likely to operate incorrectly. Zero-phase-sequence currents may be present with no positive and negative, in which case the line currents will be equal and in phase, and consequently, the indicated direction of at least one of single-phase relays must be incorrect.

As Mr. Gerell pointed out, the polyphase relay would solve the problem. When supplied with delta voltages or currents, the polyphase relay is not influenced by zero-phase-sequence quantities. This suggests another solution, namely, eliminating the zero-phase-sequence currents from the single-phase relays by delta connection of current transformers. Since a ground directional relay would then be necessary, the delta currents would have to be obtained by means of auxiliary wye-delta current transformers. The polyphase relay would

also require a ground directional relay, but no auxiliary current transformers would be required.

The use of wye-delta current transformer is equivalent to the second system mentioned by Mr. Gerell. The probable reason why no incorrect operations have been recorded on this system is because the zero-phase-sequence currents are eliminated from the relays by the wye-delta power transformers.

Mr. Kimbark's extension of the analysis of polyphase directional relay torques to include other connections is a valuable addition to the paper.

Another interesting extension is to consider the relay torques when the currents, voltages, or both are obtained from the delta side of a wye-delta transformer bank, the fault being on the wye side.

Equation 16 is one of many interesting combinations which can be derived from equations 4 to 15 inclusive by substitution of one or more of the following equations:

$$I_A + I_B + I_C = 0$$
$$I_a + I_b + I_c + I_g = 0$$
$$E_A + E_B + E_C = 0$$
$$E_a + E_b + E_c + E_g = 0$$

where $E_g$ and $I_g$ are residual voltage and current, respectively.

Referring to the term "strong ground element" a value of 4 has been used for $k_0/k_1$. It should be noted here that when this ratio has not been sufficient for the ground element to overcome the polyphase element because of load, the latter has been de-energized by means of a simple instantaneous overcurrent relay operated by ground current.

Mr. Kimbark's analysis of fault conditions when load is present is interesting. It has been usual to consider the ground element torque under fault conditions in comparison with polyphase element torque before the fault. This is conservative because the load torque during the fault is always reduced. Actually, this may be too conservative because the polyphase element also has a component of torque in the correct direction. However, if the assumed load torque is comparable with the fault torque, it is advisable to give the ground element complete control either as described in the previous paragraph or by employing a separate ground relay.

## Operational Solution of A-C Machines

**Discussion of a paper by A. R. Miller and W. S. Weil, Jr., published in the November 1936 issue, pages 1191–1200, and presented for oral discussion at the winter convention, New York, N. Y., January 27, 1937.**

**S. B. Crary** (General Electric Company, Schenectady, N. Y.): The authors have shown quite conclusively that the operational methods of Park for analyzing the performance of synchronous machines, can be reasonably expected to check actual test results. Besides showing the nature of the phenomena such checks are valuable in creating confidence in this method.

The authors, in their equations, have used the per unit system presented in Park's paper "Synchronous Machines—An Extension of Blondel's Two Reaction Theory—I." When additional circuits besides the main field circuit are to be included, we have found that it is more convenient to express the equations with coefficients which are in terms of the armature circuit rather than their individual circuits. This makes possible the use of methods presented by T. M. Linville, "Starting Performance of Salient Pole Synchronous Motors," volume 49, AIEE JOURNAL, February 1930, pages 145–47. Furthermore, it reduces in half the number of mutual reactance coefficients required and makes it possible to draw simple equivalent circuits for the machine. This allows for a fair check of the calculations of the coefficients and, therefore, tends to reduce errors at this preliminary stage of the analysis.

## A Suggested Rotor Flux Locus Concept of Single-Phase Induction Motor Operation

**Discussion and author's closure of a paper by C. T. Button published in the March 1937 issue, pages 331–2.**

**Edward Bretch** (The Advance Electric Company, St. Louis, Mo.): The method used by Mr. Button in his paper on the single-phase motor, that of considering the rotor flux as substantially constant along a fixed diameter of the rotor, enables one to clearly visualize the actions taking place in the single-phase squirrel-cage motor.

In the single-phase squirrel-cage rotor at and near synchronism, the following conditions prevail:

1. It carries the main flux produced by the primary.
2. The alternating primary magnetizing impulses are rectified with respect to the rotor through its synchronous motion.
3. The rotor flux is completely enclosed by low resistance rotor short circuits tending to hold it constant.

After the rotor flux is once established, the induced currents in the short-circuited rotor exert a strong tendency to hold this rotor flux constant and in a fixed relation to the rotor conductors. Consequently the rotor then reacts on the primary the same as if it was magnetized by a fixed magnetizing force across a diameter and by its synchronous motion carries this sustained flux around with it, establishing mechanically a true rotary field and tending to keep in synchronism.

A squirrel cage in a stationary or d-c field is commonly used to illustrate the principle of the polyphase squirrel-cage motor, the torque being developed by induced currents in the short-circuited rotor conductors as they cut across the magnetic field, utilizing what is commonly called the "speed" action. This same method can be used to illustrate the principle of the single-phase motor if we substitute a rectified single-phase a-c excitation for the d-c so that the primary excitation consists of a series of unidirectional impulses instead of a uniform unidirectional force as when excited by direct current.

This pulsating magnetizing force is the condition that prevails in the single-phase squirrel-cage rotor at synchronous speed, as the magnetic impulses produced by the single-phase exciting current are rectified with respect to the rotor, through the synchronous motion of the rotor, so that the rotor magnetism is produced through a series of unidirectional impulses. Consequently if we hold the rotor stationary and rectify the single-phase primary exciting current we will reproduce in a stationary rotor the conditions existing in the single-phase squirrel-cage rotor at synchronism.

In order to visualize what takes place in a squirrel-cage rotor, when running at synchronism in a single-phase field, let us assume a bipolar field with a single-phase winding capable of setting up a flux along the line $y$—$y$. Also let us assume the rotor has 2 individual short-circuited coils $A$ at right angles to this flux and $B$ in line with it.

Noting the positions of the coils with reference to the primary we see that $A$ encloses the total flux, and is therefore in a transformer relation to the primary. Coil $B$, however, is in line with the flux and does not enclose it and consequently is not in the transformer relation to the primary. However, the conductors of coil $B$ lie in the area of maximum flux density and in such a position that any motion of the rotor will cause them to cut across the field, thereby inducing local currents by the speed action, opposing motion and producing torque.

When the primary is excited by direct current no current will be induced in either coil as long as the rotor is at rest. Any motion of the rotor will induce currents in

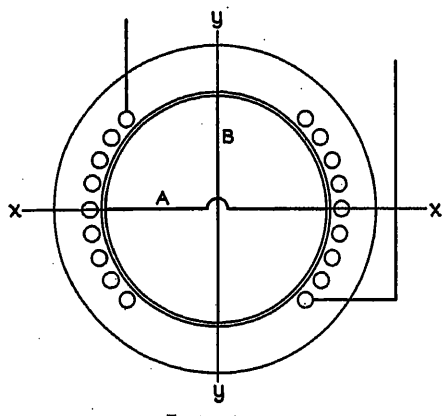


Figure 1

coil $B$ by the speed action, opposing the motion and thereby producing torque. Coil $A$ is in the neutral position with its conductors in the area of minimum or zero flux so that no current will be induced until the conductors move out of the neutral position and start cutting across the magnetic field. This is the polyphase condition.

If we now excite the primary with a rectified alternating current, to reproduce the single-phase rotor condition at synchronism, the magnetizing force will consist of a series of unidirectional impulses varying from

zero to a maximum. If it were not for coil $A$ the flux would coincide with the primary current and vary unidirectionally from zero to maximum. However, due to the transformer relation of coil $A$ any flux variation induces currents in the coil, opposing the flux change, so that when the primary magnetizing force decreases to zero, the flux does not, but is sustained between impulses by the induced currents in coil $A$. As the magnetizing impulses are unidirectional, the flux is unidirectional but varying in some degree with each impulse. The flux-sustaining currents induced in coil $A$ complete a cycle with each impulse, and there being 2 impulses for each cycle of the primary rectified exciting current, the frequency of these flux-sustaining currents is double that of the primary current. The amount of flux variation through coil $A$ between impulses depends upon its resistance. Theoretically with zero resistance the flux would be constant, and at the other limit, would coincide with the exciting current if the resistance was infinity. Both rotor resistance and magnetic leakage tend to decrease this sustained flux which is commonly called the cross flux.

With a substantially constant unidirectional flux established by the primary magnetizing impulses, stabilized by the double-frequency flux-sustaining currents in coil $A$, the opposition to the movement of coil $B$ across the field, due to speed action, produces the torque the same as with d-c excitation.

To illustrate the location and nature of the single-phase rotor reactions, a rotor with 2 individual short-circuited coils at right angles was assumed. However, in the ordinary squirrel-cage rotor, under slip conditions, the conductors are constantly shifting from the position where the speed action produces torque to the position at right angles where the transformer action produces the double-frequency flux-sustaining currents and vice versa. As the rotor slips the frequency of the flux-sustaining currents will decrease in the same manner that the frequency of the slip or torque currents increase. Thus in the single-phase squirrel-cage rotor there are superimposed 2 sets of induced currents at right angles. The one is the torque or slip currents, in the area of the maximum flux, produced by the speed action, with a frequency proportional to the slip, becoming zero at synchronism. The other is the flux-sustaining currents in the area of minimum flux density, produced by the transformer action, with a frequency of double the primary frequency less the slip and proportional to the primary exciting current.

This method of treatment indicates that the double-frequency flux-sustaining currents, proportional to the exciting current, flowing in the rotor at synchronism, although they incur an $I^2R$ loss, are produced through a transformer action at right angles to the torque currents, and thus do not act as a brake load and do not increase slip. It also indicates that the flux will not be as well maintained as slip increases due to the imperfect rectification of the primary magnetizing impulses as slip increases. The effectiveness of the rectification decreases with slip and when slip reaches 100 per cent, or with the rotor at standstill there is no rectification at all and consequently no torque producing condition.

In the polyphase motor, rotor resistance does not reduce the magnitude of the maximum, or breakdown torque, but merely lowers the speed at which it is developed.

In the single-phase motor we see that rotor resistance not only lowers the speed at which the maximum torque is developed, but through restriction of the double-frequency flux-sustaining currents and imperfect rectification of the magnetic impulses, the maximum torque is greatly reduced, as the speed at which it is developed is lowered. This explains the characteristic of single-phase motors that they must operate at less slip than polyphase motors for efficient operation.

It also indicates that high reluctance means high double-frequency rotor currents involving high rotor $I^2R$ losses, irrespective of load, and thus the desirability of both low magnetic reluctance and low rotor resistance for efficient operation under running conditions.

While the single-phase squirrel-cage motor is a rotary field motor, it is in reality not a special case of a polyphase motor since the rotary field is not produced in the primary by the combined action of polyphase currents, but is produced in the secondary from an intermittent or single-phase primary excitation, through the sustained rotor flux, mechanically rotated by the motion of the rotor. This direct method of analysis by assuming single-phase conditions as they really are, rather than the indirect method of assuming special polyphase conditions which are more or less a mathematical fiction, seems to afford a much clearer insight into the interrelations of the various factors involved in the single-phase squirrel-cage motor.

**C. T. Button:** The comments by Mr. Bretch on the "Rotor Flux Concept of Single-Phase Induction-Motor Operation" (March 1937 issue) are very interesting. I do not interpret these comments as indicating that Mr. Bretch cannot agree with any part of the original paper; but he is apparently merely advancing some thoughts prompted by reading the paper.

It is felt that one should be as precise as possible; and particularly premises should be accurately stated lest they lead to increasing divergence from actual conditions as conclusions are developed.

At the outset of the discussion, then, we would not say that the theory "considers the rotor flux as substantially constant along a fixed diameter." The statement just quoted evidently refers to the condition at synchronous speed only and should so indicate. Also, the statement neglects the pulsating component in the quadrature rotor axis (plane of coil $A$ in Mr. Bretch's figure). This is important—lack of completeness and precision leads to failure to obtain an explanation of such things as the pulsating torque component, negative torque existing at synchronous speed, etc.

The statement that "the primary magnetizing impulses are rectified with respect to the rotor through its synchronous motion" is an interesting way of expressing the situation, but is also lacking in the same way in conveying an accurate mental picture. Figure 2 of the paper is a picture that it is difficult to convey in a few words.

The paragraph by Mr. Bretch beginning with "after the rotor flux is once established" seems to be rather foggy and not to contribute anything omitted from the original paper. The concluding expression "and tending to keep in synchronism" is misleading. At synchronism the torque is negative and hence the tendency is to drop below synchronous speed.

Again, "if we hold the rotor stationary and rectify the single-phase primary exciting current," we will not "reproduce in a stationary rotor the conditions existing — at synchronism." There is a pulsating torque at synchronous speed, with a net or average negative value. The primary object of the paper was to lead to a concept of conditions as they are, rather than as they might be represented by something else, which in the case of the suggestion mentioned, would be inaccurate.

As soon as one attempts to investigate currents in rotor "coil $A$" and "coil $B$" he finds himself involved to such an extent that the only way out is to set up the mathematical expressions for voltages or currents, and proceed by the cross-field analysis as developed by H. R. West. The trouble is that "coil $A$" is only in a purely "transformer" relation to the primary for a passing instant, and "coil $B$" is only out of the transformer (or in a pure "speed") relation for a transient instant. Discussion as to which coil produces the cross field, and what the phase relations are, is not within the intended scope of the paper.

Take the statement by Mr. Bretch, "Coil $B$ by speed action induces local currents opposing motion and producing torque." True, negative torque is produced opposing motion. But this is not motor action. Well, then, coil $B$ is to set up the cross field. But if so, how can it produce a field in the $x$—$x$ axis in time quadrature with the main field, since coil $B$ itself would lie in the $x$—$x$ axis when the main flux is zero and the cross field is maximum?

The so-called "transformer" voltage and "speed" voltage are in reality fundamentally identical phenomena. A voltage may be said to be generated in coil $A$ because of change in magnitude of flux through it; and a voltage is correspondingly generated in coil $B$ because of change in direction of the primary flux with respect to it. If the primary flux is at one instant in the plane of coil $B$ and the next instant at an angle $\alpha$ with respect to coil $B$, then the next flux at the second instant has a sine $\alpha$ component which has developed in the plane of coil $A$. Thus change in direction of flux in the neighborhood of the plane of coil $B$ means a change in the component of this flux in the plane of coil $A$, or in other words a change in flux through coil $B$. This is also transformer action of course.

Thus both coil $A$ and coil $B$ as well as every conductor around the rotor periphery have voltages induced in them due to change of flux linking them, which is in turn due to change in both magnitude and direction of the total flux with respect to them. To select 2 sets of conductors one of which at a certain instant has zero voltage due to change in flux magnitude while the other set has zero voltage due to change in flux direction cannot in the opinion of the writer be used in a simple manner to arrive at a complete concept of the basic phenomena of the operation of the motor in question. The point is emphasized that, for the

purposes for which the paper was written, it seemed desirable to deal with total entities rather than any of their various possible components.

It is not necessary to proceed further through the comments submitted by Mr. Bretch with replies. The object of the paper was to present a simplified concept, and the comments do not seem to increase the clarity, accuracy, nor completeness of the theory; but rather seem to do the reverse.

Some of the remarks of Mr. Bretch, however, may inspire the derivation of further conclusions on the basis of the theory outlined in the paper—such as variation of torque with slip or with change in motor constants, and behavior of the cross field at various values of slip both below and above synchronous speed.

## Dyadic Algebra Applied to 3-Phase Circuits

August 1936 issue, pages 876–82

## Complex Vectors in 3-Phase Circuits

December 1936 issue, pages 1356–64

**Author's closure of 2 papers by A. Pen-Tung Sah published in the August 1936 and December 1936 issues, and presented for oral discussion at the tensor analysis session of the winter convention, New York, N. Y., January 26, 1937.**

**A. P.-T. Sah:** Before answering some of the specific points that have been raised regarding the author's 2 papers on dyadic algebra and complex vectors as applied to 3-phase circuits, a reiteration of the viewpoint of these papers is perhaps helpful. One of the chief objects of the papers is to apply the method of Gibbs to 3-phase circuit theory. Whether Gibbs's dyadics should be considered to be obsolescent or not is a matter of individual opinion. In fact, the appearance of such work as Lagally's "Vektor Rechnung" in 1928 and A. P. Wills's "Vector and Tensor Analysis" in 1931 and other more recent articles of a purely mathematical nature on the extension of Gibbs's ideas are probably sufficient to show that Gibbs's work is not going in the direction of the scrap pile.

All engineers will probably agree that new concepts and relations will be more easily understood and grasped by the practical men if they are given in concrete rather than abstract form. It is due to this fact that in the exposition of the set of equation 1 of the dyadic paper (page 876) the author has arbitrarily introduced the orthogonal unit vectors **i, j, k** in order to show that the triad numbers, $e_a$, $e_b$, $e_c$, and $i_a$, $i_b$, $i_c$ may be considered as the orthogonal projections of 2 vectors and that the 9 $z$'s a dyadic operator used to change one vector to another. It is true that if we choose, we can resort to matrix interpretation of this set of equations. Indeed, as pointed out by Gibbs-Wilson in their book, a dyadic may be considered as a square matrix with 9 coefficients and a row or column matrix as a vector. To give a geometrical interpretation to the set of equation 1 may appear to be "irrelevant" to a pure algebraist but certainly should not be without assistance to an applied mathematician. An analogy in this case will perhaps make the situation clearer to the electrical engineer.

In the days when complex numbers were first studied, they have been defined as a dual number with 2 components $a$ and $b$ and written as $(a, b)$. The addition of 2 such numbers is then defined as $(a, b) + (c, d) = (a + c, b + d)$ while their multiplication as $(a, b)\ (c, d) = (ac - bd,\ bc + ad)$. If this is compared with the present universal notation $a + jb$ for $(a, b)$ and the definition of the product through the relation $jj = -1$, so that $(a + jb)\ (c + jd) = (ac - bd) + j\ (bc + ad)$, it is evident that the introduction of the imaginary unit $j$ has not only clarified the algebraic work but also made a geometrical interpretation of complex numbers possible. If J. Slepian should think that $j$ is not irrelevant to the interpretation of complex numbers, probably he can also be persuaded to give proper value to the introduction of the unit vectors **i, j, k** in the present papers.

As an unbalanced 3-phase circuit is of necessity more complicated than a single-phase circuit, so are the computations and the representations. In view of the present difficulties encountered in the formulation of a satisfactory definition of power factor in an unbalanced 3-phase system, the fact that there is a definite though varying angle between the voltage and the current vectors even for an unbalanced system should be further studied to see if there is a way out of the present complications. Those who think that the elliptical representation of unbalanced 3-phase systems to be not so good may want to withhold their final pronouncement until such a study has been completed.

Slepian has also suggested that the definition of the scalar product between two complex vectors might be more attractively given as:

$$\mathbf{X}\cdot\mathbf{Y} = X_1{}^*Y_1 + X_2{}^*Y_2 + X_3{}^*Y_3$$

so that the 3 vectors **u, f, b** would become mutually perpendicular. The suggestion is interesting but has 2 defects. According to the suggestion the steady-state complex power in a 3-phase circuit would be **E·I** (or **I·E**) instead of **E·I*** (or **E*·I**) as given in the present paper. Since in single-phase circuits, complex power is either $E^*I$ or $I^*E$ and not $EI$, the unsuitability of such a suggestion when applied to electric circuit theory is at once apparent. The second drawback of such a definition lies in the fact that it invalidates the commutative law for scalar products. In other words **E·I** would not equal **I·E** unless both $E$ and $I$ be real. The attendant inconvenience to the failure of the commutative law for the scalar product lessens a large amount whatever attraction the suggestion may have in other respects.

Referring to the discussion by G. Calabrese on the formula of the force between 2 elements of current-carrying conductors, it should be emphasized that the currents therein given are currents in conductors oriented in a physically real space and should not be confused with the current vectors used by the author.

The author agrees with Irven Travis in that any simplification in actual calculation of networks will be due to symmetry of impedances. Hence, there will be a good deal of lost labor in the solution of completely unsymmetrical systems by the method of symmetrical components. The merit of the present scheme of solution lies in its systematized organization of the otherwise numerous equations. It is gratifying to note that Travis and his students have used matrices to represent Stokvis-Fortescue transformation. In this connection the author would like to call attention to the advantages of using the author's expressions 56, on page 1362, having a different scalar multiplier from Travis's expressions 3 and 4. These advantages have been pointed out in reference 5 of the paper on complex vectors.

C. E. Rose has correctly pointed out a typographical error in equation 28$d$, page 881. As given by Rose, the equation is still not right. This error together with 3 others, one of which had been mentioned by C. A. Havill in his letter to the editor (ELECTRICAL ENGINEERING, page 1287, November 1936), were all noted in the printed paper but escaped [the author's] notice on the galley proof. They were communicated on August 17, 1936, to the editor who promised to correct them later. [**Editor's Note:** Complete corrections as supplied by the author were printed on the "errata" fly leaf of the 1936 TRANSACTIONS in accordance with established practice.] In view of the fact that the correction has not yet appeared, they are here reported in order to save the readers some trouble. The corrections are as follows:

1. Page 877, equation 3: All the 9 dyads should be united by plus signs and the dyad $z_{ab}$**ik** should read $z_{ab}$**ij**.

2. Page 881, second column, line 10: The words "up" and "down" should read "down" and "up," respectively.

3. Page 881, equation 28$d$: All the double vertical lines should be single vertical lines to denote determinants and the $j$'s in front of each determinant should be $j^2$.

4. Page 882, equation 31: A dot should appear between each one of the impedance dyadics and the current vectors.

Rose's opinion regarding the covariancy and the contravariancy of the impedance and the admittance, though correct, does not apply to the first paper, because the unit vectors used therein are all orthogonal and there is no distinction between covariant and contravariant measure-numbers. Hence the indices used therein have been lower ones even in case of the admittance. Further, as shown in the author's second paper and concurred to by J. Slepian in his discussion there are covariant and contravariant measure-numbers of the same vector and measure-numbers of various degree of covariancy and contravariancy for the same dyadic. It would be better to say that both the impedance and the admittance dyadic can be expressed in one of the four forms as shown by equation 52, page 1362.

The author wants to thank K. L. Wildes for giving the new method such a fair trial in teaching it to his students. At present the author must admit that the technique

of solving actual problems by such a method has not yet reached its best possible stage. Undoubtedly if more professors can be induced to teach the method to their students, the required technique would be improved rapidly.

As regards the merits of the present method when compared with that of symmetrical components in solving actual problems, a good deal depends on the background of the user and the unbalancing condition of the system. The author has made a side-by-side calculation of several problems using both the present method and that of symmetrical components. The results speak very eloquently for the present method because it requires shorter and fewer equations besides less numerical and algebraic work. This does not mean that symmetrical components should be superseded by the present method. It simply shows that the present method is a general one, including the symmetrical components as a special transformation. In fact when machinery problems are studied from the present viewpoint, the Blondel 2-reaction theory will also come under the present scheme as a simple orthogonal transformation of co-ordinate system.

## A New Thermal Fuse for Network Protectors

**Discussion and author's closure of a paper by L. A. Nettleton published in the October 1936 issue, pages 1096–9, and presented for oral discussion at the protective devices session of the winter convention, New York, N. Y., January 27, 1937.**

**C. P. Xenis** (Consolidated Edison Company of New York, Inc., New York, N. Y.): The thermal fuse described by Mr. Nettleton incorporates an interesting principle in fuse design. The heat is generated at one point of the fuse assembly, and the circuit is interrupted at another. By properly selecting and proportioning the metals and alloys at these two points he has been able to obtain a very desirable current-time characteristic with minimum heat dissipation.

The author of the paper gives some data on 2 types of "all copper" network switch fuses, in comparison with corresponding data for the thermal fuse. In this connection it may be well to point out, that extensive investigations and tests on "all copper" fuses for use in network switches have resulted in designs which possess current-time characteristics far superior to those of "all copper" fuses used heretofore in connection with network switches. The small volume of copper fused when the circuit is interrupted makes it possible to successfully enclose such fuses in small individual fireproof enclosures which confine the arc and thus protect persons who may happen to be standing close to the fuse at the instant of blowing. This advantage, coupled with the relative simplicity and low cost of "all copper" fuses are points well worth considering in comparing with other types of construction.

Experience in the operation of distribution systems points definitely to the desirability of increased fuse protection wherever large amounts of equipment and cable insulation are liable to be in contact with the overheated conductors and arcs resulting from electrical failures. The thermal fuse, and other types of fuse designs which will adequately protect insulation from high copper temperatures and properly interrupt heavy short circuits constitute developments which will find several useful applications in energy distribution.

**F. E. Johnson, Jr.** (New Orleans Public Service, Inc., New Orleans, La.): I am glad to note that network protector fuses are now available which "follow through" the thermal-time curve of the transformer they are designed to protect. Attention was called to the need of such a fuse in connection with the discussion of a previous paper ("Developments in Network Systems," Brosnan and Kelly, AIEE TRANSACTIONS, July 1929, page 975) wherein the requirements of an ideal fuse were given. It was brought out at that time that the ideal fuse curve would lie just below, but parallel to, the safe thermal-time curve of the transformer. Figure 3 of the present paper indicates that the shape of the new fuse curve is practically ideal.

There are one or 2 points, however, which I believe warrant further discussion. The

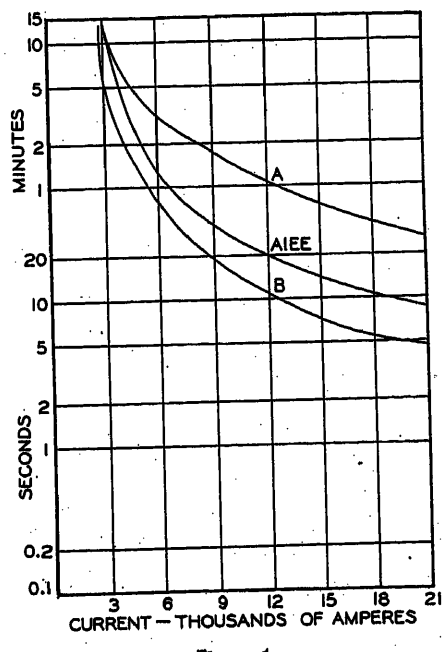



Figure 1

first of these concerns the permissible loading curve for a 500-kva network transformer, as shown in figure 3. Very little is definitely known about the life of transformers under short time overloads, and as a consequence the manufacturers have been somewhat hesitant about supplying curves which give allowable safe operating times for definite overloads. At the present time, however, the AIEE transformer subcommittee on electrical machinery has issued a proposed curve on short-time permissible overloads of network transformers 500 kva and smaller ("Proposed Transformer Standards," J. E. Clem, ELECTRICAL ENGINEERING, January 1937, page 32). This curve is to serve as a guide for intentional daily overloading (longer portion of curve) or emergency accidental short circuits (less than 5 minutes duration). For purposes of comparison, I have repeated curves *A* and *B* of figure 3 of the author's paper and have drawn in the proposed AIEE curve.

I have included the AIEE curve in order to draw attention to the need for standardization in applying the fuses to network transformer overload curves. In the present case, for instance, at 12,000 amperes the allowable overload time according to AIEE Standards is 20 seconds, while curve *A* gives a time of about 65 seconds, or over 3 times as long. Either the AIEE curve is very conservative or the operating company is willing to overload their transformers for higher final temperatures than was contemplated by the AIEE committee. Of course, in the present instance, the fuse would actually blow before the temperature set up by the AIEE curve was exceeded. In other applications, however, this might not be true. I would be interested in knowing what maximum copper temperatures were expected by Mr. Nettleton when curve *A* was drawn. If we apply the fuses on the basis of the AIEE curve in every instance, I believe that the transformer manufacturers would consider the action sufficiently conserative not to materially reduce the life of the transformer.

I would also like to ask Mr. Nettleton if fuses of this type have been developed for other sizes of network transformers.

**J. S. Parsons** (Westinghouse Electric & Manufacturing Company, East Pittsburgh, Pa.): 1. The engineers of the Brooklyn Edison Company have, I feel, made a very important contribution to the art of fusing network protectors by developing the new low melting alloy fuse described by Mr. Nettleton. The Westinghouse company has been manufacturing fuses of this type for more than 2 years, first for the Brooklyn Edison Company and later for a considerable number of other companies operating low-votage a-c network systems.

2. The earlier fuses were built just as described by Mr. Nettleton and shown in figures 1 and 2 of his paper. Due primarily to manufacturing difficulties, however, some changes have since been made and others are now about to be made in this fuse.

3. As Mr. Nettleton has pointed out, the mounting ends of the fuse are bent at a slight angle from the mounting plane so as to prevent the possibility of the copper straps coming too close together or touching after the alloy has melted even though the mounting surfaces are poorly aligned. This construction puts the alloy slab under tension. To reduce this stress the copper strap portions of the fuse are now made of 2 or more copper laminations, depending upon the size of the fuse, instead of being made of a single heavy copper strap. The use of 4 laminations instead of a single copper strap reduces the stress on the alloy slab approximately 50 per cent. This reduces the possibility of the fuse opening mechanically due to the breaking of the bond between the copper and the alloy while in service. To guard against the possible mechanical opening of a fuse in service

because of the stress mentioned and those which may result from expansion and contraction of the protector, each fuse is given a tension test of 250 pounds. The failure rate under this test in production runs as high as 25 or 30 per cent failures due to the difficulty of getting a good bond between the copper and the cadmium-lead-tin eutectic alloy. Because of this we propose to change to the second alloy mentioned by Mr. Nettleton which is a eutectic mixture of lead and tin. It is very much easier to get a good bond between this alloy and the copper. A considerable number of these fuses have been built and tested at 1,000 pounds tension without a single case of failure. As a matter of interest, I might mention that one of these fuses, using the lead-tin eutectic alloy and having a minimum blowing current of about 2,800 amperes, was put under a continuous tensile stress of 500 pounds and tested for a week carrying 2,000 amperes for 8 hours and no current for 16 hours each day without being damaged. We are also considering the use of a $\frac{1}{16}$-inch diameter "nichrome" rivet through the alloy and copper to give an added factor of safety against mechanical failure.

4. The difficulties we have had with this low melting alloy fuse have all been mechanical and the changes mentioned should entirely eliminate them. The same current-time curve can be secured using the tin-lead eutectic alloy and the nichrome rivet as we have been getting with the cadmium-tin-lead eutectic alloy. The change in alloy will also have a negligible effect on the watts loss in the fuse. In this type of fuse only a small part of the total loss is in the alloy. For example, in the case of the fuse normally supplied on a 1,600-ampere protector only about 18 per cent of the loss is in the alloy. Mr. Nettleton has pointed out that the loss in this fuse is only about 25 per cent of that in the copper fuses the Brooklyn Edison Company previously used. The loss in the alloy fuse is also roughly only 50 per cent of the loss in the zinc fuse which we have supplied in the majority of our network protectors in the past. This fuse is also considerably shorter than the zinc fuse. Because of this, its improved current-time characteristics, and its decidedly lower loss we have used this low melting alloy fuse in our new type *CM*-22 heavy duty network protector. This fuse can also be used to replace the zinc or copper fuses supplied in most designs of our type *CM*-2 protector.

5. Since we adopted this fuse as standard on the type *CM*-22 protector I have been asked many times whether the gap which is left after the alloy melts is adequate to definitely open the circuit. We have naturally made a large number of interrupting tests on this type of fuse, and have successfully opened currents ranging in magnitude from the minimum blowing current of the fuse to 59,000 amperes root-mean-square with a recovery voltage across the blown fuse of approximately 208 volts. The normal gap between the outer end of the copper straps is $\frac{1}{8}$ inch, however, when the fuse blows on high values of current the magnetic forces bend the straps away from each other. After opening 59,000 amperes the gap between the outer end of the copper straps was about $\frac{3}{4}$ inch.

6. Mr. Nettleton mentions a critical current above which the fuse will blow in the bend of the copper strap. We found this critical point to be at 20,000 amperes root-mean-square on the fuse normally used on an 800-ampere protector, however, this critical point was not reached at 59,000 amperes root-mean-square on the fuse for a 1,600-ampere protector.

**J. A. Brooks** (Consolidated Edison Company of New York, Inc., New York, N. Y.): The last decade has seen a great increase in the extent of low-tension a-c networks. A great deal of time and effort has been expended in studying network requirements and in developing and improving network equipment. The automatic network protector has received a large share of this attention and has reached a high degree of perfection. In view of all this it is indeed surprising that so little has been accomplished toward improving the fuses used with network protectors.

As Mr. Nettleton stated in his paper, fuses were originally installed in series with network protectors to insure interrupting heavy back-feed currents from the network toward the primary feeder in cases where the network protector fails to trip. At that time the fuses were not regarded as essential for protecting the transformer against overloads and probably would not have been used at all if the network protector could have been trusted to operate correctly in every case of back-feed current.

The fuse originally used was the copper link fuse which was the only kind readily available. One disadvantage of this fuse is the high melting point which requires high losses in order to blow. At ordinary loads the losses are sufficiently high to reduce the rating of enclosed type network protectors. Another disadvantage is that the fuse operates too rapidly and often blows prematurely on short circuits in the network grid. On the other hand, it is possible to overheat and damage the transformer on currents that are not quite large enough to blow the fuse.

In recent years we are awakening to a realization of the dangerous overloading of equipment that may result from a partial shutdown of a network or that may occur when attempting to reenergize a dead network. Most improvements in network engineering are associated with actual operating experience. In the case of extremely rare but severe contingencies such as a partial or complete shutdown of a network area we cannot wait for experience to teach us the best procedure. Although we all hope to escape such a castastrophe as a network shutdown, it nevertheless is necessary to give careful consideration to plans for minimizing as far as possible the area affected, and for starting up the dead sections as promptly as possible. In view of the loss of capacity due to damage that may accompany a shutdown it is vitally important to be able to take advantage of available capacity up to the maximum permissible limit of loading.

The copper link fuse is a handicap to operation since its premature blowing on high currents may contribute toward shutting down networks and will hamper efforts to start up. At the same time the high minimum blowing current may permit the burning out of transformers and associated equipment. It would appear that "back up" protection is no longer the sole function of the fuse. The fuse is essential to provide overload protection and its characteristics should be such that it will only function as a last resort to prevent costly and embarrassing damage to equipment. When a satisfactory fuse is available to meet this requirement, a great advance will have been made. Such a fuse must be reasonably simple in construction, must have low losses, must be able to interrupt maximum currents, must be consistent in performance, must be stable under repeated heating and cooling, must be harmless to nearby workmen and must be available at a reasonable cost.

The use of a low melting point alloy in the fuse has inherent advantages in that the fuse operation becomes to a large extent dependent upon transformer and network-protector temperature. Starting cold at full load, for example, the fuse immediately takes a certain temperature rise above the network protector buses. The network-protector temperature rises more slowly, leveling off after 2 or 3 hours and after that increases at a very slow rate as the transformer and manhole warm up. A moderate overload that would blow the fuse in a few hours when the transformer and protector are already hot might require from one to 2 days when starting cold. On larger overloads the fuse blows without waiting for the other equipment to warm up but the time of operation will vary considerably according to the initial temperature of the equipment. In other words this type of fuse takes all possible advantage of any additional overload capacity that may be available.

The fuse described in Mr. Nettleton's paper meets most of the desirable requirements for a network protector fuse. Further development along this line may produce a fuse which comes even closer to meeting all the requirements.

**L. A. Nettleton:** The AIEE time-current curve for transformers, referred to by F. E. Johnson, Jr., shows the maximum duration of overloads that can be permitted without reducing the normal expected life. Curve *A* is based upon winding temperatures ranging from 125 degrees centigrade for 10 minutes up to 180 degrees centigrade for 25 seconds which will cause some deterioration and will probably shorten the life of the transformer to some extent.

The fuse must protect not only the transformer but also the network protector and connected cableleads. The network protector and leads have less thermal capacity than the transformer and may overheat first on overloads. The new fuse operates in sufficiently short time to be sure of protecting the network protector and leads in addition to the transformer.

Low losses are important for fuses used with enclosed network protectors, but where the protectors are not enclosed the losses are unimportant. Copper fuses require high losses to attain the necessary high fusing temperature. A design of copper fuse having a suitable time temperature characteristic, as mentioned by C. P. Xenis, should be satisfactory for use with non-enclosed protectors.

There is a wide variation in the permis-

sible overload that the transformer and associated equipment can withstand, depending upon the initial temperature. The fusible alloy used in the new fuse melts at such a low temperature (about 145 degrees centigrade) that the fuse operation is strongly influenced by the temperature of the network protector buses to which it is bolted. The fuse will, therefore, allow much greater overloading when the network protector is cold as compared to conditions where the protector is hot. Substitution of a metal or alloy having a higher melting temperature will reduce the ability of the fuse to distinguish between high and low initial temperatures of the equipment.

This fuse was developed for use with 500-kva network units which are used almost exclusively in Brooklyn. It can, however, be readily adapted to other ratings by changing the thickness of the copper straps.

This fuse meets most of the desired features enumerated by J. A. Brooks, the principal difficulty being the mechanical weakness discussed by J. S. Parsons, which results in an occasional fuse breaking open sometime after installation. However, it should be possible to correct this difficulty after further development.

## A New Service Restorer

**Discussion of a paper by E. F. Sixtus and W. R. Nodder published in the January 1937 issue, pages 180–2, and presented for oral discussion at the protective devices session of the winter convention, New York, N. Y., January 27, 1937.**

**D. C. Prince** (General Electric Company, Philadelphia, Pa.): The service restorer described by Messrs. Sixtus and Nodder should prove effective in improving service on lightly loaded lines to a considerable extent. It would appear that it gives somewhat the same performance as a repeater fuse but, of course, has the advantage of being totally enclosed and consequently better protected from the weather. It has in common with the fuse a property of operating a total of only 3 or 4 times before it must be serviced, although at such service intervals the only expense may be that entailed in sending a line man to its location.

Both the "service restorer" and the repeater fuse are open to the objection that they represent an unknown hazard to service. When they are first installed, or immediately after having been serviced, they can ordinarily be depended upon to open and reclose in the event of a temporary fault. However, after any storm there will immediately be a question as to the condition of all such devices; how many will have operated, how many will have operated more than once, which installations require immediate attention, and which require no attention at all. For these reasons, it seems as though the specifications outlined in the 7 points of the paper should be amplified somewhat, as:

8. The device after having reclosed any number of times short of the complete cycle to lock out should reset itself in a relatively short time to its original condition.

9. In the event of a persisting fault, the device should lock out after the complete cycle of trips and reclosures and then require manual reclosure after the fault has been removed.

10. The device should require no servicing until after lock out caused by a persisting fault and then it should require only manual reclosing after the cause of the fault has been removed; or in case of no lock out if should require servicing only at infrequent intervals, such as 6 months to a year.

On oil circuit breakers immediate reclosure serves a very useful purpose because from 75 per cent to 90 per cent of faults are of the nonpersisting type and are cleared after a single trip and reclosure. On the small service restorer, or oil circuit recloser, this feature is not so important, providing the reclosing time is relatively short, in fact a small time delay may often be beneficial.

Specification number 6 is not universally applicable. A very large fraction of all distribution lines serves single phase lighting and motor circuits. For such service, single-pole devices in the single-phase branches afford adequate protection. A triple-pole device in the 3-phase line would, in case of a persisting fault, unnecessarily interrupt service on some of the single-phase branches not in trouble.

In designing the *FP*-19 recloser, the possibilities of spring and weight operation as well as local battery were considered. As pointed out, the use of short circuit current is obviously the most attractive, but was discarded by the authors because they saw no way of securing a low enough trip current. The recloser, however, does operate at a sufficiently low tripping current without either the complication or cost of the alternative arrangements. There are doubtless applications for which a 3-pole device is essential and in which the limitation of 3 or 4 operations only between servicing will not be a prohibitive objection, for which applications the "service restorer" should prove of value.

## Ultrahigh-Speed Reclosing of High-Voltage Transmission Lines

**Discussion and authors' closure of a paper by Philip Sporn and D. C. Prince published in the January 1937 issue, pages 81–90, and presented for oral discussion at the protective devices session of the winter convention, New York, N. Y., January 27, 1937.**

**I. W. Gross:** See discussion, page 1038.

**T. G. LeClair** (Commonwealth Edison Company, Chicago, Ill.): The paper by Messrs. Sporn and Prince is very timely, because it describes a new and important step in the art of furnishing greater reliability of service for transmission systems. The practical development of 6-cycle circuit breakers and one-cycle relays has made possible this forward step, the prevention of service interruptions on a single-circuit, high-voltage transmission line. The laboratory and field tests indicate that the reclosing mechanism is satisfactory and that the new device can be expected to have a number of applications.

It is not possible, and the authors have not attempted to make a general statement that reclosing circuit breakers could be used to prevent service interruptions on all single-circuit transmission lines. It is indicated that, with reasonable development, commercial circuit breakers can be made which will reclose within the minimum time allowable to prevent undue risk of restriking an arc on the transmission line. The question of whether or not this time will be short enough to prevent service interruption is a function of the system conditions rather than a function of the characteristics of the relays and circuit breakers. To know whether this principle can be applied, the important question is whether or not during the momentary interruption of the circuit the rate of acceleration of equipment at the sending end of the line and the rate of deceleration at the receiving end of the line will be too rapid to avoid instability.

On a system such as the one where the tests were made, the interconnection is between 2 large generating systems, each with a capacity of over 1,000,000 kva. In this case the inertia in each of the 2 systems is such that the frequency of neither system will drift rapidly at the moment the interconnection is broken. Therefore, the chances of successful reclosure are appreciably greater than they would be if the 2 systems were only $^1/_{10}$ as large with the same power flow through the circuit under test.

An interesting example of the possibility of reclosing circuit breakers is the 132-kv interconnection from Powerton station to Waukegan station in Illinois. One circuit of this interconnection is supplied by a single, 50,000-kw generator and carries a load of 50,000 kw distributed over more than 200 miles of circuit. A set of reclosing circuit breakers between the Powerton generator and the next adjacent load would be useless to prevent service interruptions, because the Powerton genertor would accelerate too rapidly when its full load was suddenly interrupted. However, a reclosing circuit breaker near the Waukegan end of the long transmission system could be used very effectively to prevent service interruption, because the load on the circuit between Powerton and Waukegon is great enough to prevent the Powerton and Waukegan systems from drifting apart rapidly.

This reclosing scheme could also be used very effectively to improve service to relatively small important loads carried from a high-voltage interconnected system. By the use of reclosing circuit breakers on a branch line with a single circuit, it should be possible to maintain a standard of service very nearly equal to that to be obtained on the orthodox double-circuit tower line.

**A. C. Schwager** (Pacific Electric Mfg. Corporation, San Francisco, Calif.): The authors are to be commended for contributing valuable information on a subject which promises to become of major importance in the improvement of continuity to service on transmission lines. The field as well as laboratory tests reported show that a large percentage of arc-overs on lines can be cleared by means of an extremely short service interruption.

It is interesting to note that the special reclosing mechanism is of the spring actu-

ated type, the authors apparently realizing that the conventional solenoid control is not feasible for application to such high speeds.

The restriction of the opening stroke to 8 inches appears to be a serious limitation to the general application of this mechanism.

Although the arc length during all the tests was of 7 inches or less cases will have to be anticipated where longer arc lengths must be expected. Reference is made to an AIEE paper by Messrs. Spurck and Skeet, "Circuit Breaker Field Tests on Standard and Oil-Blast Explosion-Chamber Oil Circuit Breakers," figure 9 of which shows that on a different 132-kv system arc lengths of 14.5 inches were recorded. It would be interesting to know if reclosing in this case could be accomplished without a radical change in mechanism design and without increase in the reclosing time.

The company with which the writer is associated has also designed and built a motor-operated spring-actuated mechanism suitable for ultrahigh-speed reclosing. This mechanism gives full initial opening stroke to the blades with a de-energized interval of 17 cycles. A 69-kv breaker equipped with this mechanism is in service since February 1936, a 115-kv installation having been recently completed. A paper is being prepared by the writer giving detail information on construction and field experience.

**R. D. Evans** (Westinghouse Electric & Manufacturing Company, East Pittsburgh, Pa.): 1. The authors are to be commended for their work in obtaining operating experience on high-speed reclosing breakers. Of particular value is the data on the time necessary to avoid fault re-establishment upon circuit re-energization.

2. The problem of maintaining service continuity on systems with synchronous machines (or the stability problem) has been

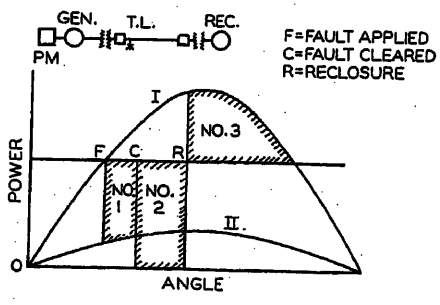



**Figure 1. Power-angle diagram for reclosure, single-circuit case**

I—Curve for normal circuit
II—Curve for fault condition (2L-G)
For stability, areas (1 plus 2) < area 3

one of particular interest to me. A number of years ago some of my associates and I proposed the high-speed clearing of faults as a means of improving system stability. This proposal was followed almost immediately by one to use high-speed reclosure to improve stability. U.S. Patent 1,899,613, filed in 1929, employed high-speed reclosure at high voltage and a superposed frequency relay scheme to obtain high-speed simultaneously opening of circuit breakers. Considerable development has been required to bring these schemes to commercial use, and the high-speed fault clearing scheme being simpler came into use first. As a part of the general investigation of high-speed reclosure, work was carried out by Messrs. Griscom and Torok, as mentioned by the authors, in order to determine the de-energizing time necessary to prevent re-establishing the arc.

3. The paper does not discuss the stability features of the problem, that is, the

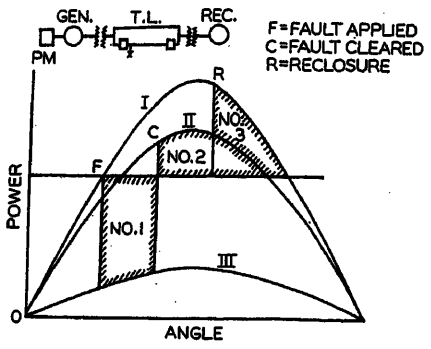



**Figure 2. Power-angle diagram for reclosure, 2-circuit case**

I—Curve for 2 lines (normal)
II—Curve for one line (normal)
III—Curve for fault (2L-G)
For stability, area 1 < (areas 2 plus 3)

relation between the fault clearing and reclosure time to the amount of load that can be carried with stability. For this reason 2 illustrations have been prepared to discuss this phase of the problem in general terms. Figure 1 assumes a simple system in which power is transmitted from a generator over a single-circuit transmission line. The line is assumed to be subjected to a fault requiring isolation to suppress the arc. This is followed by reclosure to improve stability. The power-angle diagrams for the different conditions from the application of the fault to the subsequent reclosure are shown in the figure. Stability will be secured if the sum of areas number 1 and number 2 is less than area number 3. It is of some interest to point out that for 2 breakers with equal reclosing time without arc re-establishment, the one with the slower fault clearing time will be more favorable from the stability standpoint.

4. High-speed reclosure is also applicable to improve the stability of two-circuit transmission systems illustrated in figure 2. The power-angle diagrams for this case are somewhat different than for the single-circuit case of figure 1. In this case stability will be secured if area number 1 is less than the sum of areas number 2 and number 3. The size of area number 3 is a measure of the advantage secured by high-speed reclosure.

5. In connection with the application of reclosing breakers to either single-circuit or double-circuit systems, considerable improvement in stability will be secured if the sending-end machines are not greatly unloaded during the fault condition. Hence, artificial means for loading the sending end may prove valuable in combination with reclosing circuit breakers. Such artificial loading may be obtained by the "stabilizing" resistors, the use of neutral resistors, and other measures. Such a combination may avoid the necessity for unduly high speed in reclosing breakers and make possible the use of simpler tripping mechanism than would be feasible otherwise, thus reducing first cost and maintenance expense which are obviously desirable.

**V. M. Marquis** (American Gas and Electric Company, New York, N. Y.): Ultrahigh-speed reclosing of high-voltage transmission lines places the transmission system, and especially important tie lines between systems or sections of systems, in an entirely new light. It is only necessary to consider that ultrahigh-speed reclosing allows a line to trip out and reclose without losing synchronism between systems in order to realize the field which is opened up by the development of this equipment.

Many important developments have been made for combating lightning on transmission lines but all cases of trouble do not result from lightning, so that even if the lightning problem were solved, there would still be cases where transmission line faults would cause interruptions. Ultrahigh-speed reclosing, however, offers a definite possibility for insuring substantially continuous service of lines on which it is applied.

After the successful results with the ultrahigh-speed reclosing on the Fort Wayne-Marion line, described in the paper, studies were made with reference to the application of ultrahigh-speed reclosing to the Twin Branch-Fort Wayne line. Figure 3 shows this line which is part of the Ohio-Indiana high-voltage transmission system of the American Gas and Electric Company. This line between Howard and Twin Branch forms a very important tie and it is essential that its continuity of service be maintained. The large interconnected system, of which the section shown is a part, normally has some 7,000,000 kilowatts of capacity in service; of this, approximately 2,000,000 kw of capacity is west of Fort Wayne and 5,000,000 east of Fort Wayne.

At the time this study was started, this double-circuit line had only one circuit installed, and calculations were made to determine the speed of reclosing required for various amounts of load transmitted over this tie line. With the present single circuit, it is possible to carry about 100,000 kilowatts over this line and maintain proper voltage. The calculations indicated that it would be possible to deliver this amount of power if the total time of separation was kept to about 30 cycles. The calculated curve showed that this amount of power could be increased to approximately 140,000 kw for a 12-cycle total time of separation and to approximately 160,000 kw for a 6-cycle total time of separation.

In general it can be stated that for single-circuit operation, the amount of power that can be carried through a disturbance with rapid reclosure of the faulted circuit increases appreciably as the time of separation between the systems is decreased. This, of course, indicates the desirability of keeping the fault and reclosing time to a minimum even though the systems are large.

Since these first studies were made, it has

been decided to double-circuit this line and further checks were made to determine the advisability of ultrahigh-speed reclosing for both circuits. This showed that, with double-circuit operation, rapid reclosing for faults on one of the circuits would make it possible to transmit appreciably more power by reclosing the faulted circuit than if this circuit were not reclosed. In general, it can be said that the gain to be realized by successful reclosing of the faulted circuit increases with the increase in the distances between high-tension bussing stations and also with the increase in size of the 2 systems to be interconnected. In this case, however, it is obvious that the speed of reclosing of the second circuit is not critical. For double-circuit faults, rapid reclosing on both circuits is particularly advantageous and in general to obtain full benefits in connection with a double-circuit line, both circuits should have ultrahigh-speed reclosing.

There still remains one unknown in connection with reclosing a faulted transmission circuit and that is the question whether the arc would be sufficiently deionized that it will not restrike when the circuit is reclosed. This has to be considered in connection with reclosing the faulted circuit of a double-circuit line, for if the faulted circuit is reclosed and the arc restrikes when reclosed, then the system would be disturbed more than if this circuit had not been reclosed.

In the case cited, the systems on either side of the tie line in question are very large and have correspondingly high inertias. Cases involving a single hydro plant connected to a large steam system or even a small steam plant or system connected to a larger system will require much faster reclosing. However, even in this case there is a possibility that upon reclosing, the smaller plant or system will pull into step. Each case should, of course, be carefully analyzed to definitely determine the gain to be realized in using ultrahigh-speed reclosing. This analysis should not only determine if the systems will lose synchronism but also determine, if synchronism is lost, whether synchronism can be quickly regained without undue disturbance to the systems if reclosed—that is, there may be some cases where there is a definite advantage in reclosing even though synchronism is momentarily lost.

Ultrahigh-speed reclosing seems to offer such large gains that its application should be seriously considered on all high-tension lines where their continuity of service is a major factor in the operation of the system. There are obviously still some unknown quantities in connection with the application of ultrahigh-speed reclosing. It is hoped that others will help in thoroughly investigating their unknowns to make this new tool in the art of transmission a thoroughly reliable one.

**J. B. MacNeill** (Westinghouse Electric & Manufacturing Company, East Pittsburgh, Pa.): High-speed reclosing is a natural corollary to high-speed circuit interruption. The reduced arc energy and depreciation of contacts and oil associated with modern interrupters makes it feasible to restore service without waiting for the circuit breaker to vent gases and establish dielectric strength.

To illustrate the growth of reclosing service, reference is made to data presented to the electrical equipment committee of the Edison Electric Institute for the year 1935

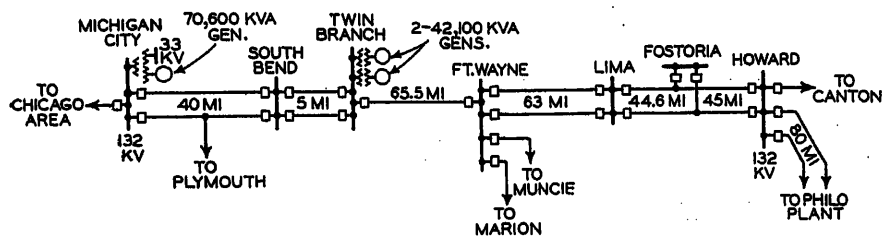



Figure 3

covering 3,680 reclosing operations on all voltage classes from 2.3 kv to 110 kv. First reclosure was successful in 78 per cent of these cases, subsequent reclosure was successful in 10 per cent, and there remained 12 per cent of lockouts.

The paper by Griscom and Torok in the *Electric Journal* for May 1933 gave at this relatively early date a good approximation of the limitations imposed by deionization of the arc stream upon the possible speed of reclosure. Other contributions have since been made, and there appeared in ELECTRICAL ENGINEERING for October 1936 an interesting paper by Pearce, Powers, Stewart, and Heberlein covering the application of carrier relaying and rapid reclosing of a 110-kv line which acted both as a trunk interconnection and a load feeder. The paper now under discussion by Messrs. Sporn and Prince adds considerably to our knowledge of the subject.

The method and apparatus used for securing high-speed reclosure by the authors is novel. By means of a very powerful duplex operating mechanism they were able to get reclosure in 16 cycles from the time the tripping impulse was given; but to secure this time the breaker was permitted to open only 8 inches. This is only a fraction of the normal travel of a circuit breaker for 138-kv service, and it would seem encroaches definitely on factors of safety for circuit interruption. There is no assurance that all types of short circuit can be ruptured at this voltage and under all operating conditions with an 8-inch stroke.

The writers summarize by stating:

"If reclosing is to be at a long enough interval to give little probability of a restrike, voltage must not be applied to the line for about 12 cycles after the arc has been interrupted. With an 8-cycle breaker this gives 20 cycles for the over-all reclosure time. At the other extreme, reclosure after 2½ cycles will be successful sometimes. If a flashover is caused by multiple lightning strokes, some reclosures longer than 20 cycles over-all may well be followed by restriking. For that reason the final limits will not have been determined until after a considerable period of experience under actual service conditions."

Since this appears to be the case, then we should investigate carefully to see if the necessary reclosing functions cannot be obtained at moderate expense and with relatively simple mechanisms. Admittedly the mechanism used by the authors is very expensive and complicated and will possibly be difficult to maintain in satisfactory operating condition.

As an illustration of what can be accomplished by relatively simple means, figure 4 shows the operating mechanism on a 3-pole 115-kv circuit breaker of large capacity normally operated from a battery, but on a recent job furnished with a "rectox" built into the mechanism for operation from an a-c source. This mechanism is practically a standard solenoid of simple and sturdy construction arranged with some features to adapt it to high-speed reclosure, such as improved relationships between the power requirements of the breaker and the physical efforts of the solenoid at different points of its stroke.

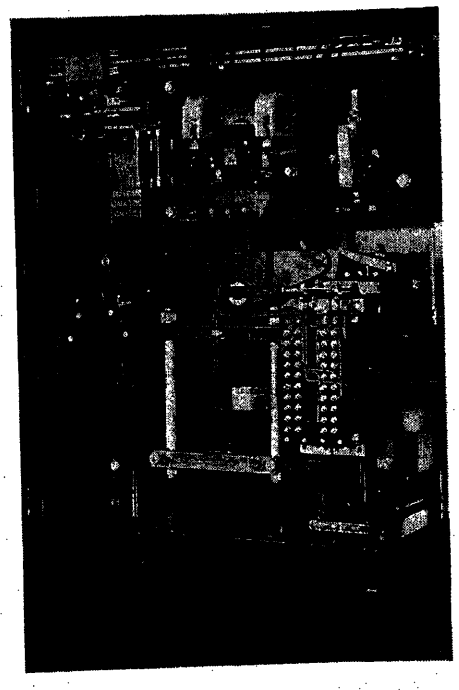


Figure 4

Figure 5 shows an oscillogram of the operation of this breaker consisting of tripping followed by reclosure, in which the breaker is permitted to reach a travel of 21 inches, or 75 per cent of its total stroke before reversing the downward movement of the contacts. This length of stroke obviously gives a large factor of safety for circuit interruption, and had this distance been encroached on to speed up the reclosing action, the time for opening and reclosing could have been materially reduced.

Of course, the high-voltage apparatus presents a more difficult problem than low

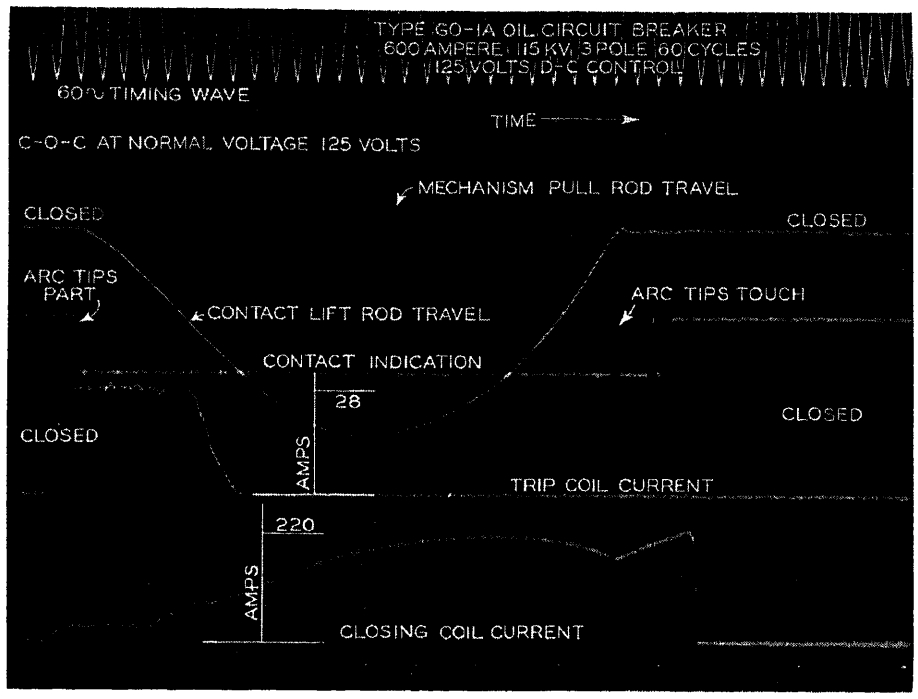



**Figure 5**

voltage, and the elapsed time for such voltages as 230 kv will be greater than on smaller devices. Considering, however, the nature of the elements involved and the necessity for having assurance of original fault deionization before reclosure is made, it seems wise to conclude that practically all reclosing requirements—at least at moderate voltages—can be taken care of with relatively simple and inexpensive mechanisms.

In discussing this subject it is well to remember that a reclosing time consists of two parts: first, the time to open the short circuit; and, second, the time to reclose the breaker. For a given total time consumed by the reclosing cycle, it is very desirable that a minimum amount be taken up by circuit rupture, leaving as large a share as possible available for reclosure. This division of the time will insure better circuit breaker action, less depreciation of line material and circuit breaker parts, and increased assurance that the original short will have been deionized at the time reclosure is complete.

**E. E. George** (Tennessee Electric Power Company, Chattanooga): From the standpoint of transmission companies, Sporn and Prince and their associates have apparently made one of the most important developments presented to the Institute in several years. Rapid reclosing of tie lines does not necessarily mean that one line will do all of the work of 2 lines heretofore, but it should mean that one line will do most of the work most of the time. The authors have actually accomplished and put in practice what some of us have only talked about. Differences of opinion about details should not detract from the luster of an outstanding accomplishment, so it may perhaps be pardonable to discuss the term "ultrahigh-speed" as applied to reclosing. The following definitions have been taken from the dictionary. "Ultra" means beyond familiar limits and indicates ordinarily something of microscopic or astronomical dimensions.

"Immediate" means consecutive, "instantaneous" means as fast as possible—with no intentional delay. This is why some of us have always preferred the name "instantaneous reclosing." Regardless of what name is used the principle will still be readily accepted by operating men.

In conclusion, it would seem that the authors have perhaps been too modest and too conservative in describing the utility and general application of this new development.

**Philip Sporn** and **D. C. Prince:** The authors are highly gratified by the reception this paper has received. All the discussion has been of such constructive character as to add materially to the value of the paper.

Mr. LeClair points out that longer reclosing time is available between large systems because of their high inertia, while smaller systems would generally lose synchronism.

Mr. Marquis develops this point further, showing actual case studies and indicating possible advantages of ultrahigh-speed reclosure even with double circuits and even in some cases though synchronism is lost momentarily. Mr. Evans has contributed stability diagrams indicating an advantage in stability from slower fault clearing while Mr. MacNeill indicates the desirability of minimum time in circuit interruption. This difference of opinion is only superficial, since the minimum time between circuit interruption and reclosure is fixed by nature rather than the over-all time of Mr. Evans's hypothesis.

Both Messrs. MacNeill and Schwager comment on the breaker contact travel and the size and complexity of the reclosing mechanism. The contact travel required is a function of the arc-extinction device. In this case 8 inches proved quite adequate for 138 kv. Had the breaker failed to clear in 8 inches the second mechanism would have opened it full stroke. Since mechanical stresses go up as the square of velocity, the minimum stroke was preferred for mechanical reasons.

The complexity of the mechanism was due to its many features of adjustability. Now that the ultimate requirements are known, much smaller departures from standard mechanisms are required.

Mr. Gross points out the possibilities of simplification of line construction by the use of ultrahigh-speed reclosure. The extent to which such simplifications will prove practical must be determined by field experience which everyone will watch with great interest.

Mr. George very modestly refrained from mentioning the important part which he and Mr. Logan have played in the development of "instantaneous" reclosure. They have shown what it is possible to do with standard mechanisms. It was the purpose of the authors in undertaking the development covered by the present paper to study and find out how much more is possible if mechanism and circuit limitations are removed, leaving only physical phenomena limitations to indicate what may or may not be done. The results, I believe, have indicated that speeds of reclosing much faster than any heretofore contemplated are possible. From this point the economics of reclosing must be developed by further system study and particularly by field experience, the final proving ground of all developments.

## The Control Gap for Lightning Protection

**Discussion and authors' closure of a paper by Ralph Higgins and H. L. Rorden published in the September 1936 issue, pages 1029–34, and presented for oral discussion at the protective devices session of the winter convention, New York, N. Y., January 27, 1937.**

**K. B. McEachron** (General Electric Company, Pittsfield, Mass.): As pointed out by the authors, the sphere gap (if used within proper limitations of spacing) gives a substantially uniform field and therefore has a relatively flat volt-time spark-over curve, while the rod gap, because of its nonuniform field has a volt-time curve which rises rapidly as the time to spark-over is decreased. As a protective device the sphere gap has excellent impulse characteristics and might have been widely used if it did not have 3 inherent disadvantages which are rather serious:

1. The wet 60-cycle spark-over is from 1/2 to 1/3 of the dry value which means that if a level of 3.5 (Lewis and Foust have shown that 13 per cent of switching surges exceed 3.5 times normal voltages: see "Lightning Investigation on Transmission Lines—II," W. W. Lewis and C. M. Foust. AIEE TRANSACTIONS, volume 50, December 1931, page 1139) times normal is established as the lowest permissible spark-over value for switching surges the sphere gap could not be expected to hold the impulse voltages to less than from 7 to 10.5 times normal, which would not be suitable since the present impulse test gap for transformers rated above 25 kv is between 6 and 7 times normal.

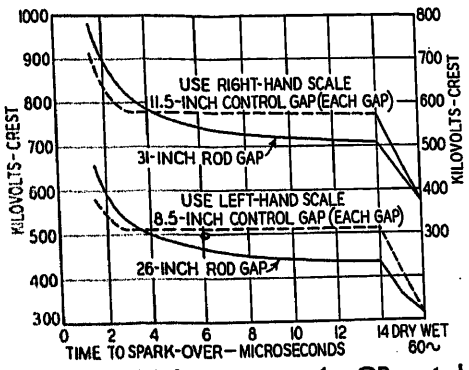



**Figure 1. Volt-time curves for OB control gaps (data from figure 5), also rod gaps spaced 26 and 31 inches (positive values plotted)**

2. The sphere gap on account of its uniform field is sensitive to any nearby conducting objects, and this limitation combined with the size of the sphere, especially for high-voltage systems, introduces a serious problem in the space required for the gap.

3. The sphere gap is not self quenching, i.e., will not stop power follow, resulting in the possibility of damage to the spheres and the probability of an outage.

The rod gap, on the other hand has much poorer impulse characteristics, but is much less affected by rain. The wet power-frequency spark potential of rod gaps is in general only 10 to 15 per cent lower than the dry value. Thus, for a spark-over time of 2 microseconds the rod gap will have a wet 60-cycle-to-impulse ratio of a little less than 2. For a 31-inch gap the ratio is 1.86, which means that if the rod gap is set so as to have a wet spark-over of 3.5 times normal line-to-ground potential, the voltage at 2 microseconds spark-over time would be 6.6 times normal which is still much too high for safe operation—leaving no margin or factor of safety between the demonstrated strength of the transformer and the potential allowed by the gap. For still higher rates of rise the situation would be still worse, since the potential allowed by the gap would be correspondingly increased.

Following the work of Austin, the authors have attempted to incorporate in the control gaps the impulse characteristics of the sphere gap and the lack of sensitiveness of the rod gap to rain conditions. It seems quite obvious that any scheme which secures the impulse advantages of the sphere gap through control of flux, which is the means the sphere gap itself uses, will be subject to the same wet and dry spark-over values if the same impulse characteristics are secured.

Comparing the wet 60-cycle and 2-microsecond flashover values of the 8.5-inch, and 11.5-inch control gaps as given in figure 5 of the paper a ratio of 1.73 and 1.70 is obtained which is only slightly less than a rod gap having the same 60-cycle spark-over value. These control gap settings apparently correspond to gaps rated 110 kv and 132 kv. I have reproduced the corresponding volt-time curves as figure 1 of this discussion. For times greater than about 4 microseconds the rod gap offers better protection. For times between 1 1/2 microseconds and 4 microseconds the data shows the control gap a maximum of 9 per cent below the rod gap. For times shorter than one microsecond more data are needed, since the shape of the curves as drawn do not indicate whether the curves might cross again or not.

Lightning arresters whose spark potentials are not affected by the weather, can be designed for much closer protection than gaps because their spark potential need not be above switching transient levels. They can in general be expected to hold potentials to values ranging from 2.5 to 5 times normal depending upon rating and whether for grounded or ungrounded neutral operation.

When reading the paper I was somewhat puzzled by the statement appearing in the second paragraph in the right hand column of page 1030 relative to the term "flat volt-time characteristic being a misnomer." It seems to me the authors' statement would be true if volt-time curves were only taken through the use of overvoltage. However, volt-time curves may be taken on sphere gaps on the front of the wave in which case flat volt-time characteristic does have a definite meaning.

On page 1031 when concluding the discussion of the "principle of control gaps" the authors state that capacities large enough to control voltage distribution in all kinds of weather must be used. This is usually a rather difficult matter when all kinds of weather are included, and I am curious to know how the authors have accomplished their objective. I know of cases where melting ice has caused unbalance under conditions which appear to be somewhat similar to that used by the authors.

A question arises concerning figure 9 *A*, *B*, and *C* where full-wave spark-over times are given ranging from 20 to 28 microseconds. This time is about twice as long as we have experienced under average laboratory conditions, and the authors' comment on this point would be helpful to those working in this field, I am sure.

On page 1034, at the end of the second paragraph under figure 10, the statement that where "insulation levels are higher than that shown, and where lightning arresters are used in combination with the control gap, higher gap spacings may be used," seems to require some further clarification.

**V. M. Montsinger** (General Electric Company, Pittsfield, Mass.): I wish to discuss this paper partly from the standpoint of protecting transformers in service against lightning with a gap having a flat volt-time curve characteristic, and partly from the standpoint of testing transformers with both long and short waves whose voltage values are controlled by flashing over a gap having a volt-time characteristic similar to that for transformer windings.

We used to consider that a sphere gap had no time lag but we now know that for short time to flashover in the order of one microsecond or less, sphere gaps have time lag.

It is, of course, possible to construct a gap that has no time lag, i.e., the volt-time curve is flat all the way from 60 cycles back to approximately zero time. Such a gap for 132-kv line has been constructed of small metal disks mounted on a rod making use of known resistances and capacitances between disks to control the flux. As pointed out by Mr. McEachron in his discussion, it was found that unless the gap was kept dry, the low 60-cycle wet flashover

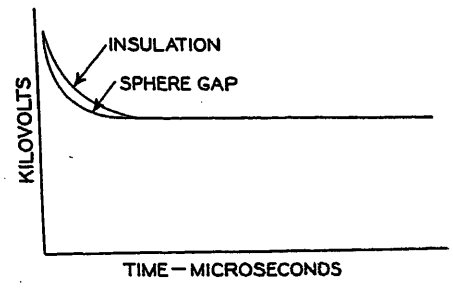



**Figure 2. Volt-time curves of sphere gaps and transformer insulation**

value required too great a spacing to properly protect against impulse voltages, although it gave considerably better protection for steep wave fronts than the control gap gives. This illustrates the point that when flux control is made use of, the low 60-cycle wet flashover makes it necessary to raise its impulse protective level up close to that of a plain rod gap. The difficulty in this particular case was overcome by enclosing the gap in the top porcelain of a 115-kv bushing to make it weatherproof: but, unfortunately, the gap was not self quenching which means that it probably would not protect the transformer if there were several strokes in rapid succession, since the gap would, no doubt, be destroyed on the first stroke if power current followed through.

If front-of-wave testing of transformers is ever standardized, it might be possible to construct a gap that has the same shape of volt-time curve as transformer insulation. Either such a gap must be developed or a general agreement must be reached on the correct kilovolt values to be applied for short times to flashover of whatever kind of gap is used to chop the wave off.

In fact a gap that is almost (but not quite) good enough for the purpose is already available. I mean the sphere gap.

Tests made on various thicknesses of barriers and with 25-, 50-, and 100-centimeter sphere gaps connected in parallel to control the kilovolts of long and steep-front waves show in all 3 cases that starting with the sphere gap to give the same kilovolts as the breakdown of the barrier on a full wave, then as the voltage is increased the sphere-gap spacing has to be slightly lengthened to keep it balanced with the breakdown of the insulation barrier. The lengthening of the gap continues and then as the time to flashover gets quite short the gap must be shortened. For very short times to flashover the gap length has to be decreased to, or even slightly less than, the spacing that corresponded to the full wave strength of the insulation.

Plotted on a volt-time curve basis the shapes of the 2 curves are as shown in figure 2. These curves mean, of course, that if a sphere gap were used with a constant spacing equal to the full-wave test kilovolts to control the voltage of both long- and short-impulse waves for testing transformers, the factor of safety (i.e., the difference between the breakdown strength and the tested value) would slightly increase as the time to flashover decreased, until the time got quite short and then it would again become the same as for the full wave test. In other words, there would be a band in which the spheres would provide an extra

safety factor during the test. It appears, therefore, that for front-of-wave testing at the present time sphere gaps could be used as a suitable test gap for transformers.

**J. R. North** (The Commonwealth & Southern Corporation, Jackson, Mich.): The control gap described in the paper by Messrs. Higgins and Rorden offers possibilities as a back-up protective device for use in the higher voltage classifications. However, some of its characteristics approximate a sphere gap and it does not have the ability to clear itself once arc-over occurs. These must be given consideration in its application.

The principal factors in the selection and application of a protective device such as a gap are:

1. The *maximum dynamic voltage* which may occur during fault conditions between the sound phases and ground.

2. The *ability of the protective device* to maintain an adequate protected level on a volt-time basis for both short time and long time intervals.

Considering the dynamic voltage limitations (item 1), studies of actual overvoltages occurring on transmission systems by the joint subcommittee on development and research—EEI and Bell system, as published in Engineering Report No. 30, have shown that the overvoltages arising from system operation are normally of the order of 2 to 5 times the normal voltage to neutral $E_n$. Therefore, it is generally conceded that a protective device should have a 60-cycle flashover or breakdown voltage under any weather conditions of at least $3^1/_2$ times normal and preferably higher.

An analysis of the performance of the control gap, based upon the characteristics as given in the paper, indicates that with gap settings as would probably be used, the 60-cycle *dry* flashover voltages are above the normal maximum dynamic voltages which may be expected. However, the 60-cycle wet flashover voltages are rather low.

For example, consider the control gap on the basis of giving protection comparable to that of a modern full-voltage arrester and assume 2 systems, one using 46-kv equipment and the other using 161-kv equipment. Figures 3 and 4, of this discussion show the volt-time characteristics of the lightning arrester and the control gap for these conditions. The table I summarizes some of the values shown on these sketches.

**Table 1**

| Apparent Voltage (Kv) | Short Time: Lightning Arrester Breakdown (Crest Kv) | Short Time: Control Gap Setting (Inches) | Short Time: Control Gap Dry FO | Short Time: Control Gap Wet FO | Short Time: Control Gap Wet FO | Long Time: Lightning Arrester IZ at 5,000 (Crest Kv) | Long Time: Control Gap Setting (Inches) | Long Time: Control Gap Dry FO | Long Time: Control Gap Wet FO | Long Time: Control Gap Wet FO |
|---|---|---|---|---|---|---|---|---|---|---|
| 46 | 170 | *4 | 145 | 85 | $2.3E_n$ | 200 | $5^1/_2$ | 175 | 110 | $2.9E_n$ |
| 161 | 570 | *8 | 440 | 355 | $2.7E_n$ | 705 | 12 | 570 | 470 | $3.6E_n$ |

* Lowest possible setting with this gap

It will be noted that in the 46-kv classification, the control gap would be given a setting of $5^1/_2$ inches to be equivalent to the voltage across the arrester during discharge and that with this setting the wet flashover voltage of the gap would be approximately 2.9 times the normal voltage to neutral $E_n$. With the control gap set at 4 inches to give performance equivalent to the breakdown of the arrester gap, the wet flashover voltage would be only 2.3 times $E_n$. Similar values are obtained for the 161-kv classification. There is a possibility that these low values of wet flashover voltage might result in undesirable outages due to flashover of the gap caused by dynamic overvoltages. It may, therefore, be concluded that the control gap must be set above the protected level afforded by a modern full-voltage-rated arrester in order to eliminate any possibility of flashover due to dynamic overvoltages. The control gap thus acts chiefly as a back-up protective device.

We would like to inquire of the authors as to the effect on the control gap structure of high values of power follow current.

**A. C. Monteith** (Westinghouse Electric & Manufacturing Company, East Pittsburgh, Pa.): Considerable work has been done to get the results of the different manufacturers' laboratories into agreement on the minimum impulse test on line insulators and rod gaps. Apparently there is still considerable disagreement for the shorter time lags as rod-gap data for a 138-kv installation at 860-kv give, from the author's data a time lag of 3.3 microseconds and for the Westinghouse data 1.8 microseconds. This difference is significant because it is largely in this zone that the authors can claim superiority of the control gap over the rod gap. It is true that the authors have done considerable work on a direct comparison of rod gaps with the control gap at the minimum impulse flashover and some at $1^1/_2$ microseconds but it is going to be necessary to have the data from the several laboratories on a common basis to be able to co-ordinate the complete substation apparatus.

To those who consider the lightning arrester as the best form of protection (the modern arrester giving protection to from 50,000 to 100,000 amperes without causing an outage) the control gap still offers the same limitations as the rod gap for the protection of transformers.

On solidly grounded systems in the higher-voltage classes the De-ion Protector offers a device that gives protection with the same limitations as the rod gap or control gap but will prevent an outage when it is called upon to operate. Although only test results with positive waves are shown it has very favorable characteristics with negative waves. A band is shown to give some indication of the variation in protection due to variation in particular designs.

These several points are illustrated in the attached figure. The maximum impulse test level on modern transformers is taken from actual tests made by Vogel and Bellaschi.

**I. W. Gross** (American Gas and Electric Company, New York, N. Y.): These 2 papers center around the problem of protection. The gap paper considers protection to apparatus; the ultrahigh-speed breaker the more comprehensive problem—protection of service. This latter objective requires, first, that interruption of power flow in a circuit should not exceed $^1/_4$ to $^1/_2$ second, as pointed out by Messrs. Sporn and Prince, and second, that the supply equipment such as generators, transformers, etc., be protected against failure. A most economical solution to this entire problem in many cases may be a protective gap of some form in combination with the ultra-high-speed breaker described by Messrs. Sporn and Prince.

The protective gap, that is, the so-called standard rod gap, has in the past had 2 weaknesses. First, at spacings generally proposed on the basis of impulse tests recommended for transformers, it was recognized the gap would not limit the volt-

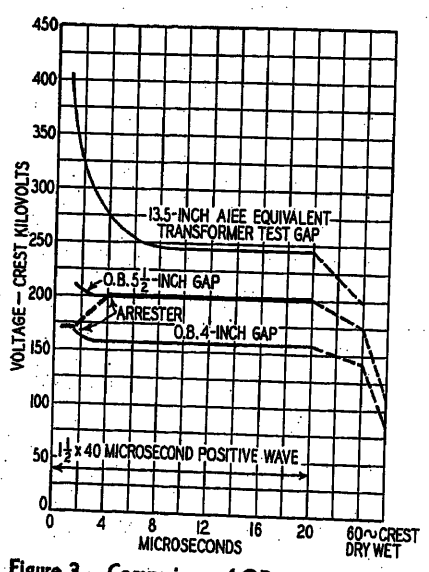



**Figure 3. Comparison of OB control gap and lightning arrester, 46-kv class**

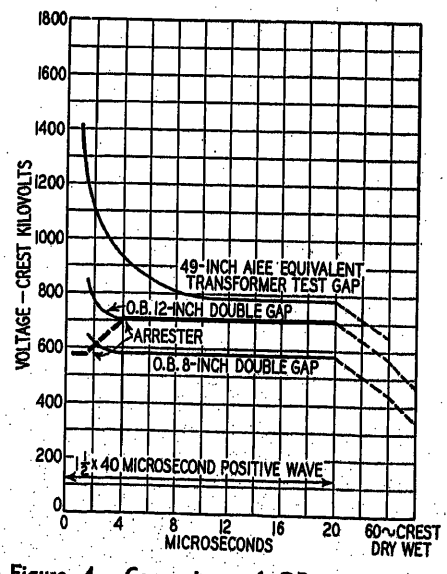



**Figure 4. Comparison of OB control gap and lightning arrester, 161-kv class**

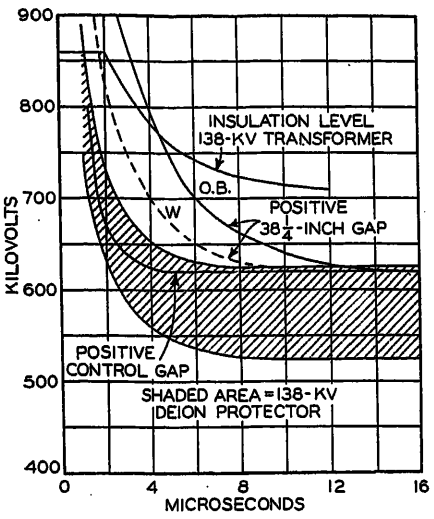



**Figure 5**

age to a value below the safe impulse strength of standard insulation, on steep wave fronts. On the other hand, if the spacing of the protective gap was reduced to supply protection for steep front waves, an increase in line outages might occur as a result of normal switching surges. In any event, if the protective gap flashed over, whatever its setting, a circuit outage was sure to follow. With the ultrahigh-speed reclosing breaker, however, it should be possible to greatly reduce, if not entirely eliminate line outages due to gap operation.

The control gap described by Messrs. Higgins and Rorden, appears from the data to have considerably better protective characteristics against steep wave front surges than the standard rod gaps, although it still has the undesirable rising characteristics at short time lags.

Based on the data given in the paper a trial design for 132-kv application with standard 132-kv transformer insulation showed that the control gap allows some 20 per cent higher magnitude of switching surge voltage without flashover as compared with a standard rod gap set for the same protective voltage level at $^1/_2$ microsecond. This is a margin that may well be considered when attempting to supply better protection against steep wave fronts, and at the same time reduce line outages due to switching surges to a minimum.

With this set-up of an inexpensive protective gap and ultrahigh-speed reclosing breaker, a reasonable frequency of line flashovers due to switching surges could be tolerated in many cases, as the circuit would be re-energized immediately without objectionable energy interruption. The frequency of breaker operation allowable would depend largely on breaker maintenance, and the degree of risk taken as regards the gap protecting the apparatus on steep wave fronts.

Should such a protective scheme as outlined above prove effective, it would entirely change the present requirements for lightning protection of transmission lines, the continuous ground wire, low tower-footing resistances, and counterpoises not being necessary. While the degree of lightning protection to apparatus with any present known gap appears to be inferior to the protection afforded by modern lightning arresters properly installed, it is well known that our knowledge of the performance of both gaps and lightning arresters under conditions of steep rates of rise of impulses is all too meager. Then too, we have little actual data on the frequency and severity of these steep-front lightning impulses in actual practice. If it is found, by continued field research, that the maximum severity of lightning is less than we are now generally considering, even the present available gaps may prove effective protection to the apparatus, and the high-speed breaker will preserve the continuity of service.

There is one question I wish to ask Messrs. Higgins and Rorden, and that is what is the relative 60-cycle wet and dry flashover of the control gap with and without the porcelain control insulators? The point I have in mind is, if the gap functions, and the power arc disrupts one or more of the control insulators the projecting supports formerly supporting the insulators may be so closely spaced that the gap may have difficulty withstanding normal line voltage, to say nothing of switching surges in the order of 3 to 5 times normal.

**Ralph Higgins** and **H. L. Rorden:** The control gap is intended to provide protection for the severe lightning surges—those that do the real damage. Existing forms of protection are capable of relieving the less severe transients, such as induced strokes and traveling waves. But failures still seem to occur, and this is evidence that existing protection does not relieve the most severe surges. It is questionable whether failures would occur from the majority of surges which cause present protective devices to function. Indications are that most failures occur at some one severe surge. The control gap is not expected to function for the majority of low-voltage and low-energy surges, since operation of the gap is accompanied by an outage. Its purpose is to maintain a voltage limit at a reasonable margin below the level of station equipment, so that it will operate only when potentials approach dangerous proportions. When direct strokes occur, an outage is almost inevitable, but whether such outage occurs over a directed protective path or breaks through expensive equipment, is a vital question.

The AIEE Standards of Lightning Arresters No. 28 (March 1936) state "Present types of lightning arresters are not in general designed to protect against direct strokes to electric circuits. ....." The control gap is intended for direct-stroke protection. On this basis, their fields of application do not conflict. We do not contend that control-gap characteristics equal that of arresters for low-energy surges. The control gap has a volt-time characteristic independent of energy (current). Arrester characteristics involve volts, current, and time, since the arrester contains resistance material.

Mr. North illustrates an outstanding point in the comparison of the control gap and lightning arresters. In his table of short-time breakdowns, he lists the kilovolts at which the series gap breaks down for 2 rated circuit voltages. In the table of long times, secondary rise or the recovery voltages across the arrester resistance material is given for the same kilovolt ratings. These crest voltages are the potentials to to which the equipment is subjected if the surge is limited to 5,000 amperes. The voltages are about $3^1/_2$ times line-to-neutral (crest). This is of interest because it is mainly above this range ($3^1/_2$ times line-to-neutral) that the control gap is intended to function. It might be said therefore, that arresters can maintain a safe potential for currents below 5,000 amperes, but that the secondary potential rise above that current limit is indefinite. Recent publications have shown that a fair percentage of the more severe surges approach 40,000 amperes.

It would be interesting to know the voltage rise under the 50,000 to 100,000 amperes mentioned by Mr. Monteith, for a high-voltage system. Since arresters in general apparently are not intended for protection against direct strokes (AIEE Standards No. 28) it would be interesting to know if the arresters Mr. Monteith suggests are for other than the lower voltage or distribution systems.

We do not agree with Mr. Monteith's rod-gap figure of 860 kv at 1.8 microseconds for $38^1/_4$-inch spacing, nor can we find any Westinghouse data to substantiate his value. In the figure of Mr. McEachron's discussion, a 31-inch rod gap reaches 860 kv at 2.4 microseconds and is in close agreement with our data. Although our rod-gap curve referred to is from a specific test and is not intended to represent an average, it is in fair agreement with Westinghouse published data also. In ELECTRICAL ENGINEERING, December 1934, Bellaschi and Teague have given very complete curves on rod-gap flashovers, in their paper "Impulse and 60-Cycle Strength of Air." These authors mention that they have measured time on their oscillograms from the point on the wave front corresponding to the 60-cycle flashover voltage. To bring their curves to the basis of measuring time from the origin of the wave, as we have done, would require adding about one microsecond or more to their figures. We are inclined to the opinion that Mr. Monteith has overlooked this correction in offering his suggestion of laboratory disagreement. We appreciate his statement that it is going to be necessary to have the data from the

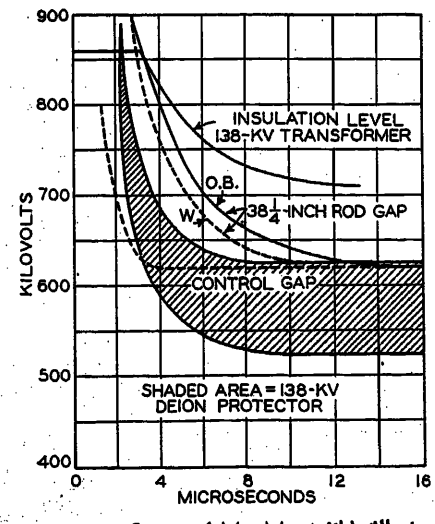



**Figure 6. Curves of Mr. Monteith's illustration shifted to time scale measured from origin of wave**

several laboratories on a common basis for co-ordination purposes. In the past, it has been the practice of most laboratories to measure voltage from the origin of the wave. We also appreciate his statement that it is largely in this (overvoltage) zone that we can claim superiority of the control gap over the rod gap. On the basis of the suggested correction to his figures, Mr. Monteith should undoubtedly understand the superiority of the control gap. In figure 6 we have replotted his curves corrected approximately to our time scale. The margin between the control gap and the several other curves for the short-time lags is apparent. We observe that the control-gap curve closely parallels the insulation throughout its range, excepting at the short time where an unusual and abrupt change in the insulation curve occurs. An explanation of this "flat" interval, indicating no increase in voltage on front of wave tests would be interesting. Mr. Montsinger (*Electrical World*, February 13, 1937, page 537) apparently does not agree that this interval should be flat.

We are interested in Mr. Monteith's comparison of De-ion tubes with gaps for station protection. Published data suggest these tubes for transmission line service and do not indicate that they are proposed for station protection. It is regrettable that the complete characteristics of the De-ion tube have not been included, since the shaded area tells only part of the story. This area indicates that in the short time intervals, the De-ion tube is equivalent to the control gap, although the complete characteristic is plotted as a band. The upper limit of the tube flashover is shown approximately equivalent to that of the various gaps at minimum flashover, while in the overvoltage range, the control gap curve is approximately an average of the band. At minimum flashover, a spread of 100 kv is apparent. What would this mean under power-frequency wet conditions?

Mr. Gross has discussed a combination which seems to be ideal, particularly for the severe surges. As previously mentioned, an outage is almost inevitable with direct strokes. The high voltage and energy must form a path to ground in any event, and the combination of the control gap with high-speed breakers affords the advantage of protection irrespective of energy and restores the system to service without the usual interruption. Under these conditions, the danger of destroying control insulators is greatly reduced. The switching time, perhaps more than the magnitude of the follow current, would seem to be the major item relative to the ability of the gap to withstand follow current. If a control insulator should be damaged, the result would be loss of advantage of the surge characteristic. The power frequency flashover would be reduced less than 20 per cent. This should not interfere with normal operation until repairs could be effected at later convenience.

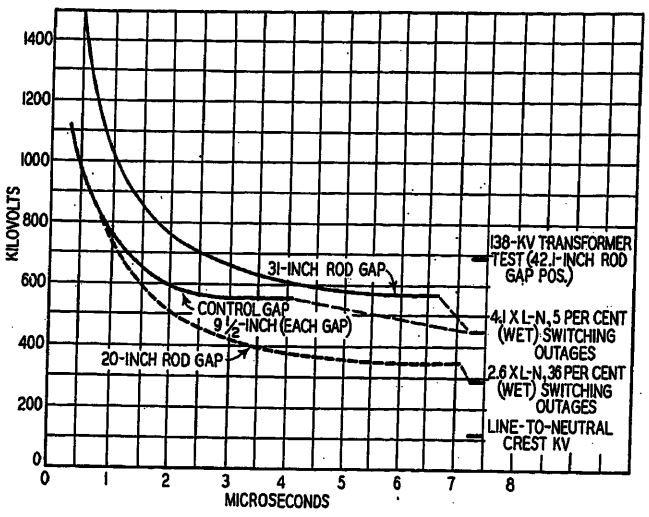



**Figure 7. Control gap versus rod gap for 138-kv transformer protection**

Negative impulse and switching surges both under rain spray

In commenting on Mr. McEachron's discussion, we wish to emphasize some characteristics of controlling flux in a dielectric field in air. For the same minimum impulse flashover the spacing of a rod gap is $3\frac{1}{2}$ or more times that of a sphere gap (spaced within its operating range). A sphere gap has a "flat" volt-time characteristic, while the rod gap has a sloping characteristic (figure 9 *A* and *E* of the control-gap paper). If smaller spheres are used for the same voltage, the spacing is greater and the curve is more sloping. At high overvoltages the rod-gap spacing must be reduced to nearly that of the sphere gap for a balance. The sphere gap and the rod gap are opposite extremes, and partial control of the field results in a spacing and volt-time characteristic proportionately between the two. Thus the general form of a volt-time characteristic may be predicted by the spacing of electrodes at the minimum flashover. For dissimilar electrodes, the same general law holds true for a given polarity.

Mr. McEachron states it is obvious that any scheme that secures the impulse advantages of the sphere gap through control of flux will be subject to the same wet and dry spark-over. We concur in this opinion and this point illustrates the advantage of the control gap. From figure 9 *A*, *D*, and *E* of the paper the control-gap curve is adjusted to be between that of the sphere gap and the rod gap. It follows that its electrode spacing and its power-frequency wet performance are also between the 2 extremes. From the previous explanation and from Mr. McEachron's statements, the control gap has a considerable advantage over the rod gap for impulse characteristics, and is considerably better than the sphere gap for wet flashovers. The control gap is designed to have the best impulse characteristic obtainable with tolerable wet flashover voltages. When so adjusted, the volt-time characteristic of the control gap closely parallels that which has been published (Montsinger, *Electrical World*, November 21, 1936; Bellaschi and Teague, ELECTRICAL ENGINEERING, January 1937) to represent transformer insulation. It is therefore only necessary to provide a reasonable margin between the breakdown strength of insulation and control gap flashover to have the protection properly co-ordinated.

Mr. McEachron's figure 1 illustrates the positive impulse comparison between a rod gap and a control gap when adjusted to the same 60-cycle wet flashover. It has been commonly accepted that 60-cycle wet flashovers are equivalent to switching surges. This must be inferred since 60-cycle wet tests are frequently cited and obviously operating voltages, particularly on grounded-neutral systems, do not rise to several times their normal value. Since publication of the paper, we have endeavored to learn if this assumption is justified. On tests with the control gap, we find that it is not. The wave used in our switching-surge tests was obtained by saturating a high-voltage testing transformer with a d-c current and then breaking the circuit abruptly by switching under oil. The wave obtained prior to flashover was very similar to that reported by Bellaschi and Teague in the January 1937 ELECTRICAL ENGINEERING ("Dielectric Strength of Transformer Insulation") though somewhat more irregular. Using these switching surges as the criterion of operating tolerance, we have attempted to show the complete performance which Mr. McEachron's figure 1 is intended to illustrate, in figure 7. The tests were made with negative polarity since direct strokes are predominantly negative (Lewis and Foust show 95 per cent, *G. E. Review*, November 1936). We have selected a 31-inch rod gap so these results will compare with Mr. McEachron's illustration for a 132-kv system. These test results are obtained by direct comparison of the 2 gaps and with oscillographic records. The analysis is based on the assumption that the limits of a gap as a protective device are its ability to relieve high overvoltages, and its performance for switching surges in rain. With switching surges applied, the 31-inch rod gap was found to balance with a control gap spaced with each gap $9\frac{1}{2}$ inches. The flashover measured 445 kv, which according to Lewis and Foust, should result in 5 per cent switching outages. When dry, the control-gap outages will be less but the rod gap will not change greatly. With high overvoltage negative surges applied to the same gaps, it was found that the rod gap had to be reduced to 20 inches to balance with the control gap having the same spacing as in the switching-surge tests. If a rod gap of 20-inch spacing were installed on a 132-kv system, its switching surge flashover would be 2.6 times line-to-neutral and would cause 36 per cent switching outages—over 7 times that of the control gap having the same short time impulse protection.

We are not quite sure what Mr. McEachron means by a rod gap offering greater

protection for times greater than 4 microseconds. By his comparison, the rod gap will flash over at a lower voltage for times greater than 4 microseconds. This, of course, means more unnecessary outages and it is not quite clear why the protection should be any better as long as the gap will flash over in any event before the voltage rises to a dangerous level. We consider an ideal protective curve one that parallels that which it is to protect. Relative to the statement that more data are needed at times less than one microsecond, we wish to point out that the curves published are intended for operating data, so that the gap may be adjusted to define a minimum flashover level. The high overvoltages are not plotted in these curves because we do not rely on indirect comparison where small deviations due to personal analysis result in uncertainty regarding the actual performance. We have cases on record, and have observed in other data, where identically the same time for flashover of a gap was recorded by a cathode ray oscillograph at voltages differing by 100 per cent in the short-time range. A graph of such data is a matter of personal judgment and it is difficult to plot a line to represent such phenomena as accurate performance. Too frequently conclusions are drawn by making indirect comparisons and stressing exactness where precision is not justified. We believe the ultimate criterion of protection is to be found by a comparison where it is possible to determine relative performance directly. Therefore, we do not attempt to show that we differ by some questionable margin from other data through the medium of comparing curves which should preferably be shown as a band.

That the parallel test method adequately illustrates the advantage of the control gap is illustrated in figure 8. This figure, with the control-gap equivalent added, is reproduced from the August 1934, *G. E. Review*, "Lightning Protection of Power Transformers Connected to Overhead Circuits," by K. B. McEachron. This curve, particularly at minimum flashover and at the high overvoltages, is substantiated by Mr. F. J. Vogel ("Adequate Impulse Tests," *Electric Journal*, January 1935). From this curve, according to Mr. McEachron, a transformer is adequately protected at the high overvoltages by a rod gap spaced 55 per cent of the spacing which would protect the transformer at minimum flashover (100 per cent). The dashed curve superimposed on this figure illustrates that the control gap is approximately 10 per cent better throughout its entire range than Messrs. McEachron and Vogel show is necessary to protect power transformers. Although Mr. McEachron's curve applies only to positive polarity, Mr. Vogel illustrates that on negative polarity the same general percentages obtain, particularly at the minimum flashover and at the high overvoltages.

The question relative to spheres having a "flat" volt-time characteristic is answered by inspection of our figure 9 *E*. This applies to any type of test and particularly to front of wave testing. Such characteristics are shown to have a rising voltage curve in the short time range. Frequently, the curve is plotted as a straight horizontal line from minimum flashover at about 2 microseconds to infinity. It is not possible to obtain long time lags in sphere gap flashovers. Some curves lead us to believe that at the minimum flashover, any time is obtainable. Actually there is no test point obtainable in the "flat" region. The curve ceases to exist once it becomes flat. Long time lags are associated with corona formation and for sphere-gap curves to be plotted illustrating that long times to flashover are obtainable under any condition (with spacing within their normal operating range) is a misnomer.

We concur that it is not easy to maintain electrical stability in multigaps under all weather conditions. In the control gap, this has been accomplished by using insulators having a capacitance approaching the range of coupling condensers, which are known to give satisfactory performance. By his question of unbalance due to melting ice, Mr. McEachron is undoubtedly concerned only with operating characteristics since we are not normally concerned with lightning storms in freezing weather.

We appreciate Mr. McEachron suggesting an explanation of variations in time to flashover at minimum voltage. This further justifies our contention that such characteristics should be plotted as a band rather than a line. The oscillograms illustrated were chosen at random during the tests and are not at all unusual. Inspection of our figure 9 *A* and *B* illustrates that while the oscillograms show times of the order mentioned, the adjacent volt-time curves show that minimum flashover is reached in about 16 microseconds. At minimum, the range in time to flashover for gaps which are dependent upon corona formation is more than 100 per cent. Successive flashovers showing 10 to 25 microseconds for gaps of the order shown are common, without a measurable difference in voltage. This band becomes narrow rapidly with increasing overvoltages, but is still measurable on front-of-wave tests. The inadequacy of drawing conclusions by representing such a characteristic as a line is apparent.

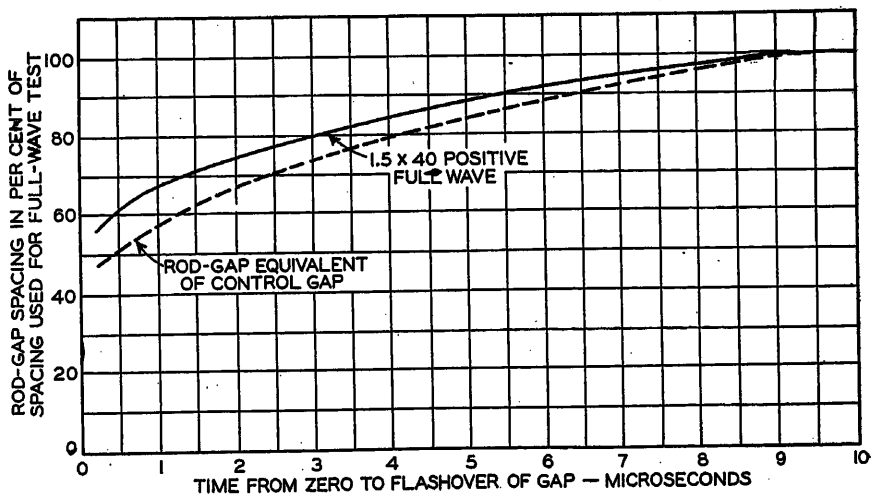



**Figure 8. Rod-gap spacings to give a constant factor of safety in power transformers (based on approximate major insulation strength) from "Lightning Protection of Power Transformers Connected to Overhead Circuits," by K. B. McEachron, "General Electric Review," August 1934**

The previous discussion has undoubtedly answered Mr. McEachron's question regarding the use of the control gap as back-up protection, since the control gap characteristic closely parallels that of insulation. A higher insulation level could be accompanied by a corresponding control-gap spacing. Where the control gap is used in conjunction with arresters, it is expected that the arrester will perform first and relieve part of the surge. The control gap should flash over only when potentials beyond the scope of the arresters are reached and therefore a somewhat closer margin might be adopted.

Mr. Montsinger points out that sphere gaps have a time lag when flashover is of the order of one microsecond or less. Mr. Montsinger has shown (*Electrical World*, November 21, 1936) that his approximate equivalent of transformer insulation has a time lag when flashover is of the order of 3 microseconds or less. He therefore shows that a sphere-gap characteristic is considerably faster than that of major insulation. The control gap has a characteristic very similar to that which Mr. Montsinger has shown to represent such insulation. His illustration of a sphere-gap curve merging with insulation at high overvoltages is of interest, since this characteristic is contrary to the general trend of flashovers. We are also interested in Mr. Montsinger's statement concerning a no-time-lag gap.

Such a characteristic is undoubtedly possible in a multigap so unbalanced that successive rather than simultaneous flashovers determine the minimum breakdown. We think his suggestion that a sphere gap be used for transformer testing is excellent, although its characteristic, as he shows, is faster than transformer insulation. The sphere gap lends itself readily to laboratory tests, is easily adjustible, and complete calibrations are available, but it is not suitable for protection in service. The control gap on the other hand is not as desirable for laboratory testing but lends itself readily to station protection.

# News
## Of Institute and Related Activities

# Milwaukee, Wis., Is Host to 53d Annual Summer Convention

IN 1906 the Institute held its 23d annual summer convention in Milwaukee, Wis. Just 31 years and 3 weeks later, Milwaukee again played host to the Institute, this time for its 53d annual summer convention (none was held in 1917). Several unusual features marked the program of the 1937 convention held June 21–25, with headquarters at the Schroeder Hotel.

All these features are covered in this issue of ELECTRICAL ENGINEERING, which brings to all members of the Institute not only a comprehensive news digest covering the high lights of the convention activities outlined in programs previously published, but also the full text of the 2 principal special addresses delivered by men prominent in the engineering profession, and several other special presentations of interest and value to the membership at large.

### Annual Business Meeting

With some 250 or more persons in attendance, and with K. L. Hansen, general chairman of the 1937 summer convention committee, presiding, the opening session convened Monday morning, June 21, in the Crystal Ball Room of the Schroeder Hotel. Chairman Hansen outlined briefly the several unusual features on the program and then introduced as honorary chairman and "an outstanding Milwaukee personality . . . for many years associated with electrical developments on a large scale," General Otto H. Falk. General Falk in his brief but generous message of warm welcome mentioned the fact that the last AIEE summer convention held in Milwaukee was in 1906.

On behalf of the summer convention committee Chairman Hansen paid special tribute to General Falk and to "Milwaukee industries that have contributed so generously to make this convention a success . . . contributed by permitting their men to use their time for convention purposes, financial contributions, hospitality, inspection trips, and in other ways." At this point the gavel was turned over to President MacCutcheon who presided for the annual business meeting.

#### REPORTS OF THE BOARD OF DIRECTORS AND THE COMMITTEE OF TELLERS

On behalf of the Institute, President MacCutcheon responded to General Falk's message of welcome. The president's address, "The Engineer of Tomorrow," is reproduced in this issue (pages 941–3).

The customary digest of the annual report of the board of directors for the fiscal year ending April 30, 1937, was presented by National Secretary H. H. Henline. Mr. Henline pointed out that the report, published in full in the July issue of ELECTRICAL ENGINEERING, is made up of a large number of brief reports covering all major phases of Institute activities, and many activities in which the Institute co-operates jointly with other organizations. In this report is a wealth of information of interest and value to every Institute member. One of the features of the year's activity has been the prodigious amount of time, effort, and energy spent by President A. M. MacCutcheon in visiting some 46 Institute Sections and 20 educational institutions and



**President A. M. MacCutcheon (left) exchanging greetings with General Otto H. Falk, honorary chairman of the general summer convention committee**

Student Branches in 29 states, the District of Columbia, and Canada; in attending the 2 national conventions and 2 District meetings, and several District student conferences held during the year; and in effectively stimulating the activities of many Institute committees.

Concerning general activities Mr. Henline reported that the 2 national conventions and 2 District meetings held during the year were well attended. He stated also that during the year new records had been set in Section activities, with a total of 621 meetings reported including numerous group meetings for special discussions, and in Student Branch activities, with 1,363 Branch meetings reported. With the organization of Student Branches at Columbia University, New York, and at Tulane University, New Orleans, La., there are now 119 Branches functioning.

Further with reference to Section activities, Secretary Henline reported that the organization of the East Tennessee Section brought the total number of Sections now functioning up to 62, with the formation of several others in prospect. During the past year a total of 23 Sections sponsored special activities, 20 holding meetings of special types in addition to their regular meetings, and 3 others conducting educational courses. The survey and reallocation of Section territory was reported as having been completed by the special committee that has been working on it since 1935, and approved by the board of directors to become effective as of August 1, 1937. In general principle, the plan so modifies and enlarges the territory assigned to Sections as to place within Section territory all members residing in continental United States with the exception of approximately 300 residing in scattered and sparsely settled areas neither contiguous nor tributary to Section territory. For convenience and accuracy, county boundaries now are used in specifying Section territory. All District officers and the officers of all Sections involved in territorial changes have been given full information concerning the changes, and membership lists for each Section as of August 1, 1937, will be prepared on the new basis.

In commenting upon the report of the membership committee, National Secretary Henline called attention to the following figures:

| Item | May 1, 1936 | May 1, 1937 |
|---|---|---|
| Total membership | 14,600 | 15,308 |
| Applications from Enrolled Students | 631 | 710 |
| Other applications | 946 | 1,040 |
| Enrolled Students | 4,049 | 4,503 |

Further details concerning Section and Branch activities for the year 1936–37 are given in the comprehensive annual report published in the June 1937 issue of ELECTRICAL ENGINEERING, beginning on page 762. Other items have been published during the year.

The report of the committee of tellers was published in the July issue of ELECTRICAL ENGINEERING, page 913, along with a report covering the election of honorary members.

#### TREASURER'S REPORT

An independent and personal verification of Institute accounts as covered in the auditor's statement published as a part of the report of the board of directors, was reported by National Treasurer W. I. Slichter, professor of electrical engineering, Columbia University, New York, N. Y. He reported that further returns had been made to the reserve capital fund in compensation for withdrawals required for

Institute activities during 1932–33–34, at the same time accommodating increased appropriation to the publication committee and to certain other committees for the further extension and development of Institute services to its members. He urgently recommended continuance of a conservative financial policy in order that future possible economic disturbances of a general nature should not injure nor unduly curtail Institute activities.

PRIZE AWARDS

Chairman H. S. Osborne of the AIEE committee on award of Institute prizes presented formally the committee's report, and President MacCutcheon made the presentations to the recipients present, Mr. P. S. Millar and Professor H. E. Edgerton. Complete text of the report may be found on page 756 of ELECTRICAL ENGINEERING for June 1937.

## Lamme Medal for 1936 Presented to Doctor Frank Conrad

"For his pioneering and basic developments in the fields of electric metering and protective systems" Doctor Frank Conrad (A '02) assistant chief engineer, Westinghouse Electric and Manufacturing Company, East Pittsburgh, Pa., received during the annual summer convention business session at Milwaukee, Wis., the ninth in the series of AIEE Lamme Gold Medals. This was the second major award made by the Institute to Doctor Conrad, the earlier award having been that of the Edison Medal for 1930.

One of 3 bequests provided in the will of Benjamin Garver Lamme (deceased July 8, 1924), the AIEE Lamme Medal was established for the encouragement and recognition of "meritorious achievement in the development of electrical apparatus or machinery." The other bequests were made to The Ohio State University, Columbus, and to the Society for the Promotion of Engineering Education (this year's awards are announced elsewhere in this issue).

LAMME CAREER OUTLINED BY PRESIDENT-ELECT HARRISON

As a background for the presentation of the Medal to Doctor Conrad, President-Elect W. H. Harrison presented the following outline of the life of Lamme as indicative of the circumstances that led to the founding of the Medal:

"Fortunately, Mr. Lamme recorded his life history, a fascinating story, from his boyhood on the farm, country schooling, natural bent for mechanical things, devotion to elementary mathematics, engineering course at The Ohio State University, and affiliation with the Westinghouse Electric and Manufacturing Company that began in 1889 in a testing department and ended with his death in 1924 as its chief engineer.

"His achievement as the guiding genius and inspirational force of the engineering work of that great organization, and in particular his contributions to the advancement of the science of electrical-machine design, hardly need to be reviewed at any Institute gathering. Monuments to the brilliance of his mind, to his industry, to his courage, to his imagination, are to be found literally wherever electric energy is generated and applied.

"Beginning early in his career he gave generously of his time and knowledge to affairs of the Institute, participating in its deliberations and particularly in its technical discussions. He served in many capacities, perhaps the most noted being his service on behalf of the Institute on the Naval Consulting Board of the United States from 1915 to 1919. He was honored by the AIEE in 1919 by the award of the Edison Medal, the most distinguished award the Institute can bestow. From his Alma Mater, Ohio State University, he was the first to receive the Joseph Sullivant Medal in recognition of the value of his work to the world. Pioneering in a field when so little was known of the science of electricity, even as to its fundamentals, and full well realizing the necessity for training and education, he gave freely to these activities. It was like the man to establish in his will a medal for the advancement of a profession he cherished and to which he contributed so much. This significant and highly prized medal will continue to serve as an inspiration to the engineers of the future."

MEDALIST INTRODUCED BY A. M. DUDLEY

With enthusiasm for the human qualities of the medalist as well as for his versatile technical genius, A. M. Dudley (A'08, F '13) marine electrical engineer, Westinghouse Electric and Manufacturing Company, East Pittsburgh, Pa., outlined the more outstanding features of Doctor Conrad's career:

"To do justice in a casual quarter of an hour to the lifetime accomplishment of a busy man is unthinkable, and to mention a few of the high spots of what he has done is to create the thought that perhaps one has omitted many of the best . . . .

"In 1890 at the very tender age of 16 years, without benefit of even a complete grade-school education, Frank Conrad went to work in the Garrison Alley Shops of the Westinghouse Electric and Manufacturing Company as a bench hand. His biography gives us an intriguing picture of a clever mischievous boy filled with an insatiable curiosity about scientific measuring instruments and about electricity. As the result of some suggestions that he made about the work which he was doing with his hands, he was selected to go to the testing floor as a laboratory assistant. While there he worked on meters and laid the groundwork of that work for which he is being cited today. He also worked on arc lamps.

"In 1904, when I first knew him, he had been designated general engineer, as a free lance under the direction of the vice-president of engineering to work on any or all engineering problems to which he might be assigned. He followed that period with work on circuit interruption on the New Haven Railroad electrification. A little later he worked on starting, lighting, and

**Table I. Analysis of Attendance at 1937 Summer Convention, Milwaukee, Wis.**

| Classification | Dist. 1 | Dist. 2 | Dist. 3 | Dist 4 | Dist. 5 | Dist. 6 | Dist. 7 | Dist. 8 | Dist. 9 | Dist. 10 | Foreign | Totals |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Members | 74 | 83 | 55 | 15 | 359 | 7 | 20 | 13 | 11 | 3 | | 640 |
| Enrolled Students | | | | | 62 | | | | | | | 62 |
| Men guests | 2 | 7 | 3 | 1 | 131 | 3 | 1 | 2 | | | | 150 |
| Women guests | 19 | 15 | 10 | 4 | 141 | 3 | 11 | 5 | 6 | 1 | | 215 |
| Totals | 95 | 105 | 68 | 20 | 693 | 10 | 34 | 19 | 19 | 4 | | 1,067 |



Left to right: Director E. S. Lee of Schenectady, N. Y., National Secretary H. H. Henline of New York, N. Y., Past Vice-President W. S. Rodman of Charlottesville, Va., and J. F. H. Douglas, chairman of the convention technical program committee



Vice - President Mark Eldredge (left) of Memphis, Tenn., conversing with Director-Elect Vannevar Bush of Cambridge, Mass.



W. O. Helwig (right) chairman of the convention registration and housing committee, checking notes with K. L. Hansen, general chairman of the summer convention committee



Left to right: Past Chairman H. H. Race of the Schenectady Section, National Treasurer W. I. Slichter of New York N. Y., Past Chairman F. C. Young of the Rochester Section and Past Vice-President C. R. Higson of Salt Lake City, Utah

## Future AIEE Meetings

**Pacific Coast Convention**
Spokane, Wash., Aug. 30–Sept. 3, 1937

**Middle Eastern District Meeting**
Akron, Ohio, Oct. 13–15, 1937

**Winter Convention**
New York, N. Y., January 24–28, 1938

**North Eastern District Meeting**
Pittsfield, Mass., Spring 1938

**Summer Convention**
Washington, D. C., June 20–24, 1938

ignition for automobiles. During the War he rendered signal service to our government in the matter of radio communication. At present he is a Lieutenant Commander in the Naval Reserve. . . . He is a sage counselor of youth; young men come to him and enjoy working with him . . . . In 1921, he was appointed assistant chief engineer, a title which still serves to designate the man to whom you can carry any kind of questions you may have.

"He followed that with some work on rectifiers, radio broadcasting, short wave radio, and . . . on voting machines.

"Four times have medals come to him . . . : In 1925 the Morris Leibmann prize of the Institute of Radio Engineers; in 1933 the John Scott Medal of the City of Philadelphia; in 1930 the AIEE Edison Medal; in 1936 the AIEE Lamme Medal . . . In 1928 the University of Pittsburgh conferred upon him the degree of doctor of science. He is a Fellow in the Institute of Radio Engineers, and a Fellow of the AIEE.

"What has he done, briefly, to deserve all this acclaim? First, unquestionably comes radio broadcasting, and perhaps more important, we would have to mention short-wave radio development . . . . Following these there is a long list of distinguished design accomplishments along many lines, including the arc lamps, meters, automotive equipment, and radio that has been mentioned; in all he has something like 250 patents to his credit, and most of these have been manufactured, or are still being manufactured in some form.

"Known to only a few is Doctor Conrad's interest in biology and physiology; in conjunction with one of the doctors in Columbia Hospital in Wilkinsburg, Pa., he developed a method for draining fluid from an infected lung in pneumonia cases, which method has been highly successful and probably will be used much more. It is characteristic that in connection with that work he had developed by one of the big rubber companies a special form of rubber tubing which has a passage through the middle to conduct ingoing liquid and corrugations around the outside to conduct outgoing fluid for use in cases of irrigation or removal of fluid.

"Frank Conrad and his work stand to me for the spirit of service . . . for the aristocracy of intellect as shown in the power of his scientific curiosity and his creative imagination . . . for the flowering of this great democracy in which we live."

### Doctor Conrad Responds

In responding to Mr. Dudley's address, Doctor Conrad stated that his pleasure in receiving the Lamme Medal is "enhanced by the fact that the Lamme Medal was provided by the generosity of a man who to an extent was responsible for the part I was enabled to take in the development of electrical measuring instruments." In recounting some of the problems incident to the development of the a-c system, Doctor Conrad said: "It became imperative that means be provided for observing all aspects of this new industrial service, and through fortune it happened that I was privileged to play a part in the subsequent development of a-c instruments . . . . Aside from the Siemens' dynamometer and the Kelvin balance, which were adapted to the laboratory but not to the station switchboard, there were some types of measuring instruments in existence at the time that did give some approximation of correct readings on alternating current although they had been designed for d-c use. Attempts were made to adapt these instruments to a-c operation by calibrating them, especially for the particular a-c circuit in which they were to be used.

"Our crude cut-and-try methods of development soon taught us that it was necessary to subdivide or laminate any iron used in the magnetic field. Also if the coils were wound on metal spools, these spools had to be slotted in some manner to avoid a closed circuit around the magnetic core. In a few years a line of instruments was made available in which the voltmeters and the wattmeters had moving coils and the ammeters had moving iron armatures; these were comparable in accuracy to those of the present, although they were unwieldy and expensive . . . . Some years later the general principle of utilizing the current induced in the moving element, employed by Shallenberger in his pioneer current meter, was incorporated in new designs of compact switchboard instruments. This type of instrument constituted an intermediate step in instrument design and made possible the use of a scale length which extended around almost the entire circle.

"As often is true, fashions in instrument design now have swung back to those early days, and at present the induction type of instrument, excepting the watt-hour meter, has been almost supplanted by types corresponding to the first moving-iron-core and moving-coil instruments. Great advances made in the improvement of magnetic materials and complete understanding of the principles involved, now permit the production of instruments of many sizes and types, completely satisfactory as to accuracy and dependability."

**Table II. Summer Convention Attendance During Recent Years**

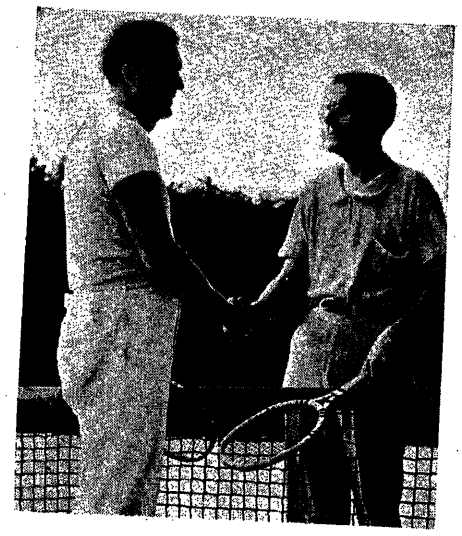
| | | | |
|---|---|---|---|
| 1937 | Milwaukee, Wis. | *(5) | 1,067 |
| 1936 | Pasadena, Calif. | (8) | 715 |
| 1935 | Ithaca, N. Y. | (1) | 904 |
| 1934 | Hot Springs, Va. | (4) | 351 |
| 1933 | Chicago, Ill. | (5) | 968 |
| 1932 | Cleveland, Ohio | (2) | 1,022 |
| 1931 | Asheville, N. C. | (4) | 525 |
| 1930 | Toronto, Ont., Canada | (10) | 1,110 |
| 1929 | Swampscott, Mass. | (1) | 1,000 |
| 1928 | Denver, Colo. | (6) | 500 |
| 1927 | Detroit, Mich. | (5) | 1,200 |
| 1926 | White Sulphur Spgs., W. Va. | (2) | 350 |
| 1925 | Saratoga Spgs., N. Y. | (1) | 900 |
| 1924 | Chicago, Ill. | (5) | 750 |
| 1923 | Swampscott, Mass. | (1) | 1,616 |
| 1922 | Niagara Falls, N. Y. | (1) | 950 |
| 1921 | Salt Lake City, Utah | (9) | 426 |
| 1920 | White Sulphur Spgs., W. Va. | (2) | 314 |

* District numbers in parentheses.

## Other Convention Features

### Technical Sessions

Two special sessions featured this year's formal program. One was an all-morning session devoted partly to a special address "The Engineer in a Changing World" by Ralph E. Flanders, past president of the American Society of Mechanical Engineers, and partly to a general discussion of the subject "How can the Institute programs be made of greatest value to the membership?" which was introduced by 7 discussions prepared by prominent Institute members. The second special session was an evening general meeting addressed by Director-Elect Vannevar Bush on the subject "The Engineer and His Relation to Government." These 2 special addresses and the 6 discussions mentioned are published in full elsewhere in this issue as part of the convention report.



S. B. Crary, Jr. (left) of Schenectady, N. Y., winner of the Mershon tennis trophy, being congratulated by W. J. Morrill of Fort Wayne, Ind., runner-up

The 10 regular technical sessions accommodated the presentation and discussion of some 39 formal technical papers and 4 technical presentations of a special character. In addition, and for the benefit of the specialists particularly interested, 2 conference meetings were included in the schedule: one on field problems, and one on electrical apparatus for 3-phase arc furnaces. These 2 technical conferences provided the opportunity for informal discussion of several topics of specialized interest.

### Attendance

With its total registered attendance of 1,067, Milwaukee sets an attendance record for summer conventions that has not been exceeded since the summer convention held in Detroit in 1927. In one of the accompanying tabulations is given an analysis of the attendance at the current summer convention; in another table are given comparative registrations over a period of years.

### Entertainment

A generous and well organized program of entertainment, and special inspection trips involving attractive entertainment features, was provided by the Milwaukee committee for both men and women. The entertainment program opened Monday evening, with some 400 men in attendance at a stag buffet supper and smoker held at the Milwaukee Athletic Club, and with the women entertained at a buffet supper in the banquet room of the Schroeder Hotel. On Wednesday evening, some 470 men, women, and children, enjoyed a 2-hour boat trip on Lake Michigan. In spite of record hot weather, more than 400 were reported present at the president's reception and dinner-dance held Thursday evening at the Schroeder Hotel. The entertainment program was terminated by a "farewell gathering" for dinner Friday evening at the Bluemound Country Club.

Provisions for the reception and entertainment of the women were thoughtfully arranged and effectively carried out. Features arranged especially for the women included special inspection trips Monday and Tuesday, a tea Tuesday afternoon, a luncheon and card party at the Wisconsin Club Wednesday, "Country Club Day" Thursday at the Tripoli Country Club, and Friday open for activities of individual choice.

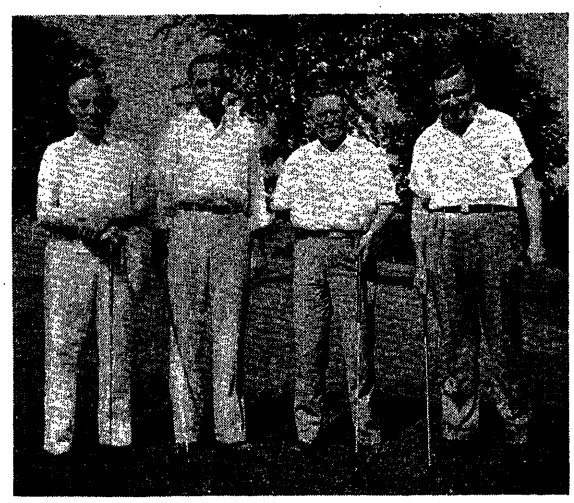
### Golf

Major golf events, of course, were the competitions for the Mershon and the Lee trophies and the District team contest.

The Mershon trophy is open for national competition among Institute members on the basis of match play under handicap. The 16 who qualified during the first day's play (low net score) were A. H. Sweetnam, Boston, Mass.; T. O. Rudd, New York, N. Y.; R. M. Darrin, Buffalo, N. Y.; R. A. Wheeler, Milwaukee, Wis.; H. T. McPhail, Denver, Colo.; G. V. Smith, Mansfield, Ohio; H. P. Kuehni, Schenectady, N. Y.; G. A. Kositzky, Cleveland, Ohio; Lee Cook, Dallas, Texas; W. O. Helwig, Milwaukee, Wis.; R. H. Fair, Omaha, Neb.; J. H. Irwin, Chicago, Ill.; R. G. Lorraine, Schenectady, N. Y.; H. O. Anderson, New Haven, Conn.; C. H. Teskey, Cleveland, Ohio; G. R. Canning, Cleveland, Ohio. Out of this field emerged:

Winner—C. H. Teskey (A'32)
Runner-up—G. A. Kositzky (M'22, F'29)

Mr. Teskey will be the second to have his name engraved on the present trophy, which is the third cup donated by Past President Ralph Mershon, the first having been won in 1931 by L. F. Deming of Philadelphia, Pa., after having withstood competitions since 1912; the second having been won in 1935 during the summer convention at Ithaca, N. Y., by L. R. Keiffer of Cleveland, Ohio, after having been in competition for only 4 years. The regulations governing the present trophy are that it shall remain on permanent exhibit at AIEE headquarters in New York bearing engraved upon it the name of the winner of each successive year's competition.



**A group of summer convention golfers (left to right): President A. M. MacCutcheon of Cleveland, Ohio, Chairman Lee Cook of the Dallas Section, Chairman E. D. Freeman of the Oklahoma City Section, and W. O. Helwig, chairman of the convention registration and housing committee**

The Lee trophy, presented in 1932 by the late Past-President W. S. Lee is awarded each year to the player having the lowest net score for 36 holes, and must be won twice by the same player for permanent possession. The results of the 36-hole medal play at Milwaukee were:

Winner—G. A. Kositzky (M'22, F'29) of Cleveland, Ohio

Runner-up—G. R. Canning (A'32) of Cleveland, Ohio

Mr. Canning narrowly missed winning permanent possession of the trophy. With the newest addition, the names now appearing on the Lee trophy are:

1932—C. H. Teskey, Cleveland, Ohio
1933—G. R. Canning, Cleveland, Ohio
1934—F. M. Craft, Atlanta, Ga.
1935—A. H. Sweetnam, Boston, Mass.
1936—H. S. Warren, Los Angeles, Calif.
1937—G. A. Kositzky, Cleveland, Ohio

District team competition, on the basis of 36-hole medal play was won by a team representing the Great Lakes District with a total of 667 gross for the 36 holes: G. F. Crowell (A'20, M'36), Milwaukee; J. H. Irwin (A'20), Chicago; E. L. McClure (A'37), Milwaukee; R. A. Wheeler (A'21), Milwaukee.

Each of the several day's play was featured by various special prizes. The winners of these special awards were too numerous to record here.

The golfing events for men were played at the Tripoli Country Club Monday and Tuesday afternoons, June 21 and 22, at the Ozaukee Country Club Wednesday and Thursday afternoons, June 23 and 24, and at the Bluemound Golf and Country Club Friday, June 25. The dinner dance held Friday evening at the Bluemound Country Club was intended to be the grand finale for the convention, at which prizes for golf and tennis competitions would be awarded. Early departures from the convention, however, restricted the attendance at this final affair.


## Membership—

Mr. Institute Member:

Please concentrate for just one minute on this thought: What man among your associates would receive most benefit from membership in the Institute?

Think over the list of men who are headed toward higher responsibilities, who would be broadened by the contacts with more experienced men in their profession, and who would profit by the discussions at the Section meetings.

Which one stands out? That man needs the Institute and the Institute needs and will welcome his membership. Why not speak to him right now?

A. B. Cooper

Vice-Chairman, District No. 10
National Membership Committee

### Tennis

The annual tennis tournament was held on the clay courts of the Milwaukee University School beginning Monday afternoon, June 21, and comprised both singles and doubles for men. The principal formal competition, of course, was for the Mershon trophy. Out of a field of 8 entrants in the singles tournament, W. J. Morrill (A'25, M'35) of Fort Wayne, Ind., and S. B. Crary, Jr. (A'31) of Schenectady, N. Y., emerged into the semifinals. Mr. Crary won the final match, and the privilege of being the third to have his name engraved on the present Mershon trophy which was donated in 1935 by Past-President Ralph Mershon to replace an earlier trophy that was permanently won in 1934 by E. F. Lopez (A'16, M'18) of Mexico City. The names now appearing on the current Mershon trophy are:

1935—Allen O. White, Washington, D. C.

1936—E. F. Lopez, Mexico City, D. F., Mex.

1937—S. B. Crary, Jr., Schenectady, N. Y.

Stipulations governing the present trophy are that it shall remain on permanent exhibit at Institute headquarters with the names of successive winners engraved upon it.

# Annual Conference of Officers, Delegates, and Members Held at Milwaukee, Wis.

SPONSORED jointly by the Sections committee and the committee on Student Branches, the annual conference of officers, delegates, and members of the Institute assembled for 2 busy sessions Monday and Tuesday afternoons, June 21 and 22, 1937, at the Hotel Schroeder in Milwaukee, Wis., as one of the regular activities of the summer convention. In attendance at the sessions were delegates from 57 of the Institute's 62 sections, 6 of the 10 District secretaries, counselor delegates from all 9 of the Districts in which committees on student activities have been organized, and many other local and national officers of the Institute and members actively interested in the conduct of Institute affairs. A complete list of the authorized representatives present is given in the accompanying tabulations. W. H. Timbie, chairman of the Sections committee, presided.

Topics discussed were essentially as outlined in a program mailed to delegates and others in advance of the meeting:

### Monday Afternoon, June 21

1. Opening remarks—President A. M. MacCutcheon.
2. Presentation of summary of past actions of delegates' meetings (1931 to date).
3. Presentation of summary of Section "self analysis" questionnaires.
4. Situation regarding registration of engineers.
   (*a*) In the East—representative from New York Section.
   (*b*) In the Midwest—representative from Chicago Section.
   (*c*) In the West—representative from Los Angeles Section.
   (*d*) General comments on Sections activities and present attitude of AIEE board of directors regarding registration—President MacCutcheon.
5. General discussion on above subjects.

### Tuesday Afternoon, June 22

6. Publication policy.
   (*a*) Report from publication committee—I. M. Stein, chairman.
   (*b*) Report from technical program committee—R. N. Conwell, chairman, of a special subcommittee of the technical program committee.
   (*c*) Mechanics and economics of past, present, and proposed schemes—G. Ross Henninger, editor.
   (*d*) General discussion.
7. Miscellaneous subjects.

Section and Branch activities were covered in some detail in a report published in the June 1937 issue of ELECTRICAL ENGINEERING, beginning on page 762. Inasmuch as this information thus already had been circulated to the entire membership, no pamphlet copies of the report were prepared for use at the conference, and nothing remains to be reported here.

### President MacCutcheon Opens Session

In brief opening remarks made at the request of Chairman Timbie, President MacCutcheon described the Institute as being "really only an organization of Sections," and sought to emphasize the responsibility of each Section delegate to these summer conferences. In speaking of the necessity for constantly planning for the future, President MacCutcheon spoke strongly of the value to the board of directors of well considered recommendations emanating from these annual conferences. He pointed out that all past recommendations of the conferences had received the attention of the board of directors and that many of them had been adopted as recommended.

In a manner supplementing the remarks of President MacCutcheon, Doctor H. H. Race, Schenectady, N. Y., of the Sections committee made available to members and delegates present a mimeographed record of all actions taken by the annual conferences since 1931, together with brief information as to subsequent action taken and disposition made of each recommendation. This report had been compiled by the Sections committee for the meeting partly as a matter of record and partly to avoid spending unnecessary time during the conference session in the discussion of matters already disposed of.

### Section Self-Analysis

Desirous of assisting in local Section activities, the AIEE Sections committee sent a questionnaire to each Section, March 23, 1937, suggesting that the questionnaire be used as a form around which to build a self-analysis of local activities. Four main considerations to which attention was called in the questionnaire were as follows:

1. Aim or objective of Section.
2. Activities carried on by the Section to accomplish the objective.
3. Results obtained by the activities during the last 5 years.
4. Changes or additions suggested in the activities by your Section.

Chairman Timbie reported that although the time allowed was short, some 25 returns out of the possible 62 had been received in time to report to the convention, and that others were expected later. Reporting for the Sections committee at the request of Chairman Timbie, Clifford M. Foust, chairman of the Schenectady Section, summarized the information given in the 18 responses that had been received by May 28:

I. *Aim or Objective of Section.* Some 60 total aims or objectives were recognized in 18 analyses returned, although cases of similarity reduced the number of definite and differing aims to about 25. The aim or objective set forth in the AIEE Constitution, article I, section 2, was specifically recognized by a considerable number of Sections:

> Its objects shall be the advancement of the theory and practice of electrical engineering and of the allied arts and sciences and the maintenance of a high professional standing among its members.

In addition the generally accepted objectives of practically all Sections may be briefly stated as follows:

> To provide opportunities for workers in the field to become acquainted, to exchange ideas, to keep up to date technically, and to advance the profession to higher standards.

Further items mentioned include the following:

1. To stimulate interest in national activities of the AIEE.
2. To stimulate contributions to ELECTRICAL ENGINEERING.
3. To inform the public of progress in electrical engineering.
4. To provide a place and an opportunity to present and discuss papers.
5. To assist the student and to retain his membership in AIEE.
6. To retain among the membership those of high professional reputation.
7. To promote individual, organizational, and civic interest.
8. To discuss topics of economic interest.
9. To co-operate with other engineering societies in promoting education and other purposes.
10. To supply where required an organization for the promotion of civic interests such as a popular lecture course.
11. To create opportunities of advancement for young engineers.

It is recognized that many of these stated objectives are means, not ends, and may be regarded as but secondary aims. However, these secondary aims are frequently the guides to the daily conduct of affairs, and must therefore be in accord with the primary aims or objectives as given in the Constitution and previously quoted.

II. *Activities Carried on by the Sections To Accomplish the Objective.* The principle

activities reported under this heading include:

1. Technical lecture meetings.
2. Combined business-social meetings.
3. Prize papers or paper competitions.
4. Combined Section and Student Branch meetings.
5. Technical discussion groups.
6. Young member discussion groups.
7. Co-operation with other engineering societies.

Some of the special activities reported to have been especially helpful to particular Sections include:

1. Popular non-technical meetings.
2. Inspection trips.
3. News letters.
4. Weekly luncheons.
5. Technical courses (particularly electronics).
6. Educational services to schools.

III. *Results Obtained From Activities as Carried on During the Last 5 Years.* Practically all Sections express confidence that substantial progress is being made toward the desired objectives summarized under item I through the program as outlined under item II.

IV. *Changes or Additions Suggested in Activities of Individual Sections.* This critical portion of the self-analysis lends itself less readily to summarizing than the preceding 3 sections, where an extensive degree of overlapping of aims, activities, and results permitted a fairly representative summary to be prepared. Under this section, however, no such overlapping prevails; each Section has its attention fixed for the moment on one or more changes that seem valuable to it. The following enumerates most of these prospective changes and attempts some classification:

**Those pertaining to organization**

1. More definite plans for active participation of young members.
2. More democratic elections.
3. Admit "local" members.
4. Make activities for members only.
5. Closer co-operation with Student Branches.
6. Establish a local advisory board.

## Table I. Record of Attendance of Section Delegates and Student Branch Counselors at Milwaukee Conference

| Section | Delegate Name and Affiliation |
|---|---|
| Akron | A. A. Austin (A'04, F'24) manufacturing engineer, Barberton, Ohio; Section chairman 1937–38 |
| Atlanta | J. M. Flanders (A'23, M'28) assistant superintendent, Georgia Power Company; Section secretary 1936–38 |
| Baltimore | R. L. Thomas (A'19, M'29) general superintendent, Pennsylvania Water and Power Company; Section chairman 1936–37 |
| Boston | C. L. Dawes (A'12, F'24) associate professor of electrical engineering, Harvard University; Section chairman 1936–37 |
| Central Indiana | L. F. Rick (A'20, M'37) assistant professor of electrical engineering, Purdue University |
| Chicago | N. C. Pearcy (A'24, M'30) electrical engineer, Public Utility Engineering and Service Corporation; Section chairman 1937–38 |
| Cincinnati | L. R. Culver (A'22, F'35) associate professor of electrical engineering, University of Cincinnati; Section chairman 1937–38 |
| Cleveland | F. E. Harrell (A'20, M'35) assistant chief engineer, Reliance Electric and Engineering Company; Section chairman 1937–38 |
| Columbus | E. E. Kimberly (A'16) associate professor of electrical engineering, Ohio State University; Section chairman 1936–37 |
| Connecticut | J. A. French (M'22) research engineer, Connecticut Light and Power Company; Section chairman 1937–38 |
| Dallas | I. R. Cook (A'25, M'35) supervisor of distribution, Texas Power and Light Company; Section chairman 1936–37 |
| Denver | H. P. McPhail (A'19, M'27) assistant chief electrical engineer, United States Bureau of Reclamation; Section chairman 1936–37 |
| Detroit Ann Arbor | D. H. Baker (A'09) transmission and protection engineer, Michigan Bell Telephone Company; Section chairman 1937–38 |
| East Tennessee | C. Hutchinson (A'30) electrical engineer, Tennessee Public Service Company; Section chairman 1936–37 |
| Erie | J. W. Teker (A'31) engineer, General Electric Company; Section chairman 1936–37 |
| Florida | W. Austin Smith (A'33) consulting engineer; Section chairman 1936–37 |
| Fort Wayne | D. H. Hanson (A'31) electrical engineer, General Electric Company; Section chairman 1936–37 |
| Houston | V. H. Clements (A'30) sales engineer, Westinghouse Electric & Manufacturing Company; Section chairman 1937–38 |
| Iowa | F. H. McClain (M'29) associate professor of electrical engineering, Iowa State College; Section chairman 1936–37 |
| Ithaca | K. P. Chamberlain (A'20) assistant professor of electrical engineering, Cornell University; Section chairman 1936–37 |
| Kansas City | A. L. Maillard (M'23) Kansas City Power and Light Company; Section chairman 1936–37 |
| Lehigh Valley | R. F. DeTurk (A'24, M'30) transmission and distribution superintendent, Metropolitan Edison Company; Section chairman 1937–38 |
| Los Angeles | J. C. Gaylord (A'11, M'26) hydro engineer, Southern California Edison Company Ltd.; Section chairman 1936–37 |
| Louisville | Stanley Warth (A'28, M'36) division transmission engineer, Southern Bell Telephone and Telegraph Company; Section chairman 1936–37 |
| Lynn | R. M. Pfalzgraff (A'29) assistant engineer, General Electric Company; Section chairman 1937–38 |
| Madison | E. D. Ayres (A'26, M'31) associate professor of electrical economics, University of Wisconsin; Section chairman 1937–38 |
| Memphis | F. G. Cartwright (A'30) relay tester, Memphis Power and Light Company; Section chairman 1936–37 |
| Minnesota | A. Nelson (A'28) sales engineer, Westinghouse Electric & Manufacturing Company; Section chairman 1937–38 |
| Montana | W. A. Boyer (A'26) electrical engineer, Anaconda Copper Mining Company; Section chairman 1936–37 |
| Nebraska | O. E. Edison (A'17, M'20) associate professor of electrical engineering, University of Nebraska; member, committee on Student Branches 1936–37 |
| New Orleans | F. G. Frost (M'22) general superintendent, electrical department, New Orleans Public Service, Inc.; Section chairman 1937–38 |
| New York | A. G. Oehler (A'18, F'26) editor, Simmons-Boardman Publishing Company; Section chairman 1936–37 |
| Niagara Frontier | R. M. Darrin (A'28, M'34) in charge of sales to central station customers, Buffalo District, General Electric Company; Section chairman 1937–38 |
| North Carolina | F. L. Moser (A'25, M'31) superintendent of maintenance, Duke Power Company; Section chairman 1932–33 |
| Oklahoma City | E. D. Freeman (A'32, M'35) superintendent, electrical department, Oklahoma Gas and Electric Company; Section chairman 1936–37 |
| Philadelphia | O. C. Traver (A'10, M'20) assistant designing engineer, General Electric Company; Section chairman 1936–37 |
| Pittsburgh | J. R. MacGregor (A'23, M'29) chief engineer, Bell Telephone Company of Pennsylvania; Section chairman 1936–37 |
| Pittsfield | A. Boyajian (A'18, F'26) technical engineer, General Electric Company; Section chairman 1937–38 |
| Portland | C. C. Boozier (A'23) sales engineer, Westinghouse Electric & Manufacturing Company; Section secretary 1936–37 |
| Rochester | E. H. Branson (A'15, M'35) director of engineering, research laboratory, General Railway Signal Company; Section chairman 1936–37 |
| St. Louis | L. O. Campbell (A'20, M'29) assistant to engineer, General Electric Company; Section secretary 1934–35 |
| San Antonio | N. B. Gussett (M'37) San Antonio Public Service Company |
| San Francisco | R. O. Brosemer (A'31) engineering department, General Electric Company; Section chairman 1937–38 |
| Schenectady | C. M. Foust (A'22, M'31) General Electric Company; Section chairman 1936–37 |
| Seattle | C. H. Hoge (A'19, M'29) assistant engineer, Puget Sound Power and Light Company |
| Sharon | T. H. Frankenberry (A'27, M'29) design transformer engineer, Westinghouse Electric & Manufacturing Company |
| Spokane | M. P. Hatch (A'33) assistant engineer, Washington Water Power Company; Section chairman 1937–38 |
| Springfield | C. G. Veinott (A'28, M'34) design engineer, Westinghouse Electric & Manufacturing Company; Section chairman 1936–37 |
| Syracuse | C. W. Henderson (A'20) professor of electrical engineering, Syracuse University; Student Branch counselor |
| Toledo | G. J. Clark (A'31) salesman, industrial division, General Electric Company |
| Toronto | M. J. McHenry (A'11, M'20) manager, Toronto district, Canadian General Electric Company; Section chairman 1936–36 |
| Urbana | H. J. Reich ('32) associate professor of electrical engineering, University of Illinois; Section chairman 1936–37 |
| Utah | C. A. Wolfrom (A'10) division manager, Utah Power and Light Company; Section chairman 1937–38 |
| Vancouver | F. L. Code (A'27) instructor, Vancouver Technical School |
| Virginia | J. E. Jackson (A'26) district manager, Appalachian Electric Power Company; Section chairman 1936–37 |
| Washington | J. F. Meyer (A'08, M'13) principal physicist, National Bureau of Standards; Section chairman 1937–38 |
| Worcester | V. Siegfried (A'32) instructor in electrical engineering, Worcester Polytechnic Institute; Section chairman 1937–38 |
| Chairman, Sections committee | W. H. Timbie (A'10, F'24) professor of electrical engineering, Massachusetts Institute of Technology, Cambridge |



(1) (2) (3) (4)

**(1) President-Elect W. H. Harrison (left) of New York, N. Y., interests Vice Chairman E. E. George of the East Tennessee Section, and Mrs. George. (2) Chairman H. S. Osborne (left) of the technical program committee, New York, N. Y., and Past-President J. B. Whitehead of Baltimore, Md., discussing a point of mutual interest. (3) Past-President H. P. Charlesworth, of New York, N. Y. (4) M. G. Malti (left) of Ithaca, N. Y., and Past Vice-President W. H. Timbie (right) of Cambridge, Mass., having an interesting discussion with a third party**

7. Better meeting place required.
8. Eliminate "local" members.
9. Representation on national committees.
10. Better co-operation with local engineering council.
11. Study and co-operate with ECPD on professional standing.
12. Refer applicants for admission to AIEE membership to local committee.
13. Appoint more young members to definite activities.
14. Increase number of contacts with engineers.
15. Elect chairmen of committees instead of appointing.
16. Give prizes for best membership work.

**Those pertaining to meetings**

1. Organize technical classes.
2. Study groups in public speaking, economics, business administration.
3. Hold meetings at other points in the Sections.
4. More inspection trips.
5. Discuss social and economic problems.
6. Take part in a monthly program with other societies.
7. Decrease number of meetings.

**Those relating to papers**

1. Exchange of papers in the District.
2. More national papers.
3. Begin a prize-paper contest.
4. Organize a committee to stimulate national papers.

In general these proposed changes are under consideration as means toward a more successful realization of avowed aims and objectives. Most of them have been tried in other Sections and frequently found valuable, while others have not been tried or have been unsuccessful experiments. However, local conditions, as has frequently been pointed out, call for local and particular treatment, and it is therefore desirable that each Section work out activities best fitted to its circumstances.

*General Results of Self-Analysis.* The 18 Section reports covered in the preceding digest are sufficient in number and of such quality as to justify the following definite conclusions concerning the analysis:

1. Each Section making an analysis has benefited by a better understanding of its own problems.
2. Through the availability of this summary, each Section can compare its own program with those of other Sections.
3. As a result of analyzing these returns, the Sections committee is in a better position to advise individual Sections concerning local problems.

Section officers are urged to communicate directly with the chairman of the Sections committee concerning any particular detail of this survey, or concerning any Section operating problem in which there may be a special interest.

## Registration of Engineers Discussed at Length

The current situation regarding the registration of engineers was the subject of practically a full afternoon's discussion. As indicated in the conference program, the general discussion was preceded by 4 informal reports: The eastern viewpoint was reflected by Chairman A. G. Oehler of the New York Section; the middlewest viewpoint was reflected by N. C. Pearcy of the Chicago Section; west-coast opinion was represented by Chairman J. C. Gaylord of the Los Angeles Section; President A. M. MacCutcheon traced briefly the evolution of the subject as it has been considered by the board of directors from time to time, and spoke at some length concerning the views that he had gathered incident to his recent contacts with a majority of the Institute's Sections.

Out of the ensuing discussion and variety of opinion concerning the various questions raised, the following general conclusions seemed to emerge as representing the consensus of opinion: (*a*) that inasmuch as laws providing for the registration of engineers have been adopted in some form or other by a majority of the States, efforts should be put forth to secure more nearly uniform legislation; (*b*) that ambiguities in existing laws should be clarified, and provisions made for the proper recognition of the different professional classes of engineers.

After extensive discussion of these and other phases of the problem, and after a generous exchange of experiences and recommendations from various Section representatives and other interested members, the entire question including a verbatim transcript of the meeting was turned over to a special national committee appointed by President MacCutcheon for the purpose of studying further into the question and for making such recommendations concerning national policy as might seem desirable.

## Publication Policy Considered at Length

In opening the Tuesday-afternoon conference session Chairman Timbie stated that the subject of publications was one of the 2 subjects for which a place on the conference program had been requested by a large number of Section representatives. He emphasized again that the principal objective of the discussions as scheduled was to provide an opportunity for the governing committees to learn "just exactly what the individual member wants," in this case "in the way of a publication policy."

## I. M. Stein Reviews Publication Policy

Chairman I. M. Stein of the publication committee read the following report:

"During the past year your publication committee has been studying our publication policy with the idea of recommending revisions which would provide an improved publication service to our membership.

"It will be recalled that a change was made in our publication policy in 1933 in order to effect economies which were necessary in view of our drastically reduced income. The arrangement adopted at that time has accomplished its primary purpose very well, namely, a substantial reduction in expenditures, and this without making any great reduction in the publication service rendered.

"Naturally it is desirable to retain all of those economies which do not materially interfere with the maintenance of a good publication service. On the other hand, there are some defects which should be remedied as soon as we can afford to do so. The arrangement adopted in 1933 reduced publication expenditures to what appears to be the practical minimum and, hence, any important modification is almost certain to result in some increase in cost, that is, unless, in providing some new desirable feature, some other feature which has been considered desirable in the past is withdrawn.

"However, in view of the improvement in general conditions, it is likely that we can afford a modest increase in publication expenditures in order to render better service.

"Among the improvements which many of our members seem to desire are the following:

1. An increased number of high-grade general interest articles in ELECTRICAL ENGINEERING.

(*Continued on page 1050*)

**Table II. Record of Attendance of District Student Branch Counselor-Delegates**

| District | Delegate Name and Affiliation |
|---|---|
| 1 | E. M. Strong ('26) assistant professor of electrical engineering, Cornell University, Ithaca, N. Y. |
| 2 | E. O. Lange (A'19) associate professor of electrical engineering, Drexel Institute, Philadelphia, Pa. |
| 3 | H. N. Walker (A'27, M'34) assistant professor of electrical engineering, New York University, New York City |
| 4 | S. W. Anderson (A'16, F'31) professor of electrical engineering, Virginia Military Institute, Lexington |
| 5 | S. S. Attwood (A'21, M'28) associate professor of electrical engineering, University of Michigan, Ann Arbor |
| 6 | G. H. Sechrist (A'20) chairman, electrical engineering department, University of Wyoming, Laramie |
| 7 | Chester Russell (A'29, M'34) acting head, department of electrical engineering, University of New Mexico, Albuquerque |
| 8 | E. F. Peterson (A'30) professor of electrical engineering, University of Santa Clara, Santa Clara, Calif. |
| 9 | J. A. Thaler (A'03, F'13) professor of electrical engineering, Montana State College, Bozeman |

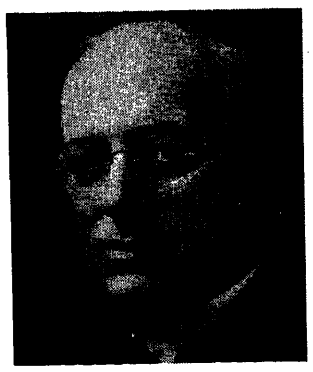
Chairman, committee on Student Branches—F. Ellis Johnson (A'13, F'31) dean of college of engineering, University of Missouri, Columbia

# Newly Elected AIEE National Officers



**M. J. McHENRY**
**Vice-President**

District Manager, Canadian General Electric Company, Toronto, Ont.



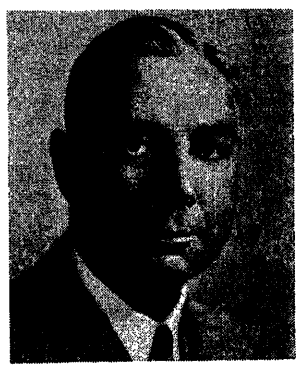
**E. D. WOOD**
**Vice-President**

General Superintendent, Louisville Gas and Electric Company, Louisville, Ky.



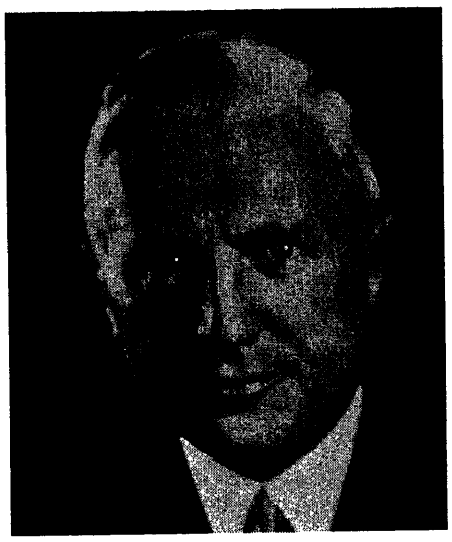
**I. M. STEIN**
**Vice-President**

Director of Research, Leeds and Northrup Company, Philadelphia, Pa.



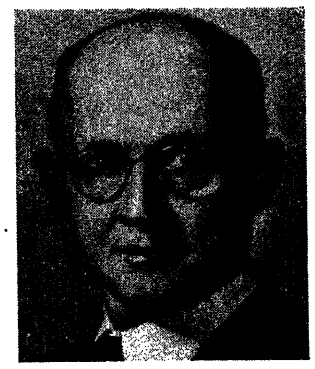
**L. N. McCLELLAN**
**Vice-President**

Chief Electrical Engineer, United States Bureau of Reclamation, Denver, Colo.



**W. H. HARRISON**
**President**

Assistant Vice-President, Department of Engineering and Operation, American Telephone and Telegraph Company, New York, N. Y.



**J. P. JOLLYMAN**
**Vice-President**

Chief of Division of Hydroelectric and Transmission Engineering, Pacific Gas and Electric Company, San Francisco, Calif.



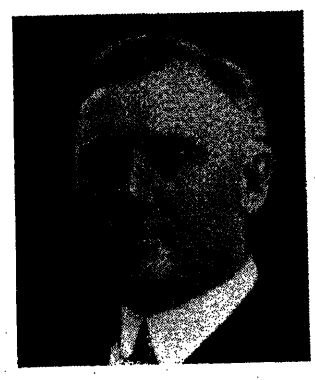
**C. R. BEARDSLEY**
**Director**

General Superintendent of Distribution Construction, Brooklyn Edison Company, Brooklyn, N. Y.



**VANNEVAR BUSH**
**Director**

Vice-President, and Dean of School of Engineering, Massachusetts Institute of Technology, Cambridge



**F. H. LANE**
**Director**

Manager, Engineering Division, Public Utility Engineering and Service Corporation, Chicago, Ill.



(1) (2) (3) (4) (5)

(1) Chairman I. Melville Stein of the publication committee, Philadelphia, Pa., and President A. M. MacCutcheon enjoying a good joke. (2) Past Chairman P. S. Biegler (left) of the Los Angeles Section. (3) Past Chairman F. R. Innes (right) of the Chicago Section. (4) Chairman J. C. Gaylord (left) of the Los Angeles Section interests E. L. Bettannier of Pasadena, Calif., and E. R. Hedrick of Los Angeles. (5) N. R. Stansel (left) of Schenectady, N. Y., past chairman of the committee on electrochemistry and electrometallurgy, conversing with M. R. Winkler of Chicago, Ill.

2. The restoration of some procedure for making available preprints of technical-program papers.

"Although the point has not been raised by many individual members, there is one important defect in the present publication policy which is quite evident to the publication committee and has been stressed by some outstanding Institute members who have clearly in mind the broad general interests of the Institute. This point has to do with the character of our annual bound volume called the TRANSACTIONS. With the adoption of the 1933 publication policy, the term TRANSACTIONS lost all real significance, as that volume then became nothing more than the annual bound volume of ELECTRICAL ENGINEERING. It seems clear that the broad general interests of the Institute would be served best if the earlier character of TRANSACTIONS were restored by publishing in TRANSACTIONS only those technical papers which mark a real advance in the electrical-engineering art. Probably this requirement could be met practically by publishing in TRANSACTIONS only those papers which have been approved by the technical program committee and which are otherwise acceptable to the publication committee.

"In keeping with these thoughts, the publication committee, at its meeting in January 1937, considered certain modifications in our publication policy. Several of these were approved by the committee and were presented to the board of directors, where they were also approved. Among these was one which is of general interest to our membership and had to do with providing a larger number of high-grade general-interest articles in ELECTRICAL ENGINEERING. The board of directors approved an increase in our publication budget in order to accomplish this, and those members who read ELECTRICAL ENGINEERING regularly have probably noticed an increased amount of such material, some dealing with economic and social subjects.

"The matters of providing preprints and of restoring the character of TRANSACTIONS were not included in recommendations to the board of directors, as it was felt that these features should have further discussion in the technical program committee and at this conference. The technical program committee referred these matters to a special subcommittee, which has made a real study of the matter and has arrived at tentative conclusions, some of which will be presented by the next speaker.

"The study made by this subcommittee has brought into the picture one feature not included in the publication committee's previous study, namely, the desirability of reducing the time between the submission of a paper to the technical program committee and its presentation at a meeting. This point will be discussed more fully by the next speaker and is mentioned here only because it ties in very closely with the matter of providing preprints. Specifically, the subcommittee's tentative recommendation is that the requirement of prepublication in ELECTRICAL ENGINEERING should be withdrawn and that the author's manuscript should be reproduced by the offset printing process so as to provide quite promptly at least a sufficient number of preliminary preprints to facilitate discussion at meetings. The subcommitee's tentative conclusions are in agreement with the publication committee's conclusions that the former character of TRANSACTIONS should be restored and that the contents of ELECTRICAL ENGINEERING should reflect the wishes of our membership in the matter of providing a large number of general-interest articles.

"It is apparent that there would be considerable opposition to making radical changes in our publication policy and procedures, and fortunately it would seem possible to provide the additional desirable features without making radical changes and with only a modest increase in publication expense. This might be accomplished about as follows:

1. Remove the requirement for the prepublication of technical-program papers in ELECTRICAL ENGINEERING and provide preliminary preprint copies of the author's manuscript by means of the offset printing process.
2. After technical-program papers have been presented, submit them to critical review and revision by the appropriate technical committees at the same time the discussion is reviewed, and then publish the paper and its associated discussion in a segregated section of ELECTRICAL ENGINEERING, the segregated section having appropriate page numbers to permit making an overrun for binding in TRANSACTIONS. The additional material in ELECTRICAL ENGINEERING, if bound at all, would be bound in a separate volume, carrying the title ELECTRICAL ENGINEERING.
3. Continue to provide a substantial number of general interest articles of a technical, economic, and social nature in each issue of ELECTRICAL ENGINEERING.

"It is not the intention of the publication committee to present at this time very definite recommendations, nor are we expecting this conference to pass any formal resolution with regard to publication policy, although, of course, this conference is at liberty to take any action that it pleases. According to our by-laws, it is the function of the publication committee to formulate a publication policy and submit it to the board of directors for approval. In formulating a publication policy, your publication committee desires to have the benefit of your advice and criticism and that is the purpose of presenting the matter here. It is hoped that you will discuss the matter freely and fully, stating just as informally as you like any dissatisfaction which you may have with the present publication policy and such changes as you may wish to have incorporated in this publication policy."

### PUBLICATION RECOMMENDATIONS FROM TECHNICAL PROGRAM COMMITTEE

Reporting for a special subcommittee appointed by the technical program committee, Director W. B. Kouwenhoven of Baltimore, Md., presented the following abstracts of recommendations endorsed by the technical program committee:

"The technical program committee, at its January 25 meeting, authorized the appointment of a special subcommittee to review our policy in regard to the handling of Institute technical papers and to report back to them any changes that were thought advisable." [Subcommittee: chairman, R. N. Conwell, past-chairman, technical program committee; J. W. Barker, past-chairman committee on production and application of light; and W. B. Kouwenhoven, director and past vice-president.]

"The problem of Institute programs and their proper handling involves not only the technical papers but also ELECTRICAL ENGINEERING, our publication, and TRANSACTIONS. As we see it, there are 4 or possibly 5 requirements that ought to be met. They are:

1. A minimum of elapsed time should pass between the preparation and presentation of a paper.
2. We should provide preprints of technical papers.
3. The TRANSACTIONS should carry high-quality contributions.
4. Development of ELECTRICAL ENGINEERING into a general-interest magazine or, as Mr. Stein put it, provision for making ELECTRICAL ENGINEERING a "balanced publication," containing a substantial number of general-interest articles in each issue.

"This subcommittee has held several meetings, and at the April 2 meeting of the technical program committee it presented a preliminary report making a few suggestions and asking for discussion. There was a gratifying response to our request, and, as a result of this discussion and further work, we submitted on June 8, to the technical program committee, a progress report suggesting 7 changes in our methods of handling technical papers and publications. In making these suggestions we had in mind 3 things:

1. To provide preprints for use at meetings.
2. Taking from ELECTRICAL ENGINEERING the necessity of publishing all technical papers submitted.
3. Making the TRANSACTIONS the principal place in which technical papers would be found.

Those suggestions are as follows:

1. The author prepares his manuscript in the

**Table III. Record of Attendance of District Secretaries**

| District | Name and Affiliation |
|---|---|
| 1 | R. G. Lorraine (A'29, M'36) central station dept., General Electric Co. |
| 2 | H. A. Dambly (A'24, M'30) asst.engr., special investigation and test div., Philadelphia Elec. Co. |
| 5 | A. G. Dewars (A'17, M'27) system planning engr., Northern States Pwr. Co. |
| 7 | L. C. Starbird (A'32, M'35) transmission and protection engr., Southwestern Bell Tel. Co. |
| 8 | Fred Garrison (A'22, M'29) commercial engr., General Elec. Co. |
| 9 | S. E. Caldwell (A'29) engr., Pacific Pwr. & Lt. Co |

form in which he wishes to present it and sends it to headquarters.

2. Manuscripts to be printed directly from the original immediately upon arrival, about 20 or 25 copies run off and the plates retained.

3. The editor of ELECTRICAL ENGINEERING receives his copy. The secretary of the technical program committee distributes the balance of the copies to the proper technical committee for review.

4. Review, grade, and recommend for or against presentation. They do no editing for the present, but retain their copies and notes.

5. If recommended for presentation, sufficient preprints are run off for distribution at the meeting. The editor of ELECTRICAL ENGINEERING may at this point elect to run all or part of the paper as a general interest article, if it suits his purpose.

6. Paper is presented and discussed.

7. Paper and discussion then edited by the proper technical committee, and recommended for inclusion in the TRANSACTIONS or discarded.

"These changes, if carried out, will tend to make ELECTRICAL ENGINEERING a general interest magazine. In the main, technical papers will appear in the TRANSACTIONS only. They will, however, be available in preprint form.

"We are hoping that at this meeting of the Section delegates and those others present, there will be considerable discussion of these proposals. Perhaps it may be that our membership is satisfied with the present arrangement; perhaps you desire changes. Not only do we want the changes and suggestions that you have here, but others that occur to you later. We would appreciate it very much if you would write Mr. H. S. Osborne (chairman of the technical program committee) and send him any suggestions that you may have."

### OTHER PHASES OF PROBLEM DISCUSSED

In discussing various questions raised with respect to publication procedures and related economics, Editor G. Ross Henninger pointed out that the so-called unified publication plan that has been followed for the past 3 years involved a minimum of cost for the amount of material published, and that any modification or broadening of any of the several phases of the Institute's publication service would require a commensurate increase in publication appropriation. Various phases of the publication problem were discussed at length by many interested delegates present.

To provide a means for expressing the opinion of members and delegates present in such a way as to guide the publication committee in formulating its policy modification, a hand vote was taken on the following questions, with the results as noted:

1. "Is our present publication policy generally satisfactory?" Yes, 16; No, 38.

2. "Shall the present general policy be continued, but provisions made for the printing of more material by using the present 'easy reading' type for only the summary of each paper, and smaller type for descriptive and technical portions?" Yes, 24; No, 36.

3. "Should ELECTRICAL ENGINEERING be 'popularized,' that is, have more general interest articles?" Yes, unanimous.

4. "Should preprints of technical papers be supplied at conventions, followed by publication in TRANSACTIONS?" Yes, 48; No, 5.

5. "Should the material of TRANSACTIONS be completely divorced from that of ELECTRICAL ENGINEERING resulting in effect in 2 separate periodicals, one of a general nature, and one technical?" Yes, 25; No, 40.

6. "Should TRANSACTIONS be split into sections according to subject matter so that each member can subscribe for individual sections?" Yes, 1; No, practically unanimous.

No formal action was taken by the group, it being the expressed opinion of Chairman Stein of the publication committee that the spoken character of the discussion had given to the several members of his committee present sufficient insight into the problem to enable the committee to proceed in due course with its disposition.



Vice-President C. F. Harding of Lafayette, Ind., and Mrs. K. L. Hansen of Milwaukee

For an hour or so prior to the closing of the conference, there was an active discussion of, and exchange of information and operating experiences concerning various operating problems confronting the Sections, such as the type of rooms provided for Section meetings and the cost thereof, and policies and procedures prevailing with respect to local members.

## Counsellor-Delegate Session

Under the leadership of Chairman F. Ellis Johnson of the committee on Student Branches, a large group particularly interested in that phase of Institute work spent all of Monday afternoon plus a dinner session Wednesday evening, in discussing various matters pertaining to Branch activity, and in exchanging experiences. These discussions concerned membership activities of the Branches, style and organization of programs, procedure in the election of officers, degree of stimulation of student participation in the preparation of technical papers, ways of developing leadership, the promotion of professional contact for student engineers, the relationship between the faculty and the Student Branches, and various suggestions concerning ways in which the Institute might aid in the development of Branch activity. No formal actions were taken nor resolutions adopted.

## Training for Marketing Industrial Products

A course of training in marketing technical products is being pursued by a group of young technical graduates employed by the Westinghouse Electric & Manufacturing Company, East Pittsburgh, Pa., under the leadership of Bernard Lester (A'06, M'13) assistant industrial sales manager of the company and lecturer at the University of Pittsburgh. The group, which consists of 25 men selected by their department heads, is taking the course as part of the University of Pittsburgh-Westinghouse graduate study program; this was described in the paper "The Pitt-Westinghouse Graduate Program" by H. E. Dyche and R. E. Hellmund in ELECTRICAL ENGINEERING, volume 53, January 1934, pages 103–08.

The days of the breezy, smart, slap-stick salesman have gone, according to Mr. Lester. Engineering selling today is a serious matter and although personality in the individual can add much to his success, the man who will attain a sound and continued success is the one who knows the technique of the product to be sold, the character of the market to be met, and above all, who is able to interest himself in his customer's problems and their solution. By study and application of principles the course aims to develop such men.

**Primer of Electric Service Costs.** A 94-page book comprising a discussion of utility problems from the standpoint primarily of utility costs has been written by Roy Page (A'11, M'21) vice-president and general manager of the Nebraska Power Company, Omaha, and published by Harper and Brothers, New York, N. Y. The book is intended primarily for educational use by public-utility employees, but according to the publisher also supplies material for all who are interested in public utility economics from any point of view. The author has been associated with the Nebraska Power Company for nearly 20 years, and formerly was employed by the Southern Pacific Company and the Pacific Telephone and Telegraph Company.

# Technical Conferences Held During Summer Convention at Milwaukee

A TYPE of meeting introduced at the 1935 summer convention at Ithaca, N. Y., and one that has proved most popular and effective, is the informal "technical conference." These conferences have been developed primarily to serve the younger members of the Institute and the technical specialists. Definitely on the program schedule at Milwaukee were 2 such technical conferences, one on field problems, and one on electrical apparatus for 3-phase arc furnaces. In addition, several technical subcommittee and other discussion-group sessions developed spontaneously during the course of convention week; these included meetings of:

1. Transformer subcommittee.
2. Joint subcommittee on insulation strength of electrical equipment.
3. Sectional committee on transformers.
4. Subcommittee on sphere-gap calibration and impulse-voltage measurements.

Available reports are given in the following paragraphs.

## Field Problems

By Ernst Weber, Chairman

The program of this meeting, which was attended by more than 50 people, was arranged as follows:

1. INTRODUCTION: The Field Concept in Physics and Engineering.
2. TOPICS:
   *a*. Graphical Field Plotting—Special Applications to Magnetic Fields.
   *b*. Analytical Solutions of Fields—Special Applications to Heat Problems.
   *c*. Conformal Representation—Special Applications to Electric Fields.
   *d*. Experimental Methods of Field Exploration—Special Applications to Hydrodynamics.

The introduction (by Chairman Weber) showed the evolution of the field concept from Newton to Maxwell in a historical survey. From the electromagnetic field the concept of continuous action then penetrated all other branches of applied physics; tables were shown to illustrate the common basis of mathematical treatment in all instances where the field concepts can be applied, such as electricity, gravitation, electron statics, magnetics, heat, electroconduction, and hydrodynamics.

To illustrate the most advanced experimental means for field exploration, films were shown by courtesy of the Institute of Aeronautical Sciences (RCA Building, New York, N. Y.) depicting experimental research in the laboratories of England and Germany. Various methods of making visible the flow of air past objects such as plates, wing profiles, and various attachments illustrated vividly the *lines of flow*.

A. L. Oklund (Marquette University, Milwaukee) described the adaptation of the electrolytic trough to obtain certain 3-dimensional field distributions important in designs of magnets. Sterling Beckwith (Allis-Chalmers, Milwaukee) delivered a discussion prepared by O. K. Marti (also Allis-Chalmers) describing the field distribution in rectifiers during the initiation of the arc.

Graphical methods to obtain field distribution were outlined by Doctor H. Poritsky (General Electric). Application of rotational symmetrical field plotting to the design of magnet poles, and for obtaining the stressed distribution in shafts under torsional forces was explained and illustrated. Professor H. B. Palmer (University of Colorado, Boulder) exhibited a motion-picture prepared under his direction, which gave the electric and magnetic field distribution about a 3-phase transmission line arranged in an equilateral triangle. This pictorial demonstration was received with great enthusiasm.

The treatment of 2-dimensional fields by conformal mapping was outlined by Chairman Weber. After a brief review of the theory of complex functions, the application of conformal representation to electron-tube problems was shown. The power of the method of transforming the boundary by means of complex functions was illustrated by an edge-correction problem, by profiling of airplane wings, and by problems in electron "guns." An application of the Schwartz-Christoffel theorem for the transformation of polygonal boundaries was given by Professor Palmer, who described the field about a capacitor.

Professor M. G. Malti (Cornell University, Ithaca, N. Y.) emphasized the difficulty of depicting the field in more complex arrangements, but Doctor Poritsky explained that at least approximate solutions always can be given by a proper combination of graphical and analytical methods. Professor Edward Bennett (University of Wisconsin, Madison) stressed the value of field methods in connection with research on antenna fields conducted under his supervision. Professor C. L. Dawes (Massachusetts Institute of Technology, Cambridge) emphasized the value of conformal representation in teaching electrostatics where time and labor can be saved to a considerable extent.

Informal group discussions continued after the conference session was formally closed.

## Electrical Apparatus for 3-Phase Arc Furnaces

By N. R. Stansel, Chairman

The first technical conference on electrical apparatus for 3-phase arc furnaces, sponsored by the AIEE committee on electrochemistry and electrometallurgy, was considered by all present to be highly successful, and by its result proved conclusively the value of such an informal conference as a means of disseminating information of use and interest to the engineers concerned, and of provoking a lively discussion on the subject under consideration. More than 100 persons attended.

As arranged by the chairman of the conference, N. R. Stansel (General Electric, Schenectady, N. Y.) the program provided for several brief and informal talks by engineers familiar with various aspects of arc-furnace equipment in which the user was particularly interested. Preceding these discussions, an illustrated talk was given by Samuel Arnold III (American Bridge Company, Pittsburgh, Pa.) concerning modern electrical equipment for arc furnaces.

The kilovolt-amperes required for arc furnaces in accordance with their dimensions and tonnage ratings was discussed by Frank Brooke (Swindell-Dressler Corporation, Pittsburgh, Pa.) and provoked some general comment.

Growth of the multivoltage arrangement for secondary voltages was outlined briefly by C. C. Levy (Westinghouse, East Pittsburgh, Pa.).

A lively discussion was aroused by F. V. Andreae (Ohio Ferro Alloys Corporation, Philo) by his comments on reactance, particularly with regard to the methods of specifying reactance in furnace circuits, and the effects of reactance.

In discussing regulations, F. E. Ackley (General Electric, Schenectady, N. Y.) emphasized some fundamental points in regulation with respect to maximum power inputs to a furnace, that are not always understood by furnace operators. He also described a newly developed electrode regulator.

Remarks concerning electrical protection for furnace circuits made by E. L. McClure (Milwaukee Electric Railway and Light Company) stressed the desirability of using service breakers for short-circuit protection independent of the furnace breaker itself, so as to avoid the problem of having an expensive circuit breaker especially designed for frequent operations.

A résumé of interesting analytical work done by the Detroit Edison Company to determine the size of sub-stations required to feed a given furnace load under prescribed conditions of maximum voltage variation, and what could be done when these prescribed conditions could not be met, was given in an illustrated discussion by L. W. Clark of that company.

**ASTM Awards Dudley Medal.** The American Society for Testing Materials has awarded the Dudley Medal for 1937 to W. H. Swanger, chief of the section of mechanical metallurgy and assistant chief of the division of metallurgy, and G. F. Wohlgemuth, associate metallurgist, of the National Bureau of Standards. The medal, which commemorates the name of the first ASTM president (1902–09), is awarded for the paper presented at the preceding annual meeting that is of outstanding merit and constitutes an original contribution on research in engineering materials. The winning paper, "Failure of Heat-Treated Steel Wire in Cables of the Mt. Hope, R. I., Suspension Bridge," describes the extensive work undertaken at the National Bureau of Standards to determine the causes of the failure.

# Last Call for the Pacific Coast Convention

THE Spokane Section extends a cordial invitation to members of the AIEE and their guests to attend the Pacific Coast convention in that city, August 31–September 3, 1937. As announced in the July issue, convention headquarters will be in the Davenport Hotel. A technical program has been arranged with papers on a wide variety of subjects, which will be presented by well-known Institute members. Social and recreational activities include a reception and dance, banquet, and golf; and a special program has been arranged for women guests. Inspection trips will be provided to points of interest.

The excellent possibilities for recreation and relaxation afforded by Spokane and nearby territory should induce many members and their families and guests to spend a few extra days in the city or at nearby lakes and resorts. There will be ample opportunity to use fishing tackle and golf clubs.

### Program

The tentative program published in ELECTRICAL ENGINEERING for July, page 911, is now the final program, with the following changes: The subject "Lighting the San Francisco-Oakland Bay Bridge" will be given as an address by C. R. Davis, and will not be published in advance. The sports committee has found it impossible to hold the golf competition on Wednesday afternoon, as originally planned. Therefore, the golf and banquet will be held on Thursday afternoon and evening, respectively, and the session on electrical machinery and the conference on electric house heating have been transferred to Wednesday afternoon and evening, respectively.

### Recreation

The golf tournament will be held on one of the several beautiful courses in Spokane. Arrangements may be made for members and guests to play at other times when desired.

Competition for the John B. Fisken Cup will be medal play on handicap in foursomes and will be open to members of the Districts 8 and 9 only. This perpetual trophy cup was donated by the electric utilities of the District 9 some 25 years ago, and competition for it has been very keen each year. Competition for a number of other golf prizes will be open to members and guests.

Excellent facilities for tennis playing are available within the city. Swimming, boating, and fishing may be enjoyed at any one of the many lakes and streams within a short distance of Spokane.

### Entertainment

On the first evening of the convention a reception and informal dance will be held in the headquarters hotel. This will provide opportunity for all to meet other delegates and officers, renew old friendships, and make other contacts.

The convention banquet and presentation of golf prizes will be on the third evening of the program. A number of interesting activities have been arranged for the women.

### Women's Program

The women's program committee, Mrs. L. R. Gamble, chairman, has arranged a number of parties in addition to the reception and dance and the banquet. These parties include a scenic trip through the home and civic gardens of Spokane, followed by an afternoon tea, putting and approaching contests for a number of prizes, a musical tea, and a luncheon and bridge tournament.

The many fine home gardens in Spokane will be an added attraction. The inspection trips also will hold the interest of many of the women guests.

### Inspection Trips

Probably of interest to the greatest number of members will be the inspection trip to the Grand Coulee Dam area. Construction work on the dam is going ahead rapidly and it is probable that at the time of the convention the entire foundation will be in place. At the present time the Columbia River has been diverted from the original channel and is flowing over some of the foundation blocks. The trip will include the model engineers' town, the contractor's electrically heated construction camp at Mason City and a ride through the several boom towns adjacent to the workings.

The inspection trip to the Coeur-d'Alene Mining District is of great scenic value, the road following the shore of Lake Coeur d'Alene to Wolf Lodge Bay and along the route of the Captain John Mullan military road through Fourth of July Canyon. In this area are found such great silver and lead producers as the Bunker Hill and Sullivan, the Hecla, the Morning, and the Sunshine mines. In Government Gulch is located one of the world's largest electrolytic zinc plants for the treatment of zinc ores. This plant is now being enlarged.

Special arrangements may be made for additional trips to nearby points of interest including the following: Long Lake and Little Falls hydroelectric plants of the Washington Water Power Company; Up-River hydroelectric plant of the City of Spokane equipped with Kaplan automatic adjustable-blade turbines; Clearwater electrified lumber mill at Lewiston; Inland Empire paper mill in Spokane; KHQ radio tower, tallest unguyed tower (828 feet) in the United States; and Comstock Park and Swimming Pool, Spokane.

### Joint Session With Radio Engineers

The Pacific Coast meeting of the Institute of Radio Engineers will be held in Spokane, September 1 and 2, concurrently with the AIEE convention and in the same hotel. Although the meetings of the IRE and the AIEE will be conducted separately, members of either organization will be welcome at the technical sessions of the other group. As previously announced, a joint session is planned for presentation of papers of interest to members of both institutes.

In addition, the inspection of Spokane's 4 broadcasting stations arranged by the IRE will be interesting to AIEE members who have not previously witnessed a broadcast.

### Hotels and Registration

All members who have received the advance registration card and who plan to attend the convention are urged to co-operate by immediately filling in and mailing the card, if they have not already done so. There is no registration fee for members or their immediate families or Enrolled Students. Nonmembers will be charged a registration fee of $2.

This card contains space for requesting hotel reservations. It is extremely important that this part of the card be filled out, because all available accommodations are expected to be taken during the convention. First and second choice should be given. Members who have not received an advance registration card and who plan to attend the convention should write promptly to D. H. Olney, chairman of the registration committee, care of Washington Water Power Company, Spokane, Wash., indicating the number of reservations desired, first and second choice, and the rate.

Rates in some of the leading Spokane hotels are:

| Hotel | Room for 1 | Room for 2 |
|---|---|---|
| Davenport (Headquarters) | $2.50–$4.00 | $4.00–$15.00 |
| Spokane | $2.00–$4.00 | $3.00– $5.00 |
| Desert | $2.50–$4.00 | $3.00– $5.00 |
| Coeur d'Alene | $2.00–$4.00 | $3.00– $5.00 |

Members should register upon arrival at the Davenport Hotel, official headquarters; registration will begin at 9:00 a.m., August 31.

### Student Activities

Besides the regular student conferences, the program includes 2 student technical sessions. Students will be welcome at all convention activities, including technical sessions, entertainment, and inspection trips. It is the hope of the Spokane Section that there will be full participation on the part of student delegates.

Special arrangements are being made for student housing facilities whereby students may have accommodations for $1.00 per night. Splendid auto camps are available for those who wish to use them. In sending in advance registration cards students should note the type and approximate price of accommodations required so that arrangements can be made in advance. They should also indicate whether transportation is desired for either or both of the major inspection trips.

# Divergent Views Expressed at Sessions on Institute Activities

DISCUSSIONS embracing widely divergent views featured the 2 general sessions on "Institute activities" held during the AIEE 1937 summer convention under auspices of the special committee on Institute activities appointed early in the year by President MacCutcheon. The first session was held on Wednesday morning, June 23, immediately following the presentation of the address "The Engineer in a Changing World" by Doctor Ralph E. Flanders (published elsewhere in this issue). The second session was held Thursday afternoon, June 24. These sessions were organized under the general chairmanship of H. S. Osborne, chairman of the committee; Director L. W. W. Morrow, and Past-President D. C. Jackson, respectively, presided at the 2 sessions.

At the first session, prepared discussions were presented by the following: Past-President A. W. Berresford (read by Past Vice-President G. G. Post); L. A. Doggett, past chairman of the committees on education and Student Branches; J. L. Hamilton, chairman of the committee on electrical machinery; F. R. Innes, past chairman of the Chicago Section; Vice-President Mark Eldredge; and Past-President J. B. Whitehead. During the second session, various interested members presented informal discussions from the floor. For the benefit of Institute members who did not attend the convention, full texts of the prepared discussions are published here.

## Institute Programs

By A. W. Berresford

My understanding of the purpose of this session is to obtain opinion as to the direction and degree in which Institute programs (and in "programs" I include activities) may profitably be extended.

In any such consideration one's thought reverts almost instinctively to social and economic problems. The years since 1929 have stressed them in degree unprecedented in the history of the Institute and many of them involve elements with which the engineer is familiar. Under these conditions nothing is more natural than that question should arise as to whether advantage would accrue to the Institute as a national body, and to its members as individuals, if consideration of and action on these public questions were accepted as an appropriate function.

Briefly stated, the objects of the Institute are the advancement of the theory and practice of electrical engineering and the maintenance of a high professional standing among its members. That it has achieved a notable accomplishment in its more than 50 years of life, and largely through adherence to these constitutional provisions, will, I believe, be generally conceded. To depart from them calls therefore for serious consideration. On the other hand, if actual advantage to the membership resides in such departure, or if the opportunity for the rendering of a real public service is presented, there should be no hesitancy. It may possibly be that some of the proposals of which I have heard could, by interpretation, be included within the present language of the Constitution, but this seems immaterial. The decision to undertake new activities is the important factor, not the question of whether or not the Constitution must be changed to permit.

It seems to me that there can be no doubt of the desirability of planned and intelligently directed discussion of these matters of public concern by the Institute membership. If no more were accomplished than the inevitably resultant self-education in the pertinent conditions, and the application of engineer thinking thereto, there would be ample warrant for the time and effort expended. If in addition the solutions evolved were of such nature and importance as to influence the thinking of other parties in interest, a definite public service would be rendered.

In my belief, however, if there is to be such practical accomplishment, the activity must begin and, at least for some years, be prosecuted locally. Only in localities can there be first-hand individual contact with the problems involved and really intelligent evaluation of all the elements which affect the ultimate decision. Moreover, an incentive to continuing interest and effective action will be needed, and this is better generated and maintained when individual welfare is directly affected than when the problems partake more of the abstract.

Such organization has had definite influence in public affairs in many places in matters involving engineering, and there is no reason for assuming other than equal influence in social and economic problems; granting only an equal intelligence, understanding, and application.

A notable instance is present, curiously enough, in the city in which we are convening. The Engineers' Society of Milwaukee, in which all of the local sections of the Founder Societies are affiliated, has for many years considered each public proposal which carried engineering content and has formulated and expressed its opinion thereon. The value of that opinion has come to such recognition that in many instances—if not in every one—the city authorities have requested it and have acted only after its receipt. In many cases it has been determinative.

Here then is one way in which both the members and the public can be advantaged by engineer consideration of these questions. If such an effort were instituted in as many as possible of the political divisions and subdivisions of the country, can there be doubt of a rapidly widening public appreciation of the engineer and of growing national prestige and recognition?

On the other hand, frankly, I doubt the possibility of directly exercising a national influence save through the foregoing procedure. The obstacles lie, not in the successful evolution of solutions, but in the securing of their adoption by the other parties in interest. Usually these are composed of people who are comparatively unskilled in the specific subject, and to whom it is of relative rather than primary importance. This would not be the case if the engineer were politically significant. But he is not. He casts perhaps 200 thousand votes out of a total of 40 to 45 million.

Unless the proposal or solution he offers is so novel and forthright as to acquire immediately "head-line" prominence (and the improbability of this is evident) the engineer alone can do little toward forwarding enactment.

It is a political axiom that the public seldom weighs the facts—that it responds only to an appeal to the emotions or the pocketbook. It is my own belief that action is finally based not on the quality of thinking, but on the quantity. Only through allying himself with others can the engineer obtain the necessary quantity, and he will succeed in so doing only in the degree that self interest is evidently absent. He will be welcomed as a consultant and adviser, but will attain prominent participation only if his individual personal qualifications indicate it.

These qualifications will, necessarily and rightly, be exterior to his purely engineering attainment. They will involve political vision, administrative experience and diplomacy in operation much more than they will the technical aspects. The economist may be necessary to the solution and the engineer valuable in making it effective and practical, but its acceptance will demand the methods and experience of the politician.

Even more will these conditions apply in any effort to locate an engineer in prominent relation for the reason that he is an engineer, and that the functions to be performed are basically engineering. Again the demand will be for general qualification rather than specifically technical ones.

If I am right in the foregoing, does there lie any advantage to either the Institute or its membership in including in its national program activities which promise so little of success through its own efforts? How much of real effect in a national, social, or economic situation would be a statement of Institute opinion unless pressed by political activity and through political alliances? And if these are employed may not the resultant disadvantages quite outweigh the gains? In such a relation the Institute must anticipate being classed with those organizations which exist for material ends and may well be obliged to sacrifice some portion at least of its present nonprofit status with its accompanying advantages. Decision should be reached neither hastily nor lightly.

## Institute Activities

By J. L. Hamilton

I think it will be generally agreed that during the last 50 years the Institute has served its purpose and has done a splendid job. This period has been one of technological development, and the Institute has fostered that line of work to a remarkable degree. A discussion yesterday showed that we have not reached 100-per cent perfection; we never will, but by and large a very good job has been done.

We seem now to be living in a new world, a world that is moving more rapidly than

any of us has seen or observed before, and we naturally are wondering what we are to do about it and what part we should take as engineers. We seem to have reached the inquiry stage as to what is going on and how we are going to fit into this developing picture. First, in any problem there is the will to do and the need of doing, and second, is the ability to carry out that will. It would seem that we have reached the stage where there is a will to do something about it, and that is most encouraging.

President MacCutcheon, you will recall, on Monday morning outlined his work of the year, and particularly his visits to all the sections of the country, and he brought to us a summary of the messages which he received from the crossroads, if you please. I consider that message of special significance to us in connection with the subject we are discussing here now.

In the East a few weeks ago I heard a very profound discussion by profound thinkers, or at least as profound as we have in the country. It was on the success that the New Deal has had; and, whether we are New Dealers or not is beside the point, the New Dealers do know what is going on at the crossroads, not only at *some* of the crossroads but at *all* of the crossroads, and they have the ability to interpret and put into words what is being discussed at the crossroads.

To my mind the important thing before this Institute is the matter of procedure. Do we want a planned economy in the Institute? Do we want our present committees, as efficient as they may be, and our board of directors to shoulder all the problems? Is it fair? Do we not want to get the crossroads working and get this information correlated?

I recently heard a very splendid executive on business reorganization and rejuvenation make this rather interesting statement. He said: "If you want to know how to sell more goods, the chances are you cannot pull it out of your own gray matter entirely. Call in your salesmen from the field. Get them around the table. Have them tell you how to sell more goods. They can tell you more in a half-day discussion than you and your staff can develop in months and months of effort."

Can we not take a cue, therefore, from what efficient business men have found true in this respect? Can we not organize so as to get the crossroads working and get their views reflected and incorporated in what we want to do, to a greater extent than at present? Some of the matters that have been discussed by Doctor Bush and Doctor Flanders and others are certainly right along this line. They have indicated that we should have the will to carry out some of these things. Here we are suggesting one possible way of fulfilling that will by getting all of our membership to work.

In the Army—as you know there is perhaps the oldest type of organization we have—we have what is called the staff and the line organization—one to plan and one to carry out. As we sense it, do we not have a splendid line organization? Imperfect though it is, it has done a splendid job. Perhaps our problem now is to develop more of a staff organization, an organization to pick up what is being thought at the crossroads and translate it into policies for our line organization to execute; and will not such a program as this be very beneficial in helping us to our goal, that is, to know more about commercial engineering, if you please, to know more about management engineering, more about executive engineering, more about government, and more about our 2 newest sciences of which we are still profoundly ignorant, namely, economics and psychology?

## Institute Publications

By L. A. Doggett

Dean Potter entitled his 1933 presidential address before the American Society of Mechanical Engineers, "Whither Engineering?" In the present article a brief survey of the publications of the American Institute of Electrical Engineers has been made in order to describe their course to date and their present status. Such a study is essentially a study of both the meetings and the publications of the society because the published matter closely reflects the whole activity of the Institute. In short, "whither publications?" or "whither Institute activities?" means approximately the same thing.

### Historical Survey

The publications of the AIEE from 1884 to 1902 reveal that the membership in that period was almost wholly interested in technical matters. Between 1902 and 1911 the same situation existed except for 5 papers on the conservation of national resources and a paper by Henry Floy on "The Engineer's Activity in Public Affairs, Public Utility Commission, Franchise, Valuations." In this period a code of ethics was initiated and later adopted.

From 1911 to 1917 considerable activity occurred in the discussion of matters of public interest and of economic content. For example:

June 1910: Conservation of Water Powers, L. B. Stillwell
June 1911: Depreciation, Henry Floy
August 1911 : Electrical Engineers and the Public, D. C. Jackson
September 1911: Appraisals, H. M. Byllesby
December 1911: Report on Water Power Development
Public Policy Committee
June 1914: Evolution of the Institute, C. O. Mailloux
January 1915: Rate System, O. B. Goldman
January 1915: Control of Public Utilities, F. G. Baum
July 1915: Class Rates, F. G. Baum
September 1915: Inventories and Appraisals, C. L. Cory and others
October 1915: Rates, P. M. Lincoln
October 1915: Public Utility Management, P. J. Kealy
February 1916: Municipal Operation, A. G. Christie
April 1916: Water Power Development, G. Dunn
November 1916: Inventory and Appraisal, P. Betts
November 1916: Continuous Inventories, H. E. Carver
November 1916: Growth and Depreciation, J. Loebenstein

From 1918 to 1937 papers of economic content and papers dealing with public questions have been almost negligible in number. From time to time, however, an occasional president of the Institute has dealt with public questions in his presidential address. In the last few years among the "Letters to the Editor" the membership has shown a very decided tendency to think more and write more on social and economic questions.

The historical picture is one of continuous and almost complete devotion to technical subjects except in the 1911–17 period. Thus for over 50 years the Institute has preserved its policy of "scholarly isolation." Within the bounds of this single objective the publications of the AIEE present a record of technical accomplishment of which the members can well be proud.

### Present Condition

In the last 5 or 10 years the answer to "whither publications?" is fairly specifically answered by the code of the AIEE technical program committee. This committee is a development of the old meetings and papers committee. Although the code of this committee has never been adopted in the sense that the code of ethics was adopted, it does represent the outgrowth of a long period of experience both in the old and in the new committee. This code includes a 15-item list of "acceptable subject matter" and a 4-paragraph list of "subjects not suitable for Institute presentation." Without taking the time to quote these in detail, the intent was primarily to fix the metes and bounds of the Institute publications, restricting them very definitely to electrotechnical subjects. Some latitude was allowed, however, in the inclusion of related technical fields. Item (*k*) put the stamp of approval on applications of electricity to social purposes and item (*o*) on ethical and social aspects of the profession.

### Suggestions for the Future

Before hazarding any suggestions, some review of the past as presented is in order. It seems that there is a distinct similarity of performance in all the engineering societies. A study of the record will disclose that engineers have shown little inclination to interrelate their activities with the whole of life and to deal with the reactions of their activities upon the community. In some quarters they have been described as mere technicians. Almost the whole record is characterized by engineering remoteness. Engineers have built around themselves a high wall outside of which some of our fraternity are well qualified to venture or over which some of us might well cast an occasional glance.

The effect of the recent depression upon the public at large has brought to the fore a definite criticism of the scholarly isolation policy of the scientist and the applied scientist. It is said: "They have applied themselves too narrowly." The opinion of the layman is that the scientists are responsible for the social and economic consequences of their advancement of the theory and practice of their particular branch of science. In President Roosevelt's October 7, 1936 letter to those in charge of technical education, he mentions "the social responsibility of engineering" and says that engineering must "consider social processes and problems and must co-operate, in designing accommodating mechanisms to absorb the shocks of the impact of science."

Dedication to public service is one of the chief requirements of a profession. This dedication is not unrelated to professional recognition. It is therefore suggested that

the Institute rededicate itself to the public welfare in its broadest implications. The appointment of an AIEE national power policy committee is suggested. It is further suggested that engineers should not labor exclusively within their own hereditary field; that they should not ignore the criticisms of laymen in other fields; and that they should not continue their scientific detachment and remain unconcerned with the human relationships of their activities. The Institute might well appoint a public relations committee to find ways and means to interpret the engineer to the public.

Lastly and specifically it is suggested that the publication policy strive to increase the percentage of papers on social and economic subjects. This is nothing new to our Institute as evidenced by the 1911–17 group of papers and this is in no way inconsistent with the code of the technical program committee as stated in items (*f*), (*k*), and (*o*).

## Social Responsibility of the Engineer

By Frank R. Innes

By a vote of practically 10 to 1 a group of some 180 engineers in attendance at a joint meeting of the AIEE Chicago Section, and of the electrical section, Western Society of Engineers in Chicago, March 22, this year, went on record in favor of "vigorous, effective action" by the professional engineering society in national affairs of engineering nature within its particular field. This vote was taken after the presentation and discussion of 2 papers, the first on the general aspect of the responsibility of the engineer in social and economic matters by Mr. P. B. Juhnke, and the second by your present orator on the specific responsibility of the electrical engineer in electrical-engineering matters that now occupy the forefront of national attention.

This meeting was planned to elicit indications of interest or the lack of it from the rank and file of engineers on, first, whether or not social and economic questions should be discussed at engineering meetings and, second, whether or not the professional engineering society should actively concern itself in national affairs within its technical scope. A ballot was taken on the 2 questions. The vote on the first was: "Yes," 186; "Yes, with reservations," 3; and "No," 2. On the second question, that of active participation of the engineering society in national engineering affairs, the vote was: "Yes," 158; "Yes, with reservations," 10; and "No," 17. This vote indicates positively that the engineer is interested in social and economic matters and wants to discuss them. It also indicates, almost as positively, that the engineer wants his professional society to represent him and act for him in national affairs.

Many of us self-appointed spokesmen for our profession have been talking about the social responsibility of the engineer. We have spoken in general and nebulous terms that are in themselves a denial of the engineering method we recommend. We cannot hope to be taken seriously in our assertions of the superiority of the engineering approach for solution of the social and economic problems of today unless and until we actually use that approach in our consideration of these problems and really begin to work on them in engineering fashion.

The engineering approach to any job is to resolve the job into its component parts so that the problems of each part may be handled and solved by minds qualified by training and experience for that particular work. Each kind of engineer works in a definite field. It is in this familiar way that the engineer must go to work on the big job of solving the social and economic problems that confront him.

We are electrical engineers. What is our share in this big problem of the social responsibility of the engineer? Obviously it is that part which involves electrical engineering. And to what aspect of that part should we give our first attention? Obviously again, we should give our first attention to that affair of electrical engineering in which government is now most active and in which the nation is now most interested. We are being asked by voices from outside our technical ranks to take action in this particular matter.

Doctor Raymond Moley in a recent issue of the magazine *Today* puts up to us this question: "All of us who are not engineers have been taught to believe that water power is the cheapest and most efficient and most permanent source of electrical power. Are we right or have we put our faith in a delusion?"

In various forms this question is appearing more and more in the public prints, as, for instance, in a Chicago Tribune editorial "Forty Years Behind," in which the government is charged with not being up-to-date in its power program. I have seen the same subject treated in other newspapers. I recently received a letter from Mr. Wesley Winans Stout, editor of the *Saturday Evening Post*, in which he stated he had editorialized on this subject 10 years ago.

Well, since the engineer as a professional class is being asked by the world outside to do something about this water-power matter, and since it is indicated by the vote in the Chicago meeting that the rank-and-file engineer wants something done, just what can the American Institute of Electrical Engineers do? This also is obvious. The Institute can examine the water-power program of the government and report on it to the nation commending what is found worthy in it and condemning what is unworthy.

Specifically, the Institute should investigate and report on criticisms of the program that are commonly current among engineers. Some of these criticisms are:

1. The only markets for the outputs of some of the government plants are those which can be taken away from existing utilities, the government thus endangering the investments of its citizens. Most of the other government plants are so remote from possible markets that it can be said for them that markets do not exist.

2. Today electricity can be supplied just as, or more, cheaply from fuel power plants close to the load than it can from remote water powers with long transmissions. It costs less to haul coal than to transmit electricity.

3. Water power, from an efficiency standpoint, is practically a completed art. At the same time its competitor, steam power, though less efficient on a thermal basis, has already surpassed it considering over-all plant economy. And the opportunity for further economy in the steam plant is very great.

4. Building water-power plants may aggravate the unemployment problem. It largely reduces plant operating labor and eliminates entirely labor for production and transportation of fuel.

5. Financing periods of half a century, which seem necessary to justify projects in the government program, appear indefensible in this day of rapid technical development.

These are the opinions of many engineers, not mine only. Probably there are some engineers who may see merit in the government program of water-power development, but I think all will agree that some of the criticisms mentioned may be justified in sufficient degree to warrant investigation and report to the people.

To be definite, I suggest that the Institute establish committees or boards of competent engineers to study and report on government projects of an engineering nature or to initiate and assure such studies by American Engineering Council or other co-oper ve agencies. Due to political emphasis on hydroelectric projects at this time it seems logical that this subject should receive first consideration. The findings of these investigations should be given the widest possible publicity.

It is a good thing for us to talk about the social and economic responsibility of the engineer, but it is a better thing for us to *do* something about it. The nontechnical world is asking us to act and the members of our professional organizations are telling us to act. Apparently then, we should act.

## Institute Programs

By Mark Eldredge

Programs for many organizations are arranged with the purpose of being interesting, but the subject for discussion puts the emphasis on "value to the membership," and that is the thought in these remarks.

We have 19 technical committees, all producing papers of keen interest to those members whose work lies along the lines of the specific subjects treated. These papers presented on Institute programs are not only interesting but are valuable to many of us because of the things we learn that have application in our individual fields of endeavor. Their value is measured in terms of our jobs which are so absorbing that frequently they are the beginning and end of our existence. Sometimes I think we engineers are like a colony of ants going here, going there, doing this, and doing that. We seldom take time to stand off and view in perspective the whole big job of living and note the part we play. Are we helping to build an ant hill or a path to a higher point? Do we comprehend where this or that new engineering development is taking us? Most of us are so absorbed in the daily routine that we give little thought to the part our own contribution to life adds to the world's real progress, or, if conscious of progress, we seldom consider the trend and whether the direction is right.

It seems to me there is one certain type of papers that would be most valuable to us all. Such would be studies or research on the effects certain details of technical progress have on general progress and improvement of human well-being. Since the first of the year, we have had some excellent general papers, such as, M. E. Leeds' "Engineering and Economics," John C. Parker's "Power and People," Harold G. Moulton's "Engineering Progress and Economic Progress," and R. C. Muir's "Some Engineering Contributions to Society." Between these

and the strictly technical papers lies the field I have in mind—papers that show the wide-reaching effect specific engineering achievements have had on social or national progress. In some cases, a chain or sequence of applications of some modern discovery might be shown to have had a very marked influence on the world. To be more definite, consider what a very romantic story might be told of the development of electron tubes; but, more important, what an amazing story might be unfolded of what they have already done to change and, we hope, to improve civilization. We can surmize some of the effects, but the results of research along this line might make a program of greatest value to the membership. It might awaken in us a greater realization of our ability to benefit the world.

Take another possible subject for a paper or a program: The discovery of a light-sensitive element made possible the light meter, which is doing so much to make people light conscious. What economic reaction is observable? Would not our lives be more purposeful if, while doing our routine tasks, we turned our thoughts more often to a consideration of the influence our particular bit of engineering progress is having on the world about us?

## AIEE Tradition and Policy

By J. B. Whitehead

For a number of years there has been increasing comment that engineers should take greater part in the discussion of questions of public interest and in the direction of certain types of public affairs. Such comment has often been heard within the AIEE, and more recently discussion and resolutions have been introduced into meetings of the board of directors proposing the formation of active committees not only for stimulating such discussion, but even proposing that the Institute should expend money and effort for examinations and investigations, and take public position on certain questions, in many instances necessarily, from their nature, of controversial character.

The Institute has so far, throughout its long and successful life been a conservative professional body devoted to the advancement of the electric art. It is the conviction of many of its members that its very life blood from the beginning has been its constant production of high-grade technical and scientific papers. It is certain that most of the young men who come into the Institute, and who ultimately become useful members, are those who are attracted by our strictly professional activity. Constructive and creative members of the Institute are almost invariably from this class. Few people will question that the high and strong position of the Institute throughout its more than 50 years of life, and its present healthy condition are due to its traditional policy of adhering to its fundamental purpose, "the advancement of the theory and practice of electrical engineering."

It becomes of great importance then to examine carefully any proposals for departures from our traditional policy. A review of some of the subjects that have been proposed for examination and discussion by the Institute, as a means of broadening its activities, reveals a startling conception on the part of some of our members of its proper range of discussion and action. One formal proposal that the Institute take a more active part in the examination of questions of the day lists among others the following: the effect of increase or decrease of values upon the workings of the national productive plant; comparison of American and Old World state of prosperity, and causes for the difference; the effect of unearned increment upon the state of American prosperity; the pros and cons of taxation; governmental efforts to regulate farms; better control of industrials; the overexpansion of productive facilities in utilities and railroads and the possibility of their regulation; the effect of regulation which destroys values, etc. Incidentally, it is proposed that the discussion of these questions should be free of political aspects! Another contributor suggests that a quarter of the activities of the Institute be devoted to the discussion of sales and commercial activities. Another wishes to see symposia for the discussion of all types of federal relief programs. Still another wishes to discuss, and presumably that the Institute should make public utterance on, the registration of engineers, the principles underlying public-works projects, the development of of engineers' unions and the depressing effect of federal power policies. Engineering examinations and public reports by the Institute on the Passamaquoddy and Fort Peck projects, and indeed on hydroelectric power in general, are seriously proposed.

In fact, if the complete list of all the proposals that have been made were given, it would be seen that there are few questions of the day, on whatever subject or of whatever character, which are not seriously proposed as proper matter for the expenditure of time, effort, and money by the membership of traditionally conservative AIEE. Here then are proposals from our own members for very radical expansions of our programs and wide departures from our avowed purpose of the advancement of the electric art and profession. We may well pause for a brief word of examination and comment.

No one will question the importance of every one of these problems and the interest in them of every good citizen. Every one of us would certainly wish to be identified with any movement which seemed likely to arrive at proper solutions of, or even to throw important light on, any of these contemporary problems. Especially so in these New Deal days when we so often experience irritation and impatience that so many of our public questions are settled, and public enterprises begun, without the careful study and examination which the engineer likes to see for all new undertakings.

The question, however, is where to begin and how to proceed? In most such problems great uncertainty exists as to essential fundamental facts, and premises based on recognized principles are not evident. Owing to their contemporary character, the causes giving rise to these questions are obscure, differences of opinion pronounced, and the elements of personal and group material and political advantages enter. How can an engineer deal effectively, even to his own satisfaction alone, with questions so involved in obscurity? The answer is that he cannot. Given the time and money, he might, it is true, examine a concrete government undertaking such as the Passamaquoddy power project, and even its economic feasibility; but would that answer the still deeper question of the validity of the government's purposes in undertaking it? Where would AIEE get with an examination of the Tennessee Valley Authority and its activities, when there are differences within its own board of engineers as to its proper development, and when there are questions between TVA and local power companies which have advanced through all legal stages up to the Supreme Court of the United States?

To my mind there are 2 very simple answers to the often repeated questions as to why an engineer does not take a more prominent part in public affairs. The first is that public questions are never sufficiently concrete, nor clearly defined, to permit quantitative determination, or even an enumeration of fundamental factors or elements. Second, even where such questions approach the tangible and concrete, it is by no means certain that legislation or public action will not be based on political expediency or group interest, rather than in accordance with correct economical engineering plan. Engineers are primarily rational and honest, and these virtues are not always at a premium in our present methods of solving contemporary public questions.

As contrasted with these extreme proposals, it is worth while to recall a report on Institute policy made to the board of directors in 1931 by National Secretary F. L. Hutchinson. The subject of the report was the desirability that the Institute's activities be extended in certain directions. The headings in the report indicating these suggestions, were as follows: Legislation Affecting the Engineering Profession; State Councils of Engineers; The Economic State of Engineers; Employment Service; Education of the Public Regarding the Engineering Profession; Engineering Education; Extension of Institute Work Throughout the Membership.

Not much suggestion here of the diverse economic, social, and political questions referred to hereinbefore. Moreover, it is a fact that every one of the subjects mentioned in Secretary Hutchinson's report is now being handled by well-organized committees, either of joint character with other societies as in American Engineering Council and Engineering Societies Employment Service, or within normally constituted committees of the Institute.

Happily, the extreme broadening programs mentioned have not been received with very wide acclaim, and those advocating them have taken a more moderate position recently. On the other hand, greater opportunity within the Institute for the discussion of questions of public interest, particularly where they touch the engineering profession, has been very extensively advocated. We have already taken some steps in that direction. And we are here today to discuss advisability of even further moves. Let us examine briefly the origin and character of this movement.

The Institute is open to anyone interested, no matter how remotely, in the development of the electrical art. As a consequence, we have among our members a very wide range of professional ability, attainment, and duty. It is a fine thing that this should be so. The Institute should nurture particu-

larly its lower grades of membership. It needs their support and it needs recruits from their ranks for the working forces of its manifold activities. With the rapid expansion of our industrialization, this group within the Institute has become increasingly large. As it becomes large, it is natural that it should become more vocal. We should not blind ourselves, however, to the fact that its members are not yet completely nor broadly developed professionally, and that their opinions and proposals are often without sound basis in tradition, knowledge, and experience. For example, from this group come those who occasionally raise the question of what they get in return for their dues, mentioning only ELECTRICAL ENGINEERING and the fact that they cannot understand much that it contains. It is a question whether members who persist in this attitude and do not develop in some phase of the Institute's work ever attain full realization of the Institute's high purposes.

It is a day of aggressive democratization and socialization. The great levelling processes that are being urged everywhere, and we are now discussing an example, invariably suppress independent thinking, the application of new knowledge, and the advance of civilization. Witness the widespread suppression of research and initiative in Europe. It begins to look as though the English-speaking races are the only ones in which intellectual liberty can be expected to continue to blossom in the results of scientific effort and experimental research. We must, therefore, look out especially for these dangers not only in our country, but also within the Institute.

Unfortunately such dangers do not always seem to be appreciated even among our older members. Not long ago I heard one of them voice the belief that, being a membership organization, it was the duty of the Institute, and so that of its board of directors, to ascertain the wishes of the greatest number of its members, and to legislate accordingly. This, to my mind, is doubtful doctrine. When it comes to duty, the onus should be on the opposite side, namely, it should be the duty of every member of the Institute to consider that which will best contribute to the maintenance and elevation of its high standing, not only of professional conduct, but of professional achievement. The Institute from its beginning has been primarily a technical, professional, and scientific society. Its usefulness, dignity, and authority will be steadily impaired by just so much as we depart from the pursuit of these high purposes.

We should therefore go slowly with our programs of expansion into general fields. Material for publication, from outside our own ranks, is correspondingly difficult to scrutinize. Our columns have on occasion even been opened, though fortunately not often, to nonmembers with pet theories to advertise or other axes to grind. Committees with a specific broadening purpose to my mind are of doubtful value. Committees do not write or create papers. They look for papers rather than at the quality of material in them. Good papers are produced by individuals, each with a message which must find utterance. Moreover, we already give substantial support to general discussion in that through the publication and education committeees we are devoting to it an increasingly large amount of space in ELECTRICAL ENGINEERING. Much of the material so presented is good, and it seems to me that in these and other available channels, we already have ample facilities for the publication and discussion of general questions of all types.

Let it be remembered also that those public questions which would appear to be better solved by engineers, usually involve engineers of all types, not merely those in the electrical field. Also that a number of agencies such as the American Engineering Council, the Engineers' Council for Professional Development, the United Engineering Trustees, Engineering Foundation, and others, have been set up especially to deliberate and serve us as channels of communication with all forms of public activities involving the interests of the engineering profession and the possibilities of its utilization. Certainly so far as formal expression of approval from the engineering profession on any great public question is concerned, examination and study by one or more of these bodies, and final utterance through them, would have far greater value and authority than if undertaken within a single constituent member society.

What then must be said in reply to the question constituting the subject of this meeting? My answer is somewhat as follows:

Many social, economic, political, and other public questions frequently touch the interests, either material or other, of electrical engineers. Intelligent discussion of such questions by electrical engineers, therefore, becomes both proper and desirable. The Institute already offers high favorable opportunities for such discussion through the columns of ELECTRICAL ENGINEERING, and in the meetings of Sections' representatives at conventions and in meetings in the Sections themselves. I know of no reason why a thoughtful, well-considered paper on any such subject should not be accepted for publication in ELECTRICAL ENGINEERING. It is my belief also that there should be no restriction upon the range of topics discussed at the meetings of Sections' delegates, or in the Sections themselves.

The essential principles to be adhered to in connection with these activities are: first, that the Institute, its Sections, and any gathering of Institute members, must avoid formal endorsement and opinion in the name of the Institute, on public questions of controversial character. Papers and reports should be distinctly under the names of their authors, and submitted for publication through the regular Institute channels. The second principle is that formal papers for publication should be only of the highest grade, always carrying the weight of authority. The grounds upon which these principles are advocated are that questions controversial in character cannot be settled in terms of known facts and knowledge, and lead frequently to differences of opinion, which in their turn, often lead to antagonism as between groups. Such a condition obviously leads to a disturbance of unanimity and that pursuit of common interest which has characterized all work of the Institute in the past.

In my opinion the programs of our meetings are already extremely good. I have little suggestion for their improvement. By all means let us have increasing opportunity for discussion of general subjects in sessions such as the present one. But as regards publication, let there be constant careful scrutiny of papers of both technical and especially those of nontechnical character, so that the quality of both types may be steadily improved, even if the quantity of published matter be thereby reduced.

## AIEE Directors Meet During Summer Convention

The regular meeting of the board of directors of the American Institute of Electrical Engineers was held at the Hotel Schroeder, Milwaukee, Wis., on June 24, 1937, during the annual summer convention of the Institute.

Present: *President*—A. M. MacCutcheon, Cleveland, Ohio. *Past-Presidents*—H. P. Charlesworth, New York, N. Y.; J. B. Whitehead, Baltimore, Md. *Vice-Presidents*—O. B. Blackwell, New York, N. Y.; L. T. Blaisdell, Dallas, Tex.; Mark Eldredge, Memphis, Tenn.; R. H. Fair, Omaha, Neb.; C. Francis Harding, Lafayette, Ind.; W. H. Harrison, New York, N. Y.; C. E. Rogers, Seattle, Wash.; A. C. Stevens, Schenectady, N. Y. *Directors*—F. M. Farmer, New York, N. Y.; F. Ellis Johnson, Columbia, Mo.; C. R. Jones, New York, N. Y.; P. B. Juhnke, Chicago, Ill.; W. B. Kouwenhoven, Baltimore, Md.; Everett S. Lee, Schenectady, N. Y.; K. B. McEachron, Pittsfield, Mass.; L. W. W. Morrow, Corning, N. Y.; C. A. Powel, East Pittsburgh, Pa.; R. W. Sorensen, Pasadena, Calif. *National Treasurer*—W. I. Slichter, New York, N. Y. *National Secretary*—H. H. Henline, New York, N. Y. Present by invitation: *Past-Presidents*—D. C. Jackson, Cambridge, Mass.; P. M. Lincoln, Ithaca, N. Y.; Charles F. Scott, New Haven, Conn. *Officers-Elect*—C. R. Beardsley, Brooklyn, N. Y.; V. Bush, Cambridge, Mass.; F. H. Lane, Chicago, Ill.; M. J. McHenry, Toronto, Ont.; I. Melville Stein, Philadelphia, Pa.; Edwin D. Wood, Louisville, Ky.

Minutes of the meeting of the board of directors held May 24, 1937, were approved.

A report was presented and approved of recommendations adopted by the board of examiners at its meeting on June 16, 1937. Upon recommendation of the board of examiners, the following actions were taken: 4 applicants were transferred to the grade of Fellow; 13 applicants were transferred and 25 were elected to the grade of Member; 116 applicants were elected to the grade of Associate; 88 Students were enrolled.

Disbursements in June amounting to $22,774.41 were reported by the finance committee and approved.

Authorization was given for the organization of a Tulsa (Okla.) Section of the Institute and of a Wichita (Kans.) Section.

Upon request of the committee on safety codes and recommendation of the Institute policy committee, the board authorized a change in name of the former committee to "committee on safety," a change in its activities to the consideration and investigation of matters relating to the protection of persons and property against hazard due to or resultant upon the presence of electricity or the use of electrical apparatus,

material, and appliances, and the inclusion of its chairman among the ex-officio members of the technical program committee. The matter of changing sections 81 and 68 of the by-laws accordingly was referred to the committee on constitution and by-laws.

A special committee on Institute activities had been appointed to arrange for a session at the summer convention for the discussion of the subject of desirable topics for presentation at Institute meetings and for publication in ELECTRICAL ENGINEERING, and to report to the board of directors its reaction to such discussion. The session was held on June 23, and the committee's report thereon was presented. Action was deferred, copies of the report to be sent to the members of the board for study before final consideration.

Upon request, Past-President Charles F. Scott, an Institute representative upon the Engineers' Council for Professional Development, also chairman of that organization, presented a report concerning certain recommendations of the committee on professional recognition of ECPD, which had been submitted to the board of directors for consideration and action. As a result, the board authorized the appointment of a committee of 3 members of the board to study the recommendations and report to the board of directors. The following members of the board of directors for the administrative year beginning August 1, 1937, were appointed members of this special committee: W. I. Slichter (*chairman*), C. R. Beardsley, and O. B. Blackwell.

The board voted to extend an invitation to the members of the International Conference on High Voltage Systems (CIGRE) who may be visiting the United States at the time to attend the AIEE summer convention to be held in Washington, D. C., in June 1938.

In connection with the 1937 summer convention held at the Hotel Schroeder, Milwaukee, Wis., June 21–25, 1937, the board adopted resolutions of appreciation of the effective services of the general convention committee and the various subcommittees, and of the ladies committee, and also expressed its appreciation of the courtesies and assistance extended by the Hotel Schroeder, convention bureau of the Milwaukee Association of Commerce, Allis-Chalmers Manufacturing Company, Harnischfeger Corporation, The Milwaukee Electric Railway & Light Company, Cutler-Hammer, Inc., and Wisconsin Telephone Company.

Authorization was given for the usual allowance for traveling expenses of regular delegates from Pacific District (No. 8) and the University of British Columbia Branch to a joint conference on student activities to be held in Spokane, Wash., during the 1937 Pacific Coast convention, including also the member of the national committee on Student Branches in Pacific District (No. 8). In view of the fact that special action on such joint conference is taken each year, it was voted that a special committee be appointed to study the matter and recommend a permanent policy for inclusion in the by-laws, the committee to consist of the vice-presidents of the 3 Districts concerned, the chairman of the committee on Student Branches, and the chairman of the Sections committee as chairman.

There was an expression of the appreciation of the members of the board of directors of the very faithful devotion of President MacCutcheon to the duties of his office and the large amount of time contributed by him in furthering the best interests of the Institute.

Other matters were discussed, reference to which may be found in this or future issues of ELECTRICAL ENGINEERING.

## New Name and Scope for Safety Codes Committee

The name of the AIEE committee on safety codes has been changed to "committee on safety," and its activities changed to: the consideration and investigation of matters relating to the protection of persons and property against hazard due to or resultant upon the presence of electricity or the use of electrical apparatus, material, and appliances. Its chairman now is to be included among the ex-officio members of the technical program committee. These changes were authorized by the AIEE board of directors at its meeting of June 24, 1937, upon request of the committee on safety codes and recommendation of the committee on Institute policy.

One of the general committees of the Institute, the committee on safety codes was established in 1902, and has functioned continuously since that time. Previously, the scope of the committee, as defined in section 81 of the Institute's by-laws, was to consider and investigate all matters relating to the formulation of rules for the protection of persons and property against fire, accidents, and other hazards in connection with electrical installations and equipments, and to confer with similar committees of other bodies regarding the same.

## Canadian Engineers Celebrate Semicentennial

The Engineering Institute of Canada, founded in 1887 as the Canadian Society of Civil Engineers, celebrated its semicentennial during a series of meetings held in Montreal and Ottawa, June 14–19, 1937. Although the society originally was chartered as a civil-engineering society, by 1918 a much broader scope seemed to be desirable and the name of the organization was changed to Engineering Institute of Canada. Today the organization claims members within almost every class of engineering, and these various interests were reflected in the sessions of the anniversary meetings.

The opening session of the celebration was devoted to greetings from other societies and to the conferring of honorary degrees and awards. President A. M. MacCutcheon was the official AIEE representative at this session. The technical program included 5 sessions at which 22 papers were presented. By way of diversion inspection trips were made to engineering works in the Montreal and Ottawa districts.

## Lamme Medals Awarded by SPEE and Ohio State

In addition to the Lamme medal awarded annually by the AIEE, other Lamme medals are awarded by the Society for the Promotion of Engineering Education and by The Ohio State University, Columbus. These medals are made possible by 3 bequests provided in the will of Benjamin Garver Lamme (deceased July 8, 1924). As reported elsewhere in this issue, the AIEE Lamme medal for 1936 was presented to Doctor Frank Conrad (A'02) during the Institute's recent summer convention at Milwaukee, Wis.

The SPEE awarded its tenth Lamme medal July 1, during its convention at Massachusetts Institute of Technology, Cambridge, to Dean Frederick E. Turneaure of the college of engineering of the University of Wisconsin, Madison, "for his influence upon the policies and people of the college of engineering of the University of Wisconsin; for his conception of a university as a co-operative enterprise of scholars and disciples in which freedom and power to initiate is diffused, not centralized; for the spirit of steadiness and confidence he has engendered; for the harmonious and co-operative relations within faculty and between faculty and students that have matured under his leadership; and in recognition of the high place he has filled in engineering education and in public estimation not only in his commonwealth but in the nation as well." Dean Turneaure was born on a farm near Freeport, Ill., July 30, 1866; graduated in civil engineering from Cornell University, Ithaca, N. Y., in 1889, and immediately engaged in railway engineering work; became an instructor in civil engineering at Washington University, St. Louis, Mo., in 1890; has been affiliated with the University of Wisconsin since 1892, since 1904 as dean of engineering. He is a past-president of the Society for the Promotion of Engineering Education (1908–09) and was a member of the board of investigation and co-ordination which directed the comprehensive study of engineering education carried out by that society from 1923 to 1929.

Two Lamme medals were awarded this year by The Ohio State University. One medal went to E. C. Bain, metallurgist and assistant to the vice-president of the United States Steel Corporation, New York, N. Y.; the other to Ellis Lovejoy, consulting engineer in ceramics, Columbus, Ohio. These medals were presented at the 1937 commencement exercises of the university, and, in accordance with the stipulations governing the awards, both are Ohio State graduates. Doctor Bain received the degree of bachelor of science in chemical engineering in 1912, master of science in 1916, and chemical engineer in 1923 from Ohio State. He received the honorary degree of doctor of engineering from Lehigh University, Bethlehem, Pa., in 1936. He has been engaged in metallurgical research for 15 years and is said to be the youngest engineer to receive the Ohio State Lamme medal. He was awarded the Robert W. Hunt medal of the American Institute of Mining and Metallurgical Engineers in 1929, and was Howe Memorial Lecturer of that society in 1932. Doctor Bain has

made important contributions to literature dealing with application of X rays in metallurgical research, the heat treatment of metals, and particularly the development of stainless and heat-resisting steels. He is president of the American Society for Metals. Mr. Lovejoy was graduated in mining engineering from Ohio State in 1885, 10 years before the department of ceramic engineering was established. He has spent more than 50 years in engineering research, invention, and management with the ceramic industry, and has been a consulting engineer in ceramics since 1904. He is the inventor of several original ceramic products, and the author of a number of papers, discussions, brochures, and books on various phases of the ceramic industry. He is a past-president of the American Ceramic Society.

## Middle Eastern District to Meet in Akron, Oct. 13–15

A 3-day meeting of the AIEE Middle Eastern District will be held in Akron, Ohio, October 13–15, 1937. Tentative arrangements indicate that an interesting program will be developed. Akron is a large industrial center and cognizance of such subjects as electrical applications in the rubber industry, lighting, and radio tower insulators, as well as the possibility of electrical applications for the production of iron and steel, will not be overlooked.

In addition to the technical sessions, arrangements will be made for entertainment events and inspection trips to places of interest in the vicinity. Other details will be announced when available.

Members of the Middle Eastern District meeting committee who are making the arrangements are as follows: Harold L. Brouse, *chairman*, I. Melville Stein, H. A. Dambly, A. G. Ennis, Paul Frederick, W. H. Harrison, W. C. Kalb, E. E. Kimberly, E. O. Lange, and O. C. Schlemmer; the following are chairmen of the committees indicated: A. O. Austin, meetings and papers; R. A. Hudson, entertainment and reception; H. H. Schroeder, attendance and publicity; H. C. Paiste, transportation and inspection; V. W. Shear, hotels and registration; J. T. Walther, student activities; Ralph Higgins, finance.

## Lamme Medal Nominations Due November 1

Attention is called again to the opportunity open to any member of the Institute to submit nominations for the 1937 Lamme Medal. All nominations must be received not later than November 1. (For further particulars, see ELECTRICAL ENGINEERING for June 1937, page 756.) The 1936 Lamme Medal was presented to Doctor Frank Conrad, assistant chief engineer of the Westinghouse Electric & Manufacturing Company, East Pittsburgh, Pa., at the opening session of the recent AIEE summer convention in Milwaukee, Wis.

## ECPD Publishes Engineering Bibliography

The committee on professional training of the Engineers' Council for Professional Development has just published 5 pamphlets which, taken together, should prove helpful to those in search of competent guidance in engineering literature. Primarily intended to aid the beginning engineer in choosing his reading, the lists should also be of service to librarians as guides in book purchasing.

The bibliography appears in 5 sections: (1) mathematics, mechanics, and physics; (2) aeronautical and civil engineering; (3) chemical and industrial engineering; (4) electrical and mechanical engineering; (5) metallurgical and mining engineering. These lists represent the considered opinion of many teachers and professional engineers. The choice of works has been confined to current American publications and, in general, to those of college grade. Annotations are provided.

The separate pamphlets can be had for 10 cents each, or for 5 cents each in lots of 50 copies, assorted if desired. Requests should be sent to Engineer's Council for Professional Development, 29 West 39th Street, New York, N. Y.

## McGraw-Hill Presidency Changes

The presidency of the McGraw-Hill Publishing Company, Inc., of New York was transferred as of June 21, 1937 to James H. McGraw, Jr., as the result of the resignation of Malcolm Muir from that post.

A Princeton graduate (1915) Mr. McGraw has served his company actively in various capacities; he became treasurer in 1923, executive vice-president in 1932, and in 1935 was elected chairman of the board to succeed James H. McGraw (A '01) founder of the company. In addition to his duties as president, he will continue as chairman of the board, according to the company's announcement

Malcolm Muir resigned the presidency of the McGraw-Hill company to assume the presidency of the company publishing *News Week*. He had served the McGraw-Hill company continuously since 1905 in various capacities including the general management of *Chemical and Metallurgical Engineering*, and later of that publication together with *Coal Age* and *Engineering and Mining Journal*. He became vice-president of the company in 1916, and president in 1928.

**ASTM Elects Officers.** At the first session on June 28, 1937, of the annual meeting of the American Society for Testing Materials, election of the following officers for 1937–38 was announced: *president*—A. E. White, professor of metallurgical engineering, and director, department of engineering research, University of Michigan, Ann Arbor; *vice-president*—H. H. Morgan, manager, rail and track fastenings department, Robert W. Hunt Company, Chicago, Ill.; *members of executive committee*—P. H. Bates, chief, clay and silicate products division, National Bureau of Standards, Washington, D. C., H. F. Clemmer, engineer of material, District of Columbia, Washington, G. E. F. Lundell, assistant chief, chemistry division, National Bureau of Standards, Washington, D. C., H. G. Mougey, chief chemist and assistant technical director, research laboratories division, General Motors Corporation, Detroit, Mich., and R. L. Templin, chief engineer of tests, Aluminum Company of America, New Kensington, Pa.

## Secretary of Institution of Civil Engineers Dead

Doctor Henry Homan Jeffcott, since 1922 secretary of The Institution of Civil Engineers, died June 29, 1937. He received his education at Trinity College and Dublin University and held the degrees of bachelor of arts, bachelor of engineering, and doctor of science. At Trinity College he was "first mathematical scholar, senior moderator and gold medalist, and M'Cullagh prizeman." Doctor Jeffcott's early engineering endeavors included brief associations with Siemens Brothers and Company, Ltd., Woolwich, England, as assistant engineer, and with Whitworth and Company, Ltd., Manchester. From 1905 until 1910 he was head of the metrology department of the British National Physical Laboratory.

In 1910 Doctor Jeffcott was appointed to the faculty of the Royal College of Science for Ireland, with the rank of professor of engineering, and remained at that institution for 12 years before being appointed to the secretaryship of The Institution of Civil Engineers. During the last 8 years of his stay at the Royal College he was dean of the college faculty. From 1918 to 1921 he was secretary of the subcommittee on water-power resources of Ireland, and since 1922 had been a member of the board of studies in civil and mechanical engineering of the University of London. Formerly, he was an examiner in mechanical engineering in the University of Belfast, and in the National University of Ireland. He held several patents on mechanical devices, and was the author of numerous technical papers.

**AIME Announces Meetings.** Dates and places for 1937 fall meetings of the American Institute of Mining and Metallurgical Engineers have been announced as follows: September 13–18, regional meeting (joint meeting with the Canadian Institute of Mining and Metallurgy), Vancouver, B. C.; September 30–October 1 (tentative) petroleum division, Los Angeles, Calif.; October 7–8, petroleum division, Oklahoma City, Okla.; October 14–16, industrial and minerals division, Washington, D. C., and College Park, Md.; October 18–22, Institute of Metals and iron and steel divisions, Atlantic City, N. J.; and October 27–28, coal division, Pittsburgh, Pa.

## H. L. Cooper, Hydroelectric Consultant, Dies

Hugh Lincoln Cooper, president of Hugh L. Cooper and Company, Inc., New York, N. Y., and a world-renowned builder of hydroelectric power plants, died June 24, 1937, at his home in Stamford, Conn., after a brief illness. Colonel Cooper was born April 28, 1865, at Sheldon, Minn. Although he never received a formal engineering education, he received the honorary degree of doctor of laws from the University of Missouri and Parsons College, an honorary degree of doctor of engineering from Syracuse University, and an appointment as honorary professor of civil engineering at the State School of Engineering of the Republic of Brazil. He began his engineering career in 1881, as an apprentice engineer for the Chicago, Milwaukee, and St. Paul Railway Company, but after 3 years joined the engineering staff of the Chicago Bridge and Iron Company, and in that company he first established a reputation for himself as a structural designer.

In 1891 he went to Spokane, Wash., as northwestern manager of the San Francisco Bridge Company, where for 3 years he designed and built bridges, including a 500-foot steel arch for the Spokane Falls and Northern Railroad Company; however, he believed that hydroelectric development extended a great opportunity for engineering achievement, and in 1894 he began bidding independently on small water-power construction projects in the state of Washington. In 1897 he sought and gained a position as assistant chief engineer for the Stillwell-Bierce and Smith-Vaile Company, manufacturers of water wheels, of Dayton, Ohio, so that he might learn the fundamentals of turbine design.

Colonel Cooper's first big hydroelectric project was a 20,000-horsepower plant in the mountains of Brazil, for the Sao Paulo Tramway, Light and Power Company. From there he went to the Mexican Power and Light Company as chief engineer, and then to the Electrical Development Company of Ontario as chief hydraulic engineer. In 1901 he established his own consulting engineering practice, and for the next 12 years supervised the construction of many hydroelectric plants, including the 165,000-horsepower Keokuk development on the Mississippi River. During the World War he served as a Colonel in the Corps of Engineers of the United States Army, but was recalled from France to supervise the construction of the Muscle Shoals dam and power house on the Tennessee River. His most recent engineering achievement was the supervision of the construction of a 750,000-horsepower plant for the Union of Socialistic Soviet Republics, the Dnieprostroy Dam. He was a member of the American Society of Civil Engineers, American Institute of Mining and Metallurgical Engineers, The American Society of Mechanical Engineers, Society of American Military Engineers, American Institute of Consulting Engineers, Institution of Civil Engineers (Great Britain), and the Institution of Water Engineers (Great Britain).

# Current Items From American Engineering Council

## Proposed Increase in Engineering-Experiment Stations

Council is being called upon by members of Congress, engineers, and educators in the land-grant-college groups to support legislation proposing to increase the number of engineering-experiment stations and for advice regarding the attitude that should be taken toward such legislation. It has also come to Council's attention that there is competition between the "A and M" colleges and state universities for the allocation of funds for the construction and operation of engineering-experiment stations.

So much confusion has arisen regarding this legislation that President Roosevelt has appointed 3 committees to study it. The National Research Council was first called upon to appoint a committee headed by Doctor Charles W. White. After that committee had gotten into action, some question arose as to whether it should make a final report, and the President appointed a committee on industrial training headed by Doctor Floyd Reeves of Chicago, Ill., who was formerly director of personnel with the Tennessee Valley Authority. A third committee has just been started by the National Resources Committee to investigate human resources, which is understood to include questions regarding engineering educational facilities in land-grant colleges.

In addition to this legislation, it is interesting to note that money is now being appropriated from relief funds to colleges for research and other purposes through 3 different organizations: under relief projects set up under the Works Progress Administration; under the National Youth Administration, which operates under a committee of which Mr. Joseph Roach is chairman and Mr. Audrey William is director, with substations in each state dealing with appropriating funds to the colleges and universites in each state; and a program of expenditure under Doctor Frank Persons of the Department of Labor for special purposes.

Such appropriations add to the confusion of purpose in current legislation and indicate that engineers should make a careful study of the entire situation before approving any of the proposed legislation or procedure. It is probable that some more acceptable form of federal support for engineering-experiment stations may result from the studies now being made by the president's committees and it may be advisable to wait for their recommendations.

Council's natural position in this matter is to represent the engineering viewpoint and the engineering profession of the country in the public welfare, and the staff is reluctant to go into controversy beyond that point in support of any legislation. Therefore, Council is endeavoring to confine its work in this connection to the accumulation and dissemination of information concerning the several pieces of legislation, including the opinions of member engineering organizations and Council's own committees.

Copies of the proposed bills have been mailed by Council to various interested parties. The AEC staff is contacting the chairmen of the President's committees and will advise its member organizations of additional information on this important issue as such information becomes available.

## Statistical Yearbook of World Power Conference

One of the objectives of the World Power Conference is the preparation of inventories of the resources of the world in fuel and power. The first inventory entitled "Statistical Yearbook of the World Power Conference," now ready for distribution, represents an excellent attempt to compile and publish international statistics of power resources, development, and utilization upon a comprehensive and comparable basis. Some of the information has not been published before in any country. As a collection of statistics on this particular subject, the work is probably unique and for this reason may prove most valuable to those interested in the development of world power resources.

Engineers, economists, statisticians, and others who require such information as comparable figures of coal consumed in the USA and the USSR, or of electricity generated in metallurgical works in Poland and Japan, or estimates of the world production of petroleum or wood, or the proportion of electricity generated by water power will find much of the information which was available in 1933 and 1934 in this compact volume which is being sold at $5 per copy by the American National Committee, World Power Conference, Interior Building, Washington, D. C.

## March of Rural Electrification

Rural electrification has increased from virtual stagnation during the depression to the highest peak in history. Without taking into consideration the new distribution lines constructed with federal financing, more new customers were connected to farm power lines in 1936 than in any other year since "electricity started to the country." Plans for 1937 indicate that privately financed lines will exceed those of 1936 and that the use of electric energy in rural areas is "on its way."

A large part of the increase in the rural use of electricity is said to be due to the

abandonment by utility companies of the practice of requiring farmers and rural industry to contribute to the cost of the lines which serve them. In many areas, distribution lines are being constructed to the consumers' property line without cash or deferred payment for such lines. Another contributing factor to the expansion is reported to be found in reductions in the cost of rural lines.

The Rural Electrification Administration reports that REA lines now equal privately financed lines. Plans and specifications prepared by engineers in private practice and approved by the engineering staff of REA are required on all projects, and Council is frequently called upon to suggest candidates for engineering positions in Washington and in the states. The compensation either by fee or salary is not always in keeping with that paid by private industry, but the engineering profession is being permitted to make its contribution to public as well as private rural electrification, and the appreciation of the value of engineering knowledge and experience is increasing and spreading to the less populated areas.

# Letters to the Editor

CONTRIBUTIONS to these columns are invited from Institute members and subscribers. They should be concise and may deal with technical papers, articles published in previous issues, or other subjects of some general interest and professional importance. ELECTRICAL ENGINEERING will endeavor to publish as many letters as possible, but of necessity reserves the right to publish them in whole or in part, or reject them entirely.

ALL letters submitted for consideration should be the original typewritten copy, double spaced. Any illustrations submitted should be in duplicate, one copy to be an inked drawing but without lettering, and other to be lettered. Captions should be furnished for all illustrations.

STATEMENTS in these letters are expressly understood to be made by the writers; publication here in no wise constitutes endorsement or recognition by the American Institute of Electrical Engineers.

## Mechanic Impedance In MKS Units

*To the Editor:*

The Giorgi, meter-kilogram-second (mks) system of units was adopted by the International Electrotechnical Commission (IEC) at Brussels in 1935.[1,2] The advantages of the mks system are notable and have been fully discussed in various papers.[3–5]

The purpose of this paper is to present the algebraic analogies of electric and mechanic impedance in a system of units that emphasizes the homogeneity of the 2 concepts. Such a system is the practical mks system of Giorgi.

Ohm's law governing continuous electric current flow in an electric circuit was published 110 years ago. In its well-known form it is:

$$I = E/R \text{ amperes} \qquad (1)$$

where $E$ is the impressed electromotive force, in volts, and $R$ is the electric resistance in *ohms*. This equation is in the mks system.

### Mechanics of Freely Falling Bodies

We may write, in analogy with Ohm's law, the velocity, v, of a freely falling mass:

$$v = F/R \text{ meters per second} \qquad (2)$$

where F is the gravitational force exerted on the falling mass in *joules per meter* or *newtons** and R is the mechanic resistance to motion of the mass. (The retarding influence of the air is neglected.) The gravitational force exerted on a mass M kilograms is gM newtons where g is the earth's gravitational acceleration at the position occupied by the mass. In mks units g is approximately 9.8 *meters per (second)*.[2] The mechanic resistance, R, may be written as M/t, M being the mass in kilograms and t the time of free fall, in *seconds*. Substituting these values in equation 2, we have the well-known equation:

$$v = gt \text{ meters per second} \qquad (3)$$

The mechanic resistance of the mass is thus expressed in *kilograms per second* and increases inversely as the time of free fall.

### Mechanic Impedance to Alternating Impressed Forces

When the mechanic force, F, impressed upon the mass, M, is not a uniform force of the gravitational type, but a simple sinusoidal alternating or vibrational force:

$$F = F_m \sin \omega t \text{ newtons} \qquad (4)$$

This vibromotive force tends to set up an alternating or vibrational velocity in the mass, according to the expression:

$$v = \frac{F_m \sin \omega t}{Z} \text{ meters per second} \qquad (5)$$

Here $Z$ is the mechanic impedance of the mass to vibrational motion. If the frequency of the impressed vibrational force is steadily maintained at $n$ *cycles per second*, the angular velocity of alternation is, according to a-c electric theory:

$$\omega = 2\pi n = 2\pi/T \text{ radians per second} \qquad (6)$$

T being the period of vibration in *seconds*. Equation 5 is similar to the well-known a-c equation.

$$i = \frac{E_m \sin \omega t}{Z} \text{ amperes} \qquad (7)$$

where $i$ is the instantaneous alternating current in a circuit having a steadily impressed alternating voltage $E_m$ sine $\omega t$ and $Z$ is the electric impedance of the circuit in *ohms*. It is known that there is a complete algebraic analogy between the mechanic impedance, $Z$, and the electric impedance, $Z$.

$$Z = R + jX = R + j(L\omega - S/\omega) \text{ ohms} \qquad (8)$$

If the electric circuit contains a resistance, $R$, *ohms*, a simple inductance, $L$, *henrys*, and a capacitance, $C$, *farads*, the electric impedance is a plane vector or complex quantity, $Z$, *ohms* with a real component, $R$, and an imaginary component, $j(L\omega - S/\omega)$ *ohms* where $S = 1/C$, an elastance in *farads*, and $j = \sqrt{-1}$. That is, the reactance $X$ is the difference between the inductive reactance, $jL\omega$, and the elastive reactance, $jS/\omega$.

If in equation 7 we replace the expression $E_m$ sine $\omega t$ by $E$, effective, or root-mean-square *volts*, it takes the well-known form:

$$I = E/Z \text{ effective amperes} \angle^{**} \qquad (9)$$

the familiar form of Ohm's law in simple a-c circuits.[6]

Returning to equation 5, the mechanic impedance, Z, takes the form:

$$Z = R + j(M\omega - S/\omega) \text{ kilograms per second} \angle \qquad (10)$$

Here R is the mechanic resistance offered by the medium surrounding the mass to vibrational motion, M is the mass of the body in *kilograms* and S is the elastic force of displacement in *newtons per meter*. It is here assumed that the mass is subjected to elastic restraint directly proportional to the displacement of the mass from its equilibrium position.

In equation 5 if we substitute the effective or root-mean-square value, F, of the impressed vibromotive force for $F_m$ sine $\omega t$, the effective value of the vibratory velocity steadily produced in the mass will be:

$$V = F/Z \text{ meters per second} \angle \qquad (11)$$

which becomes mechanic Ohm's law for vibrational velocity in the steady state. Mechanic equation 11 is the counterpart of electric equation 9 when the mechanic impedance, Z, is expressed in *kilograms per* second or *mechanic ohms*.

The $j$ operator appearing in equations 8 and 10 may be attributed to the geometric dimensional property of any small circular angle, $d\beta = ds/r$ where $ds$ is the small increment of arc perpendicular to the instantaneous radius vector $r$; so that, in the plane of reference, $ds = j\,r\,d\,\beta$. Hence, any angular velocity contains, inherently, the dimensions of a perpendicularity.

It may here be noted that the impedances dealt with in the field of acoustics are essentially mechanic impedances and may be expressed in the mks system in *kilograms per second* or *mechanic ohms*.

* The mks unit of force is known to be the *joule per meter* or that force which, exerted steadily over a distance of one *meter*, does work equal to one *joule*. This name is, however, relatively long and cumbersome. It has been suggested by several writers that this unit of force be provisionally called the *newton* until such time as action by the IEC may assign an international name. 1 newton = $10^5$ dynes.

** The angle sign $\angle$ indicates, as is well known, that the unit is not a simple but a complex quantity, or a plane vector. It may be read *"complex amperes"* or *"vector amperes."*

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4. ON THE SYSTEMS OF ELECTRIC UNITS, M. Ascoli. International Electric Congress, St. Louis, *Proceedings*, volume 1, 1904, pages 132–3.

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6. IMPEDANCE, A. E. Kennelly. AIEE TRANSACTIONS, volume 10, April 1893, pages 175–216.

Very truly yours,

A. E. KENNELLY
(A'88, F'13, HM'33, Life Member, Past-President)

JACKSON H. COOK (Enrolled Student)
Harvard University,
Cambridge Mass.

## Analogy of Magnetic Circuit and Long Transmission Line

*To the Editor:*

The solution of magnetic problems has been greatly simplified by the use of the circuit analogy. In such problems, it is generally assumed that the iron constituting the magnetic path carries all the magnetic flux and that the flux "flows" as a result of an applied magnetomotive force. With the exception of the air gap to which the flux is directed, it is generally assumed that the medium surrounding the magnetic circuit is a perfect magnetic insulator. If such an assumption is not made, the usual

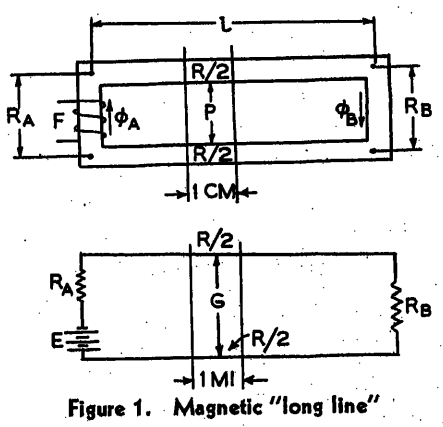



**Figure 1. Magnetic "long line"**

method is to apply arbitrary corrections to take into account the leakage flux and fringing effects.

It is at this point that the circuit analogy becomes faulty, since electric circuits are generally insulated by media which may be considered perfect. The only type of electric circuit which takes leakage currents strictly into account is the long transmission line, the characteristics of which have been worked out in detail and are readily available. The magnetic analogy of the long transmission line is one in which appreciable transverse leakage exists. It must be assumed that all the leakage flux is of a transverse nature and that the longitudinal leakage is negligible. A sketch of such a circuit is shown in figure 1.

If the constants of the material making up the circuit are known, then the following units are defined:

**Magnetic**

$\phi$—Flux
$\mathfrak{F}$—Magnetomotive force
$\mathcal{R}_1$—Reluctance per loop centimeter
$\mathcal{P}_1$—Leakage permeance per loop centimeter
$\alpha$—Magnetic hyperbolic angle per loop centimeter
$\mathcal{R}_0$—Characteristic reluctance

**Electric**

$I$—Current
$E$—Electromotive force
$R_1$—Resistance per loop mile
$G_1$—Leakage conductance per loop mile
$\alpha$—Electric hyperbolic angle per loop mile
$R_0$—Characteristic impedance

where $\alpha = \sqrt{\mathcal{R}_1\mathcal{P}_1}$, $\theta = \alpha l$, and $\mathcal{R}_0 = \sqrt{\mathcal{R}_1/\mathcal{P}_1}$.

If the analogous units are used, the relations developed for the electric long line

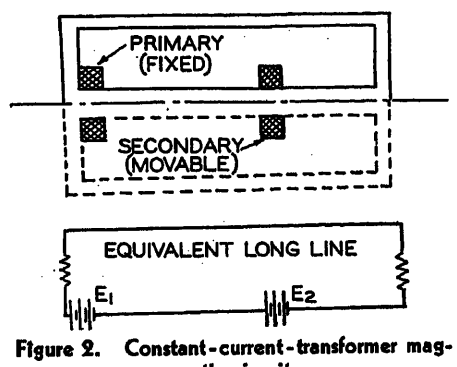



**Figure 2. Constant-current-transformer magnetic circuit**

can be used directly for the long magnetic circuit. Some useful formulas follow (refer to figure 1):

$$\phi_B = \mathfrak{F}_A \times \frac{1}{(\mathcal{R}_B+\mathcal{R}_A)\cosh\theta + \left(\mathcal{R}_0 + \frac{\mathcal{R}_B\mathcal{R}_A}{\mathcal{R}_0}\right)\sinh\theta} \quad (1)$$

$$\phi_A = \phi_B\left(\cosh\theta + \frac{\mathcal{R}_B}{\mathcal{R}_0}\sinh\theta\right) \quad (2)$$

$$\text{Leakage flux} = \phi_A - \phi_B \quad (3)$$

The particular problem to which this method of analysis may be applied is the constant-current transformer, which depends for its characteristics on the leakage flux produced by a magnetic circuit which is of the type described. The magnetic circuit of this transformer, along with its electrical analogy, is shown in figure 2.

The characteristics of a 5-kva 220-volt constant-current transformer, including the leakage inductance, necessary size of counterweights, shape of the sectored disk necessary to maintain optimum regulation, and other pertinent data were computed with ease from the physical constants of the magnetic circuit by the use of long-line formulas adapted to this particular magnetic problem. Tests made on the transformer showed a close agreement between the calculated and measured results.

This is, in general, an effective method of attacking the problem of the leaky magnetic circuit, providing, of course, that it satisfies the long-line conditions imposed on it.

Very truly yours,

J. R. RAGAZZINI (A'33)
Tutor, The College of the City of New York, New York, N. Y.

## Copper and Aluminum Cable Fusing Time-Current Formulas

*To the Editor:*

In the "Letters to the Editor" of the October 1935 issue of ELECTRICAL ENGINEERING, pages 1127–8, there is a letter by H. J. Reeves (A'30) regarding copper and aluminum cable fusing time-current formulas. There seemed to be a discrepancy in equation 2 as given; consequently, I communicated with Mr. Reeves and found that the equation had been misprinted. The equation should read as follows:

$$S_1 = \frac{2.3\,hH}{I^2\dfrac{r_0H}{y+t_0} - 1} \times \log_{10}\frac{\left(\dfrac{t_f-t_a}{t_0-t_a}\right)\left(I^2\dfrac{r_0H(y+t_f)}{(y+t_0)(t_f-t_a)} - 1\right)}{I^2\dfrac{r_0H}{t_0-t_a} - 1} \text{ (seconds)} \quad (2)$$

Very truly yours,

F. J. HORACEK
Junior Engineer, Consolidated Edison Company of New York, Inc., New York, N. Y.

## Tensor Analysis

*To the Editor:*

In ELECTRICAL ENGINEERING for March 1937, page 386, is published a very concise report about the sessions on tensor analysis at the 1937 AIEE winter convention.

Electrical engineers of the whole world, occupied in theoretical work, pay greatest attention and interest to the penetration of tensors into theoretical electrotechnics. This powerful mathematical method meets very contradictary appraisal. For that reason it would be natural to expect that the leader in this problem—United States of America—will publish all the discussion on tensors completely.

Therefore I think I shall express the opinion of all electrical engineers of the whole world, if I shall ask you earnestly to publish completely the report of the discussion on tensors at the winter convention.

Very truly yours,

V. N. LEBEDEV
Electrical Engineer, Dnepropetrovsk, U.S.S.R.

# Personal Items

H. B. DATES (A'98, F'32, member for life) professor and head of the department of electrical engineering, Case School of Applied Science, Cleveland, Ohio, has been elected president of the Illuminating Engineering Society. Professor Dates was born July 15, 1869, at New Britain, Conn., and received the degrees of bachelor of science in electrical engineering and electrical engineer (honorary, 1908) at Massachusetts Institute of Technology and Case School of Applied Science, respectively. From 1894 until early in 1896 he worked as a laboratory tester and inspector for the Westinghouse Electric & Manufacturing Company at Newark, N. J., and East Pittsburgh, Pa. In 1896 he received an appointment as professor of physics and electrical engineering at Clarkson School of Technology, where he organized the departments of physics and electrical engineering, planned the curricula, and equipped the laboratories. Professor Dates remained at Clarkson until 1903, when he became professor of electrical engineering and dean of the college of engineering at the University of Colorado. He has been head of the school of electrical engineering at the Case School of Applied Science since 1905, where, in addition to his regular teaching and administrative duties, he has served as a consulting engineer for the Cleveland Board of Education and for several commercial organizations. Professor Dates is a member of the Institute's committee on production and application of light, and was the first chairman (1907–08) of the Cleveland Section. He is a past-vice-president of the Illuminating Engineering Society, a member of the United States National Committee of the International Commission on Illumination, and a member or former member of several committees of that society. Professor Dates is the author of many books and papers on illumination. He is a member of the Society for the Promotion of Engineering Education, Sigma Xi, and Eta Kappa Nu.

F. V. MAGALHAES (A'07, F'19) assistant to vice-president, Consolidated Edison Company of New York, Inc., New York, N. Y., has been appointed executive assistant to the president. Mr. Magalhaes was born January 14, 1880, at Sao Paulo, Brazil, and received the degree of electrical engineer at the Polytechnic Institute of Brooklyn (N. Y.) in 1906. Following his graduation he was associated briefly with the Brooklyn Rapid Transit Company and the General Railway Signal Company before entering the meter department of The New York Edison Company in 1907. After 2 years he was made superintendent of the meter department, and in 1917 became superintendent of the test department also. From 1926 to 1928 he was superintendent of distribution and installation, but left the company in 1928 to become vice-president of the Hall Electric Heating Company. That company was liquidated in 1932, at which time Mr. Magalhaes became commercial representative for the General Electric Company at Lynn, Mass. He was appointed assistant to the executive vice-president of The New York Edison Company in 1935, and when the properties of that company and several others were merged recently under the Consolidated Edison Company name, he was retained in a similar capacity in the new organization. Mr. Magalhaes has been a member of the Institute's board of examiners since 1931, having served previously 1923–28, has been Institute representative on the electrical committee of the National Fire Protection Association since 1928, and since 1930 has been representative on the National Fire Waste Council, previously serving for the year 1928–29. He is at present a member of the committee on standards, has served on several other Institute committees, and for some years was secretary and vice-president of the United States National Committee of the International Electrotechnical Commission.

E. A. HARTY (A'22, M'36) designing engineer, General Electric Company, Lynn, Mass., has been awarded the AIEE North Eastern District prize for initial paper for his paper "Aging in Copper Oxide Rectifiers." Mr. Harty was born November 13, 1897, at Constantinople, Turkey, and received the degrees of bachelor of science and electrical engineer from Robert College (Turkey) in 1920. Following his graduation he entered the United States Department of State as a clerk in the American Consular Service, but in the following year became a mechanic in the construction department of the Shippley Construction and Supply Company, Brooklyn, N. Y. After serving briefly as an electrician for the New York, New Haven, and Hartford Railroad Company, he entered the student training course of the General Electric Company, Lynn, in 1923. In 1924 Mr. Harty was appointed a research assistant in the Thomson research laboratories of the General Electric Company, and for the ensuing 5 years his work embraced all phases of the design and production of copper-oxide rectifiers. Since 1929 he has been designing engineer on copper-oxide rectifiers, in which capacity he has also been responsible for the maintenance and improvement of the quality of such products. Mr. Harty is the author of several technical articles and papers, including 2 papers presented before the AIEE Lynn Section.

C. W. LEIHY (A'30) engineering editor of *Electrical West* and Pacific Coast editor of *Electrical World* has resigned from these positions to take over the editorship of *Electric Light and Power* with headquarters in Chicago, Ill. A native of Portland, Ore. (1905) Mr. Leihy received his education in that state and graduated in electrical engineering from Oregon State College, Corvallis, in 1926. Immediately following graduation, Mr. Leihy became affiliated with the General Electric Company and spent 2 years at Schenectady, N. Y., in the design and commercial departments, after which he was transferred to that company's Seattle, Wash., office as sales engineer. In the fall of 1930 he joined the McGraw-Hill Publishing Company's Pacific Coast organization in San Francisco, Calif. Mr. Leihy has maintained direct contact with electrical-engineering activities throughout the 11 far-western states, and has taken an active part there in AIEE affairs. He is a captain in the United States Field Artillery Reserve.

J. S. CARROLL (A'24, M'37) associate professor of electrical engineering, Stanford University, Calif., has received honorable mention in the 1936 AIEE national prize awards for best paper in theory and research



F. V. MAGALHAES



H. B. DATES



E. A. HARTY



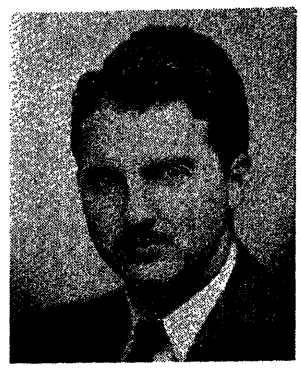
C. W. LEIHY



E. M. HUNTER



F. G. BOYCE



A. C. HERWEH



M. F. GILL

for his paper "Laboratory Studies of Conductor Vibration." Doctor Carroll was born November 26, 1891, at Orderville, Utah, and was graduated from the University of Utah with the degree of bachelor of science in electrical engineering in 1920. Following his graduation, he received an appointment to the faculty of the University of Utah as an instructor in electrical engineering, and remained there for 3 years before accepting a similar position at Stanford University in 1924. At that time he enrolled in the graduate engineering school at Stanford, and in the same year received the degree of electrical engineer from that institution; subsequently he undertook further graduate study and received the degree of doctor of philosophy in 1929. He was appointed assistant professor of electrical engineering in 1926, and has been associate professor since 1930. Doctor Carroll has been particularly active in high-voltage research work, having served as director of the Ryan high-voltage laboratory at Stanford, and is the author or co-author of many AIEE papers on that branch of engineering research.

A. C. HERWEH (A'37) instructor in electrical engineering, University of Cincinnati (Ohio) has received the 1936 AIEE Middle Eastern District prize for initial paper for his paper "An Open Arc Type of Stroboscope." Mr. Herweh was born January 29, 1907, at Cincinnati, and received the degrees of electrical engineer (1932) and master of science in engineering (1936) at the University of Cincinnati. From 1929 until 1932 he was a design engineer for the Union Gas and Electric Company. After serving for one year (1933–34) as assistant foreman in charge of loudspeaker production of the Crosley Radio Company, Mr. Herweh was designated a teaching fellow in the electrical-engineering department of the University of Cincinnati, and since 1936 has been a full-time instructor in electrical engineering. He is a member of Tau Beta Pi and Eta Kappa Nu.

M. F. GILL (A'14, M'33) formerly co-ordinator for the Pennsylvania Power & Light Company, Allentown, recently was appointed assistant to the president of the Kansas Gas and Electric Company, Wichita. Mr. Gill was born October 4, 1888, at Paris, Texas, and was graduated in electrical engineering at the University of Texas in 1910. Upon graduation he entered the employ of the General Electric Company, Schenectady, N. Y., as a student engineer but returned to Texas in 1913 as resident engineer on construction for the Texas Power and Light Company, Dallas; later he became office engineer and assistant chief engineer, in which position he was in charge of the engineering office of that company. After brief periods of service with the Stone and Webster Engineering Corporation, the United States Army, and the Phoenix Utility Company, he became assistant manager, and later manager, of the Texas Electric Service Company, Brackenridge. In the position of manager Mr. Gill was in responsible charge of all phases of operation, engineering, and construction of the company. In 1928 he was appointed general superintendent of the Phoenix Utility Company at Allentown, Pa., and remained in that capacity until 1935, when he became co-ordinator for the Pennsylvania Power & Light Company.

F. G. BOYCE (A'12, M'15) manager of electrical production, transmission, and construction, Consumers Power Co., Jackson, Mich., recently was elected vice-president of the company. Mr. Boyce was born February 8, 1884, at Philadelphia, N. Y., and was graduated from the Bliss Electrical School in 1907, following which he served for 2 years as a lineman before entering the employ of the Allis-Chalmers Manufacturing Company, Milwaukee, Wis., in 1909. He remained with that company until 1913, serving successively as an electrical tester, assistant foreman of the electrical testing department, and erecting engineer. Mr. Boyce then became construction foreman for the Stone and Webster Engineering Corporation and was placed in charge of the construction of several substations along the Mississippi River for the distribution of power from the Keokuk hydroelectric station. On completion of that work he took charge of construction, operation, and maintenance of power plants and substations for the Milwaukee Electric Railway and Light Company. He became affiliated with the Consumers Power Co. in 1917, after a brief association with the Goodyear Tire and Rubber Company at Akron, Ohio. He was made assistant manager of electrical production and transmission at that time, and in 1936 became manager of electrical production, transmission, and construction.

E. M. HUNTER (A'28, M'37) central station engineering department, General Electric Company, Schenectady, N. Y., has received the 1936 AIEE North Eastern District prize for best paper for his paper "Tests on Lightning Protection for A-C Rotating Machines." Mr. Hunter was born October 20, 1902, at Portsmouth, N. H., and received the degrees of bachelor of science in electrical engineering (1926) and electrical engineer (1930) at Worcester Polytechnic Institute; in 1931 he received the degree of master of science at Union College. After completing the General Electric test course in 1925, he was transferred to the a-c turbine-generator engineering department, where he was assigned to special design problems and the supervision of factory and field tests. Since 1928 he has been in the central station engineering department, and much of his work has been concerned with system stability studies, especially in relation to design problems. Recently much of his effort has been devoted to a study of the protection of machinery and systems against lightning. He is author or co-author of several AIEE papers on these 2 related fields.

W. E. MITCHELL (A'06, F'22) vice-president and general manager of the Georgia Power Company, Atlanta, has been elected a vice-president of the Edison Electric Institute for the term 1937–38. Recently he was also elected president of the Southeastern Electric Exchange. Mr. Mitchell was born June 23, 1882, at Milton, Mass., and received the degree of bachelor of science in electrical engineering at Massachusetts Institute of Technology. Following his graduation he entered the test course of the General Electric Company, Schenectady, N. Y., in 1903, but upon completion of the course in 1905 he went to South America as an assistant electrical engineer for the Sao Paulo (Brazil) Tramway, Light, and Power Company. In 1907 Mr. Mitchell became electrical engineer and operating superintendent of the Bahia Tramway, Light, and Power Company, where he remained until 1911, when he returned to the United States. After a brief period of service with the General Electric Company in San Francisco, Calif., he entered the employ of the Alabama Power Company as an electrical engineer in 1912, and subsequently became operating manager. During the World War Mr. Mitchell was managing director of the Anniston

Steel Company, but returned to the Alabama Power Company in 1918 as assistant general manager and held that position until he was elected president of the Georgia Power Company in 1927.

R. H. CARD (A'22, M'35) engineer for the American Telephone and Telegraph Company, New York, N. Y., has received honorable mention in the 1936 AIEE national prize awards for initial paper for his paper "Earth Resistivity and Geological Structure." Mr. Card was born at Pikeville, Tenn., July 28, 1897, and was graduated from the University of Tennessee with the degree of bachelor of science in electrical engineering in 1919, following which he entered the preliminary training course of the long-lines department of the American Telephone and Telegraph Company. In 1922 he was transferred to the division plant superintendent's office at Philadelphia, Pa., where his duties embraced supervisory work on inductive co-ordination. After 5 years Mr. Card was appointed division engineer in the Philadelphia offices, and was placed in charge of various aspects of transmission engineering, including inductive and structural co-ordination of power and telephone lines within the Philadelphia area. Since 1927 he has been stationed in the office of the long-lines engineer at New York, pursuing investigations of crosstalk and inductive co-ordination for the entire long-lines plant of the company.

E. L. BAILEY (A'19, M'25) electrical engineer for the Chrysler Corporation, Detroit, Mich., has received honorable mention in the 1936 AIEE national prize awards for initial paper for his paper "Induction Heating at Low Temperatures." Mr. Bailey was born January 3, 1885, at Lawrence, Kans., and was graduated from the University of Kansas with a degree in electrical engineering in 1907. Immediately following his graduation he entered the test course of the General Electric Company, Schenectady, N. Y., and upon his completion of the course in 1909 was transferred to the engineering department of the Chicago, Ill., offices of that company. Later he was transferred to the Detroit, Mich., offices of the General Electric Company as district engineer. During the World War he became superintendent of the Gas and Electric Company, Port Huron, Mich., and later a sales engineer for several electrical machinery manufacturers in Detroit. In 1925 he joined the electrical engineering staff of the Fisher Body Division of the General Motors Corporation, and in 1930 became affiliated with the Chrysler Corporation in his present position.

A. H. LAUDER (A'24) motor and generator engineering department, General Electric Company, Schenectady, N. Y., co-author of the paper "Pull-In Characteristics of Synchronous Motors," with S. B. Crary, Jr. (A'31) and D. R. Shoults (A'35) has received honorable mention in the 1936 AIEE national prize awards for best paper in theory and research. Mr. Lauder was born December 27, 1900, at Evanston, Wyo., and received the degree of bachelor of science at the University of Wyoming in 1922. During his senior year he served as an instructor in applied electricity, and following his graduation entered the testing department of the General Electric Company. After completing the test course, Mr. Lauder was transferred to the a-c engineering department, but later was transferred to the motor and generator engineering department, where he has remained continuously. His work in that department consists principally of the design of synchronous machines.

D. R. SHOULTS (A'35) industrial department, General Electric Company, Schenectady, N. Y., co-author of the paper "Pull-In Characteristics of Synchronous Motors," with S. B. Crary, Jr. (A'31) and A. H. Lauder (A'24) has received honorable mention in the 1936 AIEE national prize awards for best paper in theory and research. Mr. Shoults was born June 23, 1903 at Storms, Ohio, and received the degree of bachelor of science in electrical engineering at the University of Idaho in 1925, following which he entered the test course of the General Electric Company. In 1926 he was placed in charge of some of the tests on large motors and generators, and after 3 years was transferred to the industrial department, where his work has been concerned with electrical applications in the paper, lumber, and rubber-mill industries. He is the author of several technical articles.

S. B. CRARY, JR. (A'31) central station engineering department, General Electric Company, Schenectady, N. Y., co-author of the paper "Pull-In Characteristics of Synchronous Machines," with A. H. Lauder (A'24) and D. R. Shoults (A'35) has received honorable mention in the 1936 AIEE national prize awards for best paper in theory and research. Mr. Crary was born May 17, 1905, at Marquette, Mich., and was graduated from Michigan State College with the degree of bachelor of science in electrical engineering in 1927. Upon graduation he entered the test course of the General Electric Company, and has remained in the employ of that company continuously; in 1928 he was transferred to the transformer design department, but served there only briefly before being assigned to the central station engineering department in 1929.

R. D. MAILEY (F'30) vice-president in charge of engineering and manufacture, General Electric Vapor Lamp Company, Hoboken, N. J., recently was awarded an honorary degree of doctor of science by Stevens Institute of Technology as "an electrical engineer and physicist in whose laboratory were developed to their present efficiency as illuminants the mercury-arc lamp, the high-pressure mercury lamp, the sodium lamp, and other notable vapor-lamp equipment . . . . . internationally recognized expert in his field of physical research and industrial development." Mr. Mailey is a member of the Institute's committee on production and application of light.

JACK DELMONTE (A'36) who has been a laboratory technician in the engineer research laboratories of the Firestone Tire and Rubber Company, Akron, Ohio, now is assistant to the chief engineer of development and research, Chicago (Ill.) Flexible Shaft Company. Mr. Delmonte is a native (1913) of New York, N. Y., and an electrical engineering graduate of New York University. He pursued graduate studies in electrical engineering at Massachusetts Institute of Technology and the University of Pennsylvania. Before becoming associated with the Firestone Tire and Rubber Company, he was employed in the Naval Aircraft Factory, United States Navy Yard, Philadelphia, Pa.

E. M. WILLIAMS (Enrolled Student) graduate student in electrical engineering Yale University, New Haven, Conn., with R. F. Huminski, co-author of the paper "Frequency Multipliers," has received honorable mention in the 1936 AIEE national prize awards for Branch paper. Mr. Williams was born February 2, 1915, at New Haven, and received the degree of bachelor of engineering at Yale University in 1936. His present course of study leads to the degree of doctor of engineering. He presented a paper "A High-Voltage Parallel-Plate Electrostatic Voltmeter," at the North Eastern District student convention, Buffalo, N. Y., May 7, 1937.

H. B. FUGE (A'37) assistant engineer, Diehl Manufacturing Company, Elizabethport, N. J., has received honorable mention in the 1936 AIEE national prize award for Branch paper for his paper "A Direct Reading Linear Accelerometer." Mr. Fuge was born December 31, 1915, at Brooklyn, N. Y., and received the degree of bachelor of engineering at the Polytechnic Institute of Brooklyn (N. Y.) in 1936. Immediately after his graduation he entered the employ of the Diehl Manufacturing Company as an assistant in the engineering laboratory. In January 1937 he was promoted to assistant engineer, and has been assigned to fractional-horsepower motor design work.

D. R. BARNEY (Enrolled Student) graduate student in electrical engineering, Massachusetts Institute of Technology, Cambridge, has received honorable mention in the 1936 AIEE national prize awards for Branch paper for his paper "Tidal Power." Mr. Barney is a native (1915) of East Orange, N. J., and an electrical engineering graduate of the Newark College of Engineering. He expects to receive his master's degree in electrical engineering in February 1938.

A. D. FLESHLER (A'34) junior electrical engineer, Transit Commission, New York, N. Y., has been promoted to assistant electrical engineer. Mr. Fleshler is a native (1895) of Bessarabia, Russia, and a graduate of Cooper Union Institute and New York University. Before becoming affiliated with the New York Transit Commission he was employed by the Westinghouse Electric & Manufacturing Company and the Ajax Electric Company.

J. H. TREADWELL (Enrolled Student) Menard, Texas, has received the 1936 AIEE South West District prize for Branch paper for his paper "A Rotating Ball Slip Meter." Mr. Treadwell was born February 22, 1915, at Menard, and is at present enrolled as a student in electrical engineering at The Rice Institute, where he expects to receive the degree of bachelor of science in electrical engineering in 1938.

F. W. SMITH (A'05, M'12) retired president of the Consolidated Edison Company of New York, Inc., New York, N. Y., recently received the honorary degree of doctor of engineering from Stevens Institute of Technology. A brief biographical sketch of Doctor Smith appeared in the June 1937 issue of ELECTRICAL ENGINEERING, page 770, at the time of his retirement.

F. X. LAMB (A'36) chief of the commercial division, engineering department of the Weston Electrical Instrument Corporation, Newark, N. J., recently went to Japan to represent the Weston company as consulting engineer and adviser to the Nippon Electric Company, Tokyo. Mr. Lamb has been associated with the Weston company for more than 15 years.

ASGER VILSTRUP (A'20, M'27) chief electrical engineer, British Columbia Electric Railway Company, Ltd., Vancouver, has been elected chairman of the Northwest Electric Light and Power Association for the term 1937–38. A biographical sketch of Mr. Vilstrup appeared in the February 1937 issue of ELECTRICAL ENGINEERING, page 289.

T. S. TAYLOR (M'21) professor of physics, Washington and Jefferson College, Washington, Pa., recently resigned to become manager of the engineering laboratory and experimental department of the Diehl Manufacturing Company, Elizabethport, N. J. Doctor Taylor formerly was a research physicist for the Westinghouse Electric & Manufacturing Company, East Pittsburgh, Pa.

R. C. GIESE (A'19, M'32) division plant engineer, American Telephone and Telegraph Company, Chicago, Ill., has been made district plant superintendent, with offices at Springfield, Ill. Mr. Giese is a native (1893) of Des Moines, Iowa, and attended the State University of Iowa. He has been associated with the American Telephone and Telegraph Company since 1919.

MATTHEW LUCKIESH (A'11, M'15) director of the lighting research laboratory, General Electric Company, Nela Park, Cleveland, Ohio, recently was elected an honorary member of the American Academy of Optometry, in recognition of his contribution to optometric science.

B. H. RULE (A'36) formerly a meter and test engineer, Department of Light and Power of the City of Vernon, Calif., recently was appointed electrical engineer in the astrophysical observatory of California Institute of Technology, Pasadena.

M. V. MAXWELL (M'36) who has been an assistant engineer in the Bureau of Reclamation, Denver, Colo., recently became district engineer in the Detroit, Mich., offices of the Westinghouse Electric & Manufacturing Company.

H. P. BARLOW (A'36) who has been a switchman in the central office of the Associated Telephone Company, Ltd., Ontario, Calif., has been transferred to the Long Beach offices of that company in the capacity of assistant traffic engineer.

M. D. ENGLE (A'21, M'26) superintendent of the station engineering department, Edison Electric Illuminating Company of Boston, Mass., recently was elected a member of the executive committee of the National District Heating Association.

J. T. MOONEY (A'25) has resigned his position with the Lago Oil and Transport Co., Ltd., Aruba, Netherlands West Indies, to become superintendent of the generating plants of the Loup River Power District, Columbus, Nebr.

W. M. SHOBER (A'22) formerly a distribution engineer, Department of Water, Light, and Power, City of Springfield, Ill., now is an electrical installation engineer for the Aluminum Company of America, Alcoa, Tenn.

E. W. HOVER (A'25, M'32) formerly an electrical distribution engineer for the Central Hudson Gas and Electric Corporation Poughkeepsie, N. Y., recently was appointed electrical engineer in the Rural Electrification Administration, Washington, D. C.

ROBERT TRIPLETT (A'32) who has been a junior engineer for the Mackay Radio and Telegraph Company, San Francisco, Calif., now is employed as a receiving engineer at the Point Reyes station of RCA Communications, Inc. Inverness, Calif.

E. C. KELTON (M'26) lieutenant colonel, Engineers Corps, United States Army, who has been stationed at the Army Industrial College, Washington, D. C., as an instructor, has been transferred to Fort McKinley, Philippine Islands.

LIONEL HOECHSTETTER (A'35) has resigned his position as junior engineer with the Westchester Lighting Company, Mount Vernon, N. Y., to become an electrical engineer for the Electricoil Company, New York, N. Y.

J. C. WINSLOW (A'26) electrical engineer for the Westinghouse Electric & Manufacturing Company, Springfield, Mass., has been transferred to the Lima, Ohio, offices of that company.

W. R. WOOD (A'33) has left the employ of the United Fruit Company, New York, N. Y., to become a d-c motor design engineer for the General Electric Company, Lynn, Mass.

GODFREY MORGAN, JR. (M'36) assistant engineer with the Public Service Electric and Gas Company, Camden, N. J., has been transferred to the Princeton, N. J. offices of that company.

E. L. ANGELL (A'34) who has been a clerk in the right of way department of the Narragansett Electric Company, Providence, R. I., has entered the test course of the General Electric Company, Pittsfield, Mass.

H. F. PARK (A'35) formerly chief draftsman for the Fidelity Electric Company, Lancaster, Pa., recently was employed by the Rural Electrification Administration, Washington, D. C.

L. B. LEVESCONTE (A'36) switchgear representative, Westinghouse Electric & Manufacturing Company, Newark, N. J., has been transferred to the Chicago, Ill., offices of that company.

F. C. POAGE (A'25) formerly assistant to the superintendent of power, Idaho Power Company, Boise, has joined the staff of Ebasco Services, Inc., with headquarters at New York, N. Y.

P. W. SEAL (A'33) formerly an engineering assistant, Consolidated Edison Company of New York, Inc., New York, N. Y., now is electrical foreman with the Allegheny Steel Company, Tarentum, Pa.

C. F. WAYER, JR. (A'32) who has been employed by the General Electric Company, Bloomfield, N. J., now is an assistant examiner in the United States Patent Office, Washington, D. C.

B. B. BROWNELL (A'36) formerly employed by the Delco Products Corporation, Dayton, Ohio, now is a junior electrical engineer with the Electro-Motive Corporation, LaGrange, Ill.

K. C. WHITE (A'35) who has been employed by the General Electric Company, Schenectady, N. Y., has been appointed an instructor in electrical engineering at Cornell University, Ithaca, N. Y.

E. H. SCHOENFELD (A'35) formerly employed by Heintz and Kaufman, Ltd., South San Francisco, Calif., now is an engineer for the United Geophysical Company, Pasadena, Calif.

F. J. ELSER (A'32) recently was employed as a radio transmitter tester for the Westinghouse Electric & Manufacturing Company, Chicopee Falls, Mass.

F. B. CONLON (A'31) formerly a sales engineer with the Sheffler Gross Company, Philadelphia, Pa., now is employed by Airtemp, Inc., Dayton, Ohio.

## Obituary

GUGLIELMO MARCONI (HM '17, John Fritz Medalist '23) Italian inventor famous for establishing wireless telegraphy on a commercial basis, died quietly of heart paralysis July 20, 1937 at the ancient palace in Rome where he lived and worked. He was born in Italy on April 25, 1874, and was educated privately. Destined by his father to be a musician, Marconi nevertheless turned to science, and by 1895 the idea had become firmly rooted in his mind that a system of telegraphy through space could be provided by means of electromagnetic waves, the existence of which already had been determined by earlier experimenters.

Marconi was the first to devise practical means by which these waves could provide a new method of communication. In 1896 he went to England, taking out during that year the first patent ever granted on wireless telegraphy. An extended series of experiments followed, and his first commercial company was organized in 1897. During the next few years Marconi took out many patents on new devices for wireless telegraphy, and had much to do with the remarkable growth of this new industry in many countries of the world. In December 1901 a prearranged wireless signal was flashed from a station on the coast of Cornwall, England, to another on the rocks of Newfoundland some 2,000 miles away. After several unsuccessful attempts, communication finally was established between these 2 stations. These and other related efforts of Marconi attracted to him the attention of the world during 1901 and 1902. On January 13, 1902, at the annual dinner of the Institute held at the Waldorf-Astoria Hotel, Marconi was the guest of honor in recognition of his contributions to wireless telegraphy. He also was one of the pioneers in the use of short waves for radio communication. During the World War, Marconi served in both the Italian army and navy, and also visited America as a member of the Italian War Commission to the United States Government. He was appointed a delegate to the Peace Conference in Paris in 1919. Among the many honors received by Marconi during his lifetime are the Nobel Prize for Physics in 1909, the Albert Medal of the Royal Society of Arts of Great Britain, and the 1932 Kelvin Medal of the Institution of Civil Engineers of Great Britain. He has been decorated with the Italian order of St. Maurice and St. Lazarus, and with the Grand Cross of the Crown of Italy. In 1915 he was nominated senator of the Kingdom of Italy. In the United States, Marconi has received the Franklin and John Fritz medals and the Medal of Honor of the Institute of Radio Engineers, and other citations. Much of Marconi's time in late years has been spent aboard his yacht "Elettra" on which he had a completely equipped experimental laboratory.

PETER WILLIAM SOTHMAN (A'07, M'09, F'17) consulting engineer, Mount Tabor, N. J., died June 25, 1937. Mr. Sothman was born May 20, 1870, at Haderslev, Denmark, and was graduated from the Technological Institute of Charlottenburg (Germany) in 1891, with a diploma as electrical and mechanical engineer. Following his graduation, he became construction engineer for Siemens and Halske Company, Berlin, Germany, in which capacity he supervised the construction of several central stations and substations in Germany, South Africa, Russia, and Switzerland. In 1897 he became chief engineer and director of a power plant of Allgemeine Electricitaets Gesellschaft at Strassburg, Germany, and at the same time acted as expert on high-voltage transmission for several German cities. In 1899 Mr. Sothman was appointed technical commissioner for the German government and expert for all the courts in Alsace Lorraine and Baden; concurrently he served as commissioner of law for the Verein Deutscher Electrotechniker and as commissioner and director of the Technological School of Strassburg. He was honored as "ehren doctor Von Academie de Parisienne," in 1905, and in the same year came to the United States and established his own consulting engineering offices at New York, N. Y. In the following year Mr. Sothman was appointed chief engineer of the Hydro-Electric Power Commission of Ontario, in which position he was responsible for the design and construction of several of the Commission's generating plants and transmission lines. He returned to New York in 1912 to establish the consulting engineering firm of the Sothman Corporation, and for the ensuing 25 years continued in that work in the city of New York and its vicinity.

CHARLES L. CADLE (A'08) president of the New York State Electric and Gas Corporation, Binghamton, N. Y., died July 3, 1937. Mr. Cadle was born March 10, 1879, at Mentor, Ohio, and was graduated from the Case School of Applied Science in the class of 1904, following which he became battery manager for the Cleveland (Ohio) Electric Railway Company. In the following year he became associated with the Electric Railway Improvement Company, Cleveland, and in 1907 was promoted to the position of assistant general manager; however, after only one year in that position he went to Rochester, N. Y., to become electrical engineer for the Rochester Railway Company. Mr. Cadle remained with that company until 1912, when he was appointed to a similar position in the New York State Railways Company, with offices at Rochester. In 1919 he became chief engineer of that company. After serving briefly as superintendent of public works at Albany and pursuing for a time his own consulting engineering business, he became general manager of the Rochester Gas and Electric Company in 1926. In 1932 he was appointed vice-president of the Utilities Management Corporation, New York, N. Y., and in 1935 president of the New York State Electric and Gas Corporation.

ROGER S. TAYLOR (A'17) plant superintendent, Susquehanna Electric Company, Conowingo, Md., died April 27, 1937. Mr. Taylor was born October 7, 1881, at Dukenfield, Cheshire, England, and received his formal education at the Technical School at Ashton-under-Lyne. In 1898 he came to the United States and obtained employment in the motive-power department of the Philadelphia (Pa.) Rapid Transit Company. He remained with that company until he transferred his affiliation to the Philadelphia Suburban Gas and Electric Company in 1912 and was placed in charge of that company's plants at Pottstown and Phoenixville. In 1916 Mr. Taylor joined the operating staff of the Philadelphia Electric Company, later becoming assistant power-plant superintendent and power-plant superintendent, and remained with that company for almost 10 years before becoming associated with the Susquehannah Electric Company as plant superintendent.

NORMAN MCLEOD BAXTER (A'26) transmission engineer, Ohio Public Service Company, Elyria, died June 24, 1937. Mr. Baxter was born at Halifax, Nova Scotia, June 27, 1883, and attended University Delhousie (Nova Scotia) and the University of Nebraska. In 1905 he became affiliated with the Lincoln (Nebr.) Gas and Electric Light Company as a draftsman, but later was placed in charge of construction and eventually became superintendent of gas and electric distribution before transferring to The Lorain County Electric Company, which later became a part of the Ohio Public Service Company, as general superintendent in 1916. From 1919 to 1922 Mr. Baxter was associated briefly with a public utility company in Connecticut and with the engineering department of The Toledo (Ohio) Edison Company. In 1922 he returned to the employ of the Ohio Edison Company as transmission engineer, and served continuously in that capacity for almost 15 years.

RALPH T. ROSSI (A'18, M'34) assistant plant engineer, RCA Communications, Inc., New York, N. Y., died May 28, 1937. Mr. Rossi was born in New York, N. Y., April 27, 1878, and received his formal technical education through private instruction in Europe. From 1904 until 1916 he was associated briefly with several consulting engineering firms and construction companies in New York. In 1916 he became superintendent of distribution for the Public Service Electric and Gas Company, Trenton, N. J., where he remained for 3 years before becoming affiliated with RCA Communications as assistant engineer in charge of construction in 1919. Mr. Rossi was responsible for the construction of many of the transmitting and receiving stations of RCA Communications on every continent except Australia. He was a member of the Institute of Radio Engineers.

WALTER CARY (A'07, M'14) vice-president, Westinghouse Electric & Manufacturing Company, New York, N. Y., died July 3, 1937. Mr. Cary was born April 26, 1871, at Milwaukee, Wis., and was graduated from Harvard University in 1893 with the degree of bachelor of arts. In 1894 he entered the employ of the Gibbs Electric Company, Milwaukee, as secretary of the company, but 4 years later became vice-president of the Milwaukee Electric Company. In 1910 he became president of the Milwaukee Electric Company, and in 1904 vice-president and general manager of the Westinghouse Lamp Company, New York, N. Y. He had been vice-president of the Westinghouse Electric & Manufacturing Company since 1918.

WILLIAM M. O'BRIEN (A'36) service department, Northwestern Electric Company, Rainier, Ore., was drowned May 2, 1937. Mr. O'Brien was born August 5, 1909, at Portland, Ore., and was graduated from Oregon State College with the degree of bachelor of science in electrical engineering in 1935. He had been associated with the Northwestern Electric Company since his graduation. He was a member of the Society of American Military Engineers.

# Membership

## Recommended for Transfer

The board of examiners, at its meeting on July 21, 1937, recommended the following members for transfer to the grade of membership indicated. Any objection to these transfers should be filed at once with the national secretary.

**To Grade of Fellow**

Bonney, R. B., educational director and employment supervisor, The Mountain States Telephone and Telegraph Company, Denver, Colo.
Pearson, E. F., chief engineer, Northwestern Electric Co., Portland, Ore.
Stevenson, A. R., engineer, General Electric Company, Schenectady, N. Y.
Terry, I. A., assistant engineer, motor and generator engineering department, General Electric Company, Schenectady, N. Y.

4 to Grade of Fellow

**To Grade of Member**

Arnold, N., assistant professor of engineering drawing, Purdue University, Lafayette, Ind.
Atkinson, F. W., electrical engineer, Owens-Illinois Glass Company, Newark, Ohio.
Brosemer, R. O., assistant engineer, General Electric Company, San Francisco, Calif.
Chapman, F. W., superintendent, Commissioners of Public Works, Greenwood, S. C.
DeWeese, F. C. engineer, Carolina Power and Light Company, Raleigh, N. C.
Eggertson, E. G., assistant electrical engineer, American Gas and Electric Company, New York, N. Y.
Evans, G. T., assistant chief engineer, The Bristol Company, Waterbury, Conn.
Ferri, L. F., protection engineer, The Ohio Public Service Company, Elyria.
Gaston, J. R., manager, industrial transformer division, American Transformer Company, Newark, N. J.
Geer, G. D., superintendent of distribution, Texas Electric Service Company, Sweetwater.
Gehr, G. A., communication engineer, Los Angeles County Department of Forester and Fire Warden, Los Angeles, Calif.
Houston, H. H., electrical engineer, Federal Power Commission, San Francisco, Calif.
Knerr, L. R., assistant engineer, California Railroad Commission, San Francisco.
Lyman, W. J., electrical planning engineer, Duquesne Light Company, Pittsburgh, Pa.
Miner, R. R., electrical engineer, Kansas Gas and Electric Company, Wichita.
Plummer, C. E., chief electrical engineer, Modesto Irrigation District, Modesto, Calif.
Ritter, A. S., planning engineer, Commonwealth Edison Company, Chicago, Ill.
Rogers, T. A., instructor, department of electrical engineering, University of California, Berkeley.
Rogers, T. I., engineer, American Telephone and Telegraph Company, New York, N. Y.
Snyder, W. R., electrical engineer, Manila Electric Company, Manila, P. I.
Wagner, H. H., head design engineer, Pennsylvania Transformer Company, Pittsburgh, Pa.

21 to Grade of Member

## Applications for Election

Applications have been received at headquarters from the following candidates for election to membership in the Institute. If the applicant has applied for direct admission to a grade higher than Associate, the grade follows immediately after the name. Any member objecting to the election of any of these candidates should so inform the national secretary before August 31, 1937, or October 31, 1937, if the applicant resides outside of the United States or Canada.

Adkins, P. LeR., Mountain States Power Company, Albany, Oregon.
Allard, E. P., Philadelphia Navy Yard, Philadelphia, Pa.
Beisber, M. F., Line Material Co., Memphis, Tenn.
Bloedorn, E., Acro Welder Manufacturing Company, Stegeman Machinery Company, Milwaukee, Wis.
Cramer, J. F., Central Nebraska Power and Irrigation District, Hastings.
Darroch, J. W., Berkeley Steel Construction Company, Berkeley, Calif.
Duffy, E. (Member), New Orleans Public Service, Inc., New Orleans, La.
Eistrat, T., California State Board of Equalization, Sacramento.
Ferrill R. M. (Member), Tennessee Electric Power Company, Chattanooga.
Foreman, W. R., Department of Water & Power, Boulder City, Nevada.
Frakes, J. H., Westinghouse Electric & Manufacturing Company, East Pittsburgh, Pa.
Goodridge, H. L., 157 Pleasant Street, Malden, Mass.
Grant, V. H., Bureau of Aeronautics, Navy Department, Washington, D. C.
Hero, A. A., General Electric Company, New Orleans, La.
Hildenbrand, C. F., Electric Light and Power Company of Baltimore, Baltimore, Md.
Kelley, J. R., Department of Water and Power, Los Angeles, Calif.
Kirk, D. H., Baton Rouge Electric Company, Baton Rouge, La.
Kobke, W. J., Brooklyn Edison Company, Inc., Brooklyn, N. Y.
Mahannah, W. D., Florida Power and Light Company, Ft. Pierce.
McDougald, A. D., Navy Department, Mare Island, Calif.
McHenry, J. C., Lorain-Medina Rural Electric, Inc. Wellington, Ohio.
McKinley, W. H., 1930 *B* Street, San Diego, Calif.
McReynolds, A. C., Columbia Electric Company, Kennewick, Wash.
Miller, A. N., International Business Machines Corporation, Endicott, N. Y.
Palmer, J. E., Pacific Gas and Electric Company, Fall River Mills, Calif.
Pappas, P. S., Great Lakes Dredge and Dock Company, New York, N. Y.
Parrish, J. L., Tennessee Valley Authority, Norris, Tenn.
Peatfield, R. R., New York and Queens Electric Light and Power Company., Flushing, N.Y.
Phillips, E. J., Jr. (Member), Simmons-Boardman Publishing Corporation, Chicago, Ill.
Preston, J. D. (Member), Florida Power and Light Company, Miami.
Purcell, W. W. R., Alabama Power Company, Birmingham.
Ryan, J. J., Signal Engineering and Manufacturing Company, New York, N. Y.
Santos, E. J., 88 Charlotte St., Detroit, Mich.
Schenck, S. B. (Member), Bessemer and Lake Erie Railroad Company, Greenville, Pa.
Shaffer, E. E., City Hall, San Diego, Calif.
Stanley, H. C., American Gas and Electric Company, New York, N. Y.
Woodward, B. W., International Sound Photos System, San Francisco, Calif.

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**Foreign**

Bapat, M. N., Tata Hydro Companies, Bombay India.
Epple, R. J., Mene Grande Oil Company, Maracaibo, Venezuela.
Hydari, M., Messrs. Crompton Engineering Company, Ltd., Madras, India.
Kusumoto, S., in care of Hitachi Engineering Works, Sukegawa-cho, Ibaraki-ken, Japan.
Natarajan, K., First Line Beach, Madras, India.

5 Foreign

## Addresses Wanted

A list of members whose mail has been returned by the postal authorities is given below, with the addresses as they now appear on the Institute record. Any member knowing of corrections to these addresses will kindly communicate them at once to the office of the secretary at 33 West 39th St., New York, N. Y.

Charlton, H. C., 4827 Wilson Avenue, Montreal Que., Canada.
Evans, Maldwyn F., Canadian Comstock Company, Ltd., Toronto, Ont., Canada.
Gregory, G. A., 1217 Jefferson Street, Olympia, Wash.
Hardy, John E., 1741 Pennsylvania Avenue, Denver, Colo.
Jones, K. B., Trumbull Electric Manufacturing Company, Inc., Ludlow, Ky.
Phillips, Eugene H., 3006½ South Hoover, Los Angeles, Calif.
Phillips, Robert J., 94–26—34th Road, Jackson Heights, N. Y.
Roberts, Fred A., 2010 West Michigan Street, Indianapolis, Ind.
Schaefer, Philip E., 5154 St. Paul Avenue, Chicago, Ill.
Sikofsky, George L., 1206 East New York Avenue, Brooklyn, N. Y.
Stivender, P. M., Allis-Chalmers Manufacturing Company, 135 South La Salle Street, Chicago, Ill.

11 Addresses Wanted

# Engineering Literature

## New Books in the Societies Library

Among the new books received at the Engineering Societies Library, New York, recently are the following which have been selected because of their possible interest to the electrical engineer. Unless otherwise specified, books listed have been presented gratis by the publishers. The Institute assumes no responsibility for statements made in the following outlines, information for which is taken from the preface of the book in question.

GREAT BRITAIN, DEPARTMENT of SCIENTIFIC and INDUSTRIAL RESEARCH. REPORT for 1935–36. London, His Majesty's Stationery Office, 1937. 195 pages, tables, 10x6 inches, paper (obtainable from British Library of Information, 270 Madison Ave., New York, N. Y., $0.95). Affords a summary of the work carried on during the year in the various establishments of the Department.

HOUSE WIRING, by T. W. Poppe and H. P. Strand. New York, Norman W. Henley Publishing Company, 1937. 256 pages, illustrated, 7x4 inches, paper, $1.00. A manual for the wireman, giving directions for planning and installing the wiring in dwellings.

A COURSE in ELECTRICAL ENGINEERING. volume 1. DIRECT CURRENTS. By C. L. Dawes. 3 edition. New York and London, McGraw-Hill Book Company, 1937. 751 pages, illustrated, 8x6 inches, cloth, $4.00. An enlarged edition of a standard textbook on electrical engineering, the first volume of which covers direct currents. Includes fundamental electrical characteristics, magnetism, electrostatics, and d-c machinery.

SOUND WAVES, Their Shape and Speed. By D. C. Miller. New York, Macmillan Company, 1937. 164 pages, illustrated, 9x6 inches, cloth, $2.75. Contains a chapter upon electric-spark photography of sound waves and its application to the study of projectiles in flight and the acoustics of auditoriums.

WAHRSCHEINLICHKEITEN und SCHWANKUNGEN Vorträge von M. Czerny, K. Franz, F. Lubberger, J. Bartels and R. Becker. Edited by F. Lubberger. Berlin, Julius Springer, 1937. 100 pages, illustrated, 10x6 inches, paper, 8.40 rm. A group of 5 treatises on the fundamentals, theory, and application of probabilities and variations.

WAVE MECHANICS, Elementary Theory. By J. Frenkel. 2nd edition. London and New York, Oxford University Press, 1936. 312 pages, illustrated, 10x6 inches, cloth, $6.75. Contains chapters on light, matter, motion of particles or systems of particles, statistical mechanics, application of the quantum statistics to electron theory, and theory of chemical forces.

MITTEILUNGEN aus den FORSCHUNGSANSTALTEN. Bd. 5, Heft 2, February 1937. Berlin, VDI-Verlag. 52 pages, illustrated, 12x8 inches, paper, 3.15 rm. Includes a report on end sleeves for high-tension cables and a description of a new portable mirror galvanometer for spectroscopic analyses of metals.

THOMAS' REGISTER of AMERICAN MANUFACTURERS. 27th edition 1937. New York, Thomas Publishing Company, illustrated, 12x9 inches, cloth, $15. ($10. to former subscribers). Contains classified and indexed lists of manufacturers of all kinds; lists of banks, boards of trade and other commercial organizations, trade papers, leading manufacturers, and trade names.

# Industrial Notes

**Western Electric Sales.**—Sales of the Western Electric Co. totalled $97,355,000 for the first six months of this year as compared with $65,651,000 for the corresponding period last year.

**Near-Record Business for G-E.**—During the first six months of this year the General Electric Co. received orders amounting to $217,265,619, an increase of 59 per cent over the $136,968,597 received during the same period last year. The record first half year was in 1929 when orders amounted to $220,716,456. Orders during the second quarter of 1937 amounted to $111,518,589, compared with $77,398,718 for the corresponding quarter of 1936, an increase of 44 per cent. The second quarter of this year was the largest, for orders received, since the third quarter of 1929.

**General Cable Appointment.**—R. S. Hopkins has been appointed by the General Cable Corporation as manager of the New York City sales office, 205 East 42nd St.

**Roller-Smith Appointment.**—H. R. Kimball, 176 Federal St., Boston, has been appointed by the Roller-Smith Co., New York, as district sales agent for New England.

**B-L Electric Appointments.**—According to a recent announcement of the B-L Electric Mfg. Co., St. Louis, Mo., producers of rectifiers and condensers, changes in executive personnel have been made as follows: Harold J. Wrape, president; Irvin W. Veigel, treasurer; Carl E. Peters, secretary; R. W. Mansfield, superintendent; Carl H. Massot, purchasing agent.

**New Motors.**—The Century Electric Co., St. Louis, Mo., announces a new complete line of fractional horsepower motors in sizes from $^1/_6$ to $^3/_4$ hp, repulsion start induction, single phase, split phase, capacitor, polyphase and direct current. This line is designed with interchangeable mounting dimensions for a given horsepower size.

**Westinghouse Furnaces to Ford.**—The Ford Motor Co. has purchased from the Westinghouse Electric & Mfg. Co., 12 additional bell type furnaces for annealing automobile body stock. Each furnace will be rated at 230 kw with a capacity for annealing two coils 52 inches in diameter, 48 inches in height, giving a total loading of 32,000 pounds per charge. This new installation will give the Ford Motor Co. a total of 38 bell annealing furnaces, 24 of which are of Westinghouse manufacture.

**Ground Rods.**—Sectional Copperweld ground rods and couplings for deep, low-resistance grounds are a new development, announced by the Copperweld Steel Co., Glassport, Pa. Cold-drawn for rigidity, the Copperweld sections are threaded on both ends and joined as they are driven by means of a threaded bronze coupling. It is claimed that sectional Copperweld rods may easily be driven to depths of 40 or 50 feet.

**Porcelain Case Capacitors.**—A line of porcelain case, high voltage, mica capacitors is announced by Aerovox Corporation, 70 Washington St., Brooklyn, N. Y., for use in radio transmitters and for other electronic purposes. Each unit is housed in a glazed porcelain case and is provided with heavy brass terminal studs and lock nuts. Capacities range from .00005 to .1 mfd. as well as d-c test voltages from 2000 to 12,500.

**Reversing Motor Starter.**—Allis-Chalmers Mfg. Co., Condit Works, Boston, has announced a new reversing motor starter designated type AP-7-R, furnished for $7^1/_2$ hp, 550 volts or less. The starter consists of two type AP-7 motor starter units, mechanically interlocked so that either unit cannot be closed if the other is closed. The starter units are equipped with Ruptors—enclosing chambers which confine and depotentiate the arc formed by circuit interruption. Other features include large, silver, double-break contacts; solenoid operated, vertical make and break; unit construction, pole units consisting of individual molded bases mounted on a steel chassis, and enclosed temperature overload relays, affording positive motor protection; undervoltage protection inherently provided.

# Trade Literature

**Switches.**—Bulletin 54, 8 pp. Describes group operated air switches, tilting insulator type. Pacific Electric Mfg. Corp., 5815 Third St., San Francisco, Calif.

**Circuit Breakers.**—Bulletin GEA-2406A, 4 pp. Describes type FKO outdoor oil-blast circuit breakers; 7500 volts, 400 and 600 amperes, 50,000 kva, 2 or 3 poles, framework or pole mounted. General Electric Co., Schenectady, N. Y.

**Bakelite.**—Bulletin, 16 pp., "The Versatile Service of Bakelite Materials." Describes the development of Bakelite resinous materials, their general characteristics, properties and applications. Bakelite Corp., 247 Park Ave., New York City.

**Testing Equipment.**—Bulletin, 8 pp. Describes R-F signal generators, R-F oscillators, service laboratories, oscillographs, power supplies, vacuum-tube voltmeters, etc. The Clough-Brengle Co., 2815 W. 19th St., Chicago, Ill.

**Rectifier Tubes.**—Bulletin, 44 pp. Describes various types of gaseous discharge rectifier and control rectifier tubes. Characteristics and applications are presented at length. Prices are listed. Electrons, Inc., 127 Sussex Ave., Newark, N. J.

**Splices and Tapes.**—A new and revised edition of this book, which includes such chapters as the importance of a perfect splice, requirements for a splicing compound, for adhesive tape, and instructions for joining, The Okonite Co., Passaic, N. J.

**Switchgear.**—Bulletin GEA 2605, 18 pp., "Modern Switchgear." Summarizes 137 separate products from the complete line of G-E switchgear and contains publication numbers of descriptive bulletins giving additional information. General Electric Co., Schenectady, N. Y.

**Rubber Substitute.**—Bulletin 16 pp. Describes Neoprene, an engineering material with rubber-like properties which resists the deteriorating effects of oil, heat, sunlight, chemicals and oxidation. Among its applications is that of insulating electrical cables. E. I. du Pont de Nemours & Co., Wilmington, Del.

**Neon Transformer.**—Bulletin 143. Describes a neon transformer, the Acme "Autopak," to illuminate neon signs and displays installed in automobiles. No special equipment or extra generator is necessary as current is supplied from the regular automobile generator. The Acme Elec. & Mfg. Co., 1446 Hamilton Ave., Cleveland, O.

**Temperature Instruments.**—Catalog 1060C, 56 pp. Describes indicating and recording temperature and pressure instruments. Much of the data on the latest developments in these instruments has not heretofore been published. Numerous illustrations show the manner of operation and how the instruments are serving the process industries. C. J. Tagliabue Mfg. Co., Park & Nostrand Aves., Brooklyn, N. Y.

**Cables.**—Bulletin C-27, 20 pp. Describes Anaconda Duraseal cable, a non-metallic sheathed cable for direct burial in the ground. In addition to complete descriptions of the types available and their uses, helpful information relative to application, installation and other engineering data are included. Anaconda Wire & Cable Co., 25 Broadway, New York City.

**Motors.**—Catalog 60 pp. Describes construction features, advantages and applications of practically every commercial type of motor. Included are engineering data on various types of special motor applications and construction. A detailed analysis is presented on the characteristics of squirrel-cage motors, motors for centrifugals, etc. The Louis Allis Co., Milwaukee, Wis.

**Insulation Test Set.**—Catalog E-54(1), 4 pp. Describes a new insulation resistance test set, using a guarded circuit, entirely free from the effects of leakage currents. Switches are designed to simplify operation and eliminate calculation. Calibration of the galvanometer deflections is facilitated by the specially designed Ayrton shunt. Simply turning the shunt to the calibrating portion automatically connects the circuit for calibration. Results are obtained by merely dividing the calibration reading by the test reading. The instrument conforms with the ASTM "Standard Methods of Test for D-C Resistance of Insulating Materials." Leeds & Northrup Co., 4962 Stenton Ave., Philadelphia, Pa.

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Registered U. S. Patent Office

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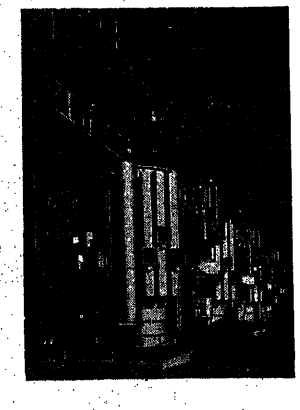
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## The Cover

**Westport 230/33-kv substation of the Consolidated Gas, Electric Light and Power Company, Baltimore, Md. The transformers are 42,000-kva units**



# High Lights

**Coupling Between Earth-Return Circuits.** Induced voltages recorded in communication circuits paralleling d-c electric railways, at times of short circuit on the railway, have shown marked divergencies from computed values. Because of the numerous factors that might contribute to these divergencies, experimental studies of the transient coupling between parallel earth-return circuits, free from the effects of shielding conductors, and with concentrated rather than distributed grounds, have been made in order to provide a better understanding of the problem (*pages 1159–64*).

**American Engineering Council.** From its very beginning, in 1920, American Engineering Council has aimed to aid the engineering profession in presenting a united front in matters of interest to government and to the public. A review of some of the problems, policies, and activities of AEC, prepared by the president of Council, appears in this issue (*pages 1082–4*). A report on coal-price fixing and the Bituminous Coal Act of 1937, from a current "news letter" of AEC is included in the news section (*pages 1211–12*).

**Electricity in Steel Mills.** This issue contains 4 papers on the applications of electricity in the manufacture of steel products. One summarizes the entire range of electrical applications in steel mills (*pages 1115–23*); a second describes a 72-inch strip mill (*pages 1105–14*); another describes more specific uses of electricity in the measurement and control of tension in cold-strip mills (*pages 1141–4*); and a fourth indicates the important characteristics of carbon brushes for steel-mill equipment (*pages 1165–8*).

**Limiters.** One solution to the problem of providing short-circuit protection for secondary distribution networks consists of the use of "limiters," which are reduced metallic sections incorporated in connectors, lugs, or other connecting devices used in normal cable installation procedure. A large eastern metropolitan power company has installed 16,000 of these devices on its distribution system during the past year (*pages 1191–6*).

**Inductances for Ultrahigh Frequencies.** With short-wave (or ultrahigh-frequency) radio receivers becoming common, it is important that the inductances for these receivers be properly designed. From the results of experimental and analytical studies of the resistance of small single-layer inductances for frequencies between 4 and 25 megacycles, a procedure has been deduced for the "optimum" design of such inductances (*pages 1169–76*),

**Middle Eastern District Meeting.** Akron, Ohio, world's largest rubber manufacturing center, will be the scene of a 3-day meeting of the AIEE Middle Eastern District, October 13–15, 1937. A program including 23 technical papers, an excellent variety of inspection trips to local industries, and sports and social events has been arranged. A District student conference also will be held during the meeting (*pages 1205–07*).

**Engineers' Income.** The earning power of engineers varies widely, according to information obtained in a comprehensive survey of the profession in which incomes for 1929, 1932, and 1934 were reported. Striking differences exist within each professional class, and within each group classified on the basis of educational background (*pages 1089–1104*).

**Matrices in Engineering.** The matrix not only is "a convenient notation that summarizes in a natural and convenient form whole groups of operations, but . . . it is . . . possible to solve the sets of differential or algebraic equations written in matrix form in a most convenient manner" (*pages 1177–90*).

**Resistance Welder Control.** Fully automatic repeat control devices are needed to obtain maximum operating speeds in resistance-welding machines without sacrificing the quality of the welds. Operating speeds of 350 or more welds per minute are said to be made practical with a new type of control equipment(*pages 1145–8*).

**Selection and Training of Engineers.** Many members of the Institute will recall having heard Retiring - President MacCutcheon speak on this subject at their local Section meetings during the past year. In response to many requests, Mr. MacCutcheon has prepared this address for publication (*pages 1085–8*).

**Noise Test Code.** A proposed test code for apparatus noise measurement has been developed by an AIEE subcommittee. The purpose of this code is to establish uniform methods of conducting and reporting sound-level tests on apparatus. Discussion is invited (*pages 1079–82*).

**Silver-Tellurium Alloys.** Compensation of temperature errors in electrical instruments may be accomplished by the use of series resistors having negative temperature coefficients of resistance. A method of making such resistors of tellurium and silver has been described (*pages 1128–33*).

**Electric Shock.** That low-voltage house circuits can give fatal shocks is shown by the death of from 100 to 200 persons annually in the United States from this cause. Preventive measures will reduce the hazard, and resuscitation will save many victims (*pages 1077–9*).

**Alternator Short Circuits.** Formulas for armature currents in the faulted phases and for the main field current at any time after the short circuit have been developed for a double line-to-neutral short circuit of an alternator (*pages 1149–55*).

**Engineering Education.** An eminent engineering educator has prescribed a new type of engineering curriculum for undergraduate students, intended to produce engineers interested in assuming places in public leadership (*pages 1073–6*).

**Prize Awards.** National and some District prize awards for 1936 AIEE technical papers were announced in the June issue; additional awards, for Districts 5 and 8, have now been announced (*page 1208*).

**Flywheels for A-C Units.** A compendium of the theory of flywheels for a-c generating units and of the parallel operation of such units is included in a paper in this issue (*pages 1158–60*).

**The 2-Reaction Theory.** Extensions of the 2-reaction theory as applied to multiphase synchronous machines are included in 2 papers in this issue (*pages 1124–7 and 1197–1201*).

**Rectifier Regulation.** Several factors may affect the "angle of delay" which is used in calculating the regulation of grid-controlled rectifiers, and their effect should be included in the determination (*pages 1134–40*).

**Letters to the Editor.** Comments on AIEE publications and incandescent-lamp voltages appear in the "letters" columns of this issue (*pages 1212–13*).

# DISCUSSIONS

Appearing in this issue are discussions of the following papers:

**Watt-Hour Meter Bearings**—Kinnard and Goss **1202**

**First Report of Power System Stability**—Subcommittee Report **1204**

Statements and opinions given in articles and papers appearing in ELECTRICAL ENGINEERING are the expressions of contributors, for which the Institute assumes no responsibility. Correspondence is invited on all controversial matters. ¶ Subscriptions—$12 per year to United States, Mexico, Cuba, Porto Rico, Hawaii, Philippine Islands, Central and South America, Haiti, Spain, Spanish Colonies; $13 to Canada; $14 elsewhere. Single copy $1.50. ¶ Address changes must be received by the fifteenth of the month to be effective with the succeeding issue. Copies undelivered because of incorrect address cannot be replaced without charge. ¶ ELECTRICAL ENGINEERING is indexed annually by the Institute, weekly and monthly by *Engineering Index*, and monthly by *Industrial Arts Index*; abstracted monthly by *Science Abstracts* (London). ¶ Copyright 1937 by the American Institute of Electrical Engineers. Number of copies this issue—19,800

# Engineering Education and Democracy

By ROBERT E. DOHERTY
FELLOW AIEE

**Most engineers are agreed that the engineering profession is not sufficiently active in civic and governmental affairs; that engineers are not sufficiently insistent in voicing their opinions to public officials who administer affairs vital to the profession. With a view to the future, an eminent educator here prescribes one form of engineering education intended to build engineers interested in assuming their places as effective citizens in our democratic government.**

PREVIOUSLY I have had the privilege of discussing before the Institute[1] and elsewhere[2,3,4,5] certain problems of engineering education, especially those relating to the undergraduate program. On such occasions I have stressed the importance of a thorough understanding of fundamental science and have expressed concern over the relatively high degree of specialization in undergraduate work at the expense of such understanding; I have contended, moreover, that educators should give to students a start toward that rounded-out education which is so essential to professional activity on a high plane, and which is indispensable in placing engineers in effective leadership alongside other professional men. This latter phase I shall now discuss further, and emphasize as much as possible the critical necessity for prompt attention to this matter. Educational machinery for readjustment moves slowly; the process of bringing young men from freshman year to professional maturity requires from 15 to 20 years; and social and economic change continues at an accelerated rate with little or no intelligent control. Hence time is important.

Increasing complexity confounds us. Technology with all its blessings yet subverts traditional habits and attitudes of mind; narrow specialists multiply endlessly; interdependence of individuals and of communities increases apace; pressure groups spring up on all sides; rackets thrive; selfish interest reigns supreme. Surrounded by all of this, we find ourselves, our hopes for our children, and the great possibilities of American democracy, primarily in the hands of confused lawyers and economists. They are not to be condemned; on the contrary, they are to be given great credit for at least some serious thought regarding the matter. Merely, things have moved too fast for them. But to what extent has the engineering profession taken a hand? It has added fuel to the technological flame that has illuminated and warmed the whole social community with physical comfort and convenience, but apparently it has not occurred to the profession that the flame, though beautiful and interesting, may yet consume us. Engineers, who understand technology, must give more thought to consequences. They, in common with lawyers, economists, and other responsible professional people, must consider a new kind of educational preparation for their oncoming generations, for if these generations grow up with the limited understanding, and with the attitudes that characterize present professional groups, it would seem our hopes are forlorn, because the enemy's strength now is growing faster than ours.

Believing, as I do, that new professional attitudes are essential and that these can be created in sufficient strength only by education of the professional generation yet in college, or just graduated; and believing further, that the accomplishment of adequate changes in educational programs will require, first, the adoption of a significantly modified philosophy by both educators and industrialists; and still further, that to change attitudes in older generations regarding education itself is difficult—believing these things, I have grown to be less optimistic. In any case, the first basis for optimism will be a concerted move toward a readjusted philosophy.

What are the fundamental attitudes from which our thinking should proceed? More specifically, what is *the* fundamental attitude? What others are implied?

Unquestionably we must start from the premise that competent citizenship is the first responsibility, and that the more the individual's educational opportunity is extended, the greater this responsibility. This aspect of educational philosophy, although recognized here and there, is almost wholly overlooked in higher education. Great credit and gratitude are due those educators that preside over primary and secondary education for their attitude in this connection, but the matter must not rest at that point. Competency as a citizen requires more than a preliminary knowledge of the origin, purpose, and form of our government, the early disposition to co-operate and accept majority opinion, and the other attitudes cultivated in the first levels of education. It requires, as well, especially of the better minds that have had the privilege of higher education, an understanding of principles and forms of government, a cultivated ability and attitude to weigh the complex issues that arise; and some feeling of obligation to decide intelligently and give support to

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Essentially full text of an address presented at a meeting of the AIEE Lehigh Valley Section, Bethlehem, Pa., May 14, 1937.

ROBERT E. DOHERTY is president of Carnegie Institute of Technology, Pittsburgh, Pa. Doctor Doherty served as a designing engineer for the General Electric Company, Schenectady, N. Y., from 1910 until 1920, when he became an assistant to Doctor C. P. Steinmetz (A'90, M'91, F'12, and past-president). Upon the death of Doctor Steinmetz in 1923, Doctor Doherty became consulting engineer for the General Electric Company, and served in that capacity until he became professor of electrical engineering at Yale University in 1931. In 1932 he was appointed dean of the school of engineering, and in 1936 was elected president of Carnegie Institute of Technology. He has served on many of the Institute's technical and general committees, and has contributed much to technical literature.

1. For all numbered references, see list at end of article.

the decision. Our experiment in democracy rests foursquare upon the assumption that the citizens themselves are competent to settle issues wisely. My question is: If most of those, including engineers, whose minds are trained to think carefully, are to be directed merely to enterprises that create still more of the social and economic complexities that confound us, who will do the thinking in our community and national life? For, after all, are we not interested quite as much as a nation in where we are going and taking our children, as in the thrill and fascination of the journey itself? If we are not interested as trustees of American freedom, then are we not interested as parents of our children? I can answer the question. If more professional people, who presumably are trained to think, do not take interest in these matters, then the future talent exercised upon the problems of state will be unchanged, and the result is clear. The American experiment is too great, its ramifications too complicated, its growth in complexity too rapid, its values too precious to be guided by emotion and selfish interest. A successful issue of the experiment demands guidance that is based on intelligent, dispassionate study, and this cannot come from a mere handful of men; it must, by the very nature of democracy, come from large numbers. If this nation is to endure as a free nation, we must not forget, as we certainly have done, the fundamental philosophy of 1776 that competent citizenship is our first responsibility, and that this responsibility becomes proportionally greater as the educational privilege is extended.

If this point of view is once again seriously accepted, then new attitudes are implied in higher education and business. Professional education must devote to this end more of the precious time in its programs, and this means either that the programs must be extended, or that industry and business must be willing to accept graduates with training less specialized then they now have. I wish to discuss the problems into which we should thus be led, confining myself to engineering education and to industries that absorb engineering graduates.

What would engineering education do if industry gave it a free hand? The following is what it might do, and what I think it ought to do: The indispensable parts of engineering education, in my opinion, are an understanding of mathematics and the basic physical sciences; a characteristic habit of mind engendered by dealing with the purpose of utility and with definite facts, laws, and predictable outcomes; and thus a combination of these which has been termed "the engineering method." Science alone is not enough; neither is a superficial dabbling with the method without the science. Both are necessary. So the first step is to provide these, or else we shall be beyond the limits of engineering education. But having provided them, we shall have a curriculum that qualifies by definition; and anything further on the technical, scientific side is to be regarded as specialization.

But I am now proposing that we change the definition. It should include as well the requirement of an adequate background and discipline for the new responsibility: that of dealing with problems involving social elements. Both as a citizen and as a professional man active in matters that affect environmental relationships in society, the engineer is under obligation to be prepared for this responsibility, and he should not be regarded as an engineer in the professional sense without it. The civic aspect of this responsibility already has been discussed. I now add the professional, since the educational preparation for the one is also for the other.

Some two-thirds of all engineering graduates eventually have entered work involving personnel management, and perhaps half that number have assumed this reponsibility in a major way. The dark labor situation that recently has sprung up throughout the country indicates the extent to which engineers, even though involuntarily, are rapidly being thrown by the onrushing technological tide into positions where their plans and decisions may have pervasive social implications. No other group is in such a key position as are engineers to make great contributions to industrial peace. By virtue of such a position, which yearly is growing in importance, engineers' professional responsibility is an additional reason for their active interest and competency in dealing with social and economic problems, and in framing an educational program these aspects of responsibility should be recognized as on equal footing with technical responsibility so far as their being essential factors is concerned.

What, then, are the practical implications regarding the curricula? Stated generally, they are the necessity for a redistribution of time and emphasis, and the question of whether industry is willing to assume a share of the responsibility by accepting graduates with broader and more thorough training, but with less specialization.

Before entering these particular matters I wish, in the interest of clarity of discussion, to dispense with certain questions that are closely related. In the first place the thesis of this discussion should not become confused or lost by the mention of the 5-year curriculum. In the view of that portion of past industrial generations that built rapidly and inefficiently, the way to get increased output was merely to extend the plant. With allowances there is a parallel here which might be profitably drawn when the 5-year plan is pressed. Unquestionably some students desire, and can afford the time and money, to spread their education over 5 or 6 years at undergraduate level, and they should be able to do so. Moreover, a relatively small part of them should extend formal education into graduate study in higher scientific levels. These would constitute the supply of professional technical specialists. All of this seems clear. However the great mass of those who study engineering should not be required to take an added year or two out of their professional lives either because we feel, like the past generation of industrialists, that the only way to change is to add, or because certain phases of present industries require at graduation specialized skills that could equally or better be learned on the job. I am convinced that if industry will do its part, graduates can be prepared, along the lines I have indicated, within the 4-year period.

I believe industry will do its part. There are many

leaders of industry whose views I do not know, but practically every one of them whose opinion I have read or heard has not urged specialization, but breadth of view. The classical report of the Society for the Promotion of Engineering Education (1923–29) includes composite opinions of industrial leaders and practicing engineers regarding the character of education desired in an engineer; and questionnaires of similar purpose have been analyzed and reported in numerous other publications. One certainly cannot conclude from the well-known results of these inquiries that in general industry demands specialized training at the expense of fundamental breadth and humane understanding. Yet the necessity of retaining existing courses of specialized nature seems to hinge on the idea that a graduate will not be able to get a job if he does not have them. To whatever extent it is true that industry, by insisting upon the teaching of special, routine skills, prevents us from educating our students along broader lines that seem to be so clearly necessary, then to that extent it becomes our responsibility to convince industry that its position is ill-advised. The stakes are too large in this matter to permit a narrow view of a small part of industry to dictate general educational policy. In any case, I set down as the problem before us, a 4-year program that will recognize the educational policy outlined, and yet be a preparation for entering those fields that now employ engineering graduates.

The first critical question is the distribution of time between the technical and social phases, or stems, of the curriculum. This will depend in a limited way upon such factors as the field of activity for which students are preparing. For instance, a course looking primarily to management would demand a larger portion of the curriculum for the social phase than one looking primarily to technical engineering. Moreover, if the students were divided into general course and honors groups, as presumably they will be more and more, the programs of the honors group probably would include more time for the social stem. Naturally, individual judgment as to the division of time also will vary. My own opinion is that the social stem should be accorded from one quarter to perhaps one third or more of the total time, depending upon the factors referred to.

There is an additional specification regarding the time distribution: the social stem should be continuous. The purpose is to build up a habit of mind; to create a desire to become broadly educated; to cultivate a *stem* which will continue to grow after graduation. And I am clear that this cannot be accomplished by discontinuous effort. The program must be continuous and sequential, beginning in the freshman year and extending through the senior year into professional life.

The second critical question is the specific nature of the social and economic side of the program. What subjects should be included? How should they be taught? I have found only one way in which to answer these questions. It is first to state specifically the outcomes desired, and then frame the program so that it will achieve these outcomes. Perhaps the program cannot be defined in traditional terms; merely of subjects to be studied and courses to be taken. The things that cultivate those definite outcomes must be considered, and traditional courses in history, English, economics, government, and sociology, will not accomplish the purpose. In the first place, there would not be enough time for the student to cover these subjects in the traditional way, and secondly, even if he did so, he would not achieve the ends.

What, then, should be the outcomes? I recommend (1) a clear historical understanding of the parallel growths of science and engineering, on the one hand, and social customs, relations, and institutions, on the other, and how these have reacted on each other. In other words, a historical perspective of social evolution, especially since the invention of the machine: (2) The ability to read purposefully in order to make a critical analysis of a problem involving social and economic elements, and arrive at an intelligent opinion about it. The ability to analyze technical problems does not, as sometimes assumed, imply an ability to analyze these others: (3) The ability to organize thoughts logically and with purpose: (4) The capacity to use the English language and thus express those thoughts effectively: (5) Appreciation of English literature: And (6) a continuing interest in all these matters, and thus the desire to become educated.

These outcomes imply the general character of the social stem of the curriculum. They imply extensive and carefully selected reading and seminar or class discussion during the first 2 years, in order to acquire general background and to establish clear conceptions of both the decisive turning points in social development and the attempts that have been made by social scientists to generalize from the recorded experience. This preliminary study must not be too detailed. It must be directed toward establishing an over-all pattern that can be examined as a whole. What is essential is a clear picture of the general features of the highway system by which civilization has reached its present stage—the junction points, the sign posts and traffic signals, the most general character of the main routes, and possibly some of the important detours. The less essential features of the individual highways, of the scenery and towns along the way, and of detailed social customs must be left to future study when more time may be spent in a particular section. I cannot emphasize too strongly the importance I attach to such an integrated view. It must be achieved at all costs, but it does not cost much. There is adequate time in 2 years if only one can restrain the habitual insistence of many textbook authors upon the gorging of details, and of instructors thus to administer them. With such a general picture in mind, subsequent study of problems and subject matter regarding a particular area then becomes both intelligent and interesting.

In the last 2 years only a few special problems should be studied; that is, definite social and economic questions about which the student would be required to read under competent guidance, and come to an intelligent opinion. He should have 3 or 4 of these in the junior year, one or 2 in the senior, each being more difficult than the last, and have the responsibility of defending his solution, pre-

sented in an essay before a small seminar—not more than 7 or 8 participating students, each of whom had read the essay. Such a program would not involve many scheduled classes, especially in the last year. There would be seminars only at times when problems were ready for review, and a few other meetings found to be necessary to keep students under way. These latter would occur more frequently at the beginning of the junior year, and almost not at all in the second semester of the senior year. But the transition from frequent meetings to few is necessary. The rest of the time would be devoted to reading, study, and writing.

I wish to stress especially this feature of independent study of a question. It gives actual experience in *doing*. One can read for background, take course after course in this and that, but until one has actually gone through the process of reading around a question and has one's self thus formed an intelligent judgment that must stand the test of critical discussion—until then, one has missed a fundamental first step in achieving a disciplined intellect. And if that educational experience is not acquired in college, it may never be.

May I add one or 2 more comments about this particular feature of the plan? I may be accused of proposing graduate activity in undergraduate work. Perhaps I am. Undergraduate students may seem immature, but I feel that the character of much undergraduate work tends to keep them so. I am convinced that the sooner they can be introduced to the *method*, however simple the problem, of high-grade graduate activity, the more we shall help students achieve intellectual maturity.

Or it may be said I am proposing merely an honors course, after the English model. Perhaps I am. There is this distinction, however, that simplifies our problem: Here the student's reading centers around a specific question, not a whole field. Indeed, he may be led to read in 2 or 3 fields to solve his problem, but his entire activity has a perfectly definite focus, and the character of the problem always can be adjusted to his ability and available time.

Finally, it may be suggested, and with some reason, that such a program would be too expensive and administratively complicated, but it is not as bad as it appears. The first 2 years would be largely class work as to time and schedule, but with emphasis different from the usual. And in the last two, although much of the guidance may be individual in character, the conferences would not be frequent—perhaps biweekly. And those aspects of the work which, in the earliest part of the junior year may seem to require more frequent meetings, are those which can be handled in group meetings. Moreover, I acknowledge that a portion of the class may require group guidance for an extended period, and these should be so guided. Although the program may involve careful planning, the values are too great to forego, especially for those students who can pursue the work with a minimum of guidance.

Returning now to the other features of the program implied in the proposed outcomes, I have mentioned the ability to organize thought and to express it effectively. A rigorous discipline in achieving logical relationships of ideas, and in writing, should be a characteristic of the program throughout the whole 4 years. Through the medium of essays, very simple at first, the student's mind should be kept in constant challenge as to logical thought and statement.

With respect to an appreciation of English literature, I confess I see no better way to foster this than the best type of English courses. The purpose should be to create an interest and desire to read for pleasure; it should not be to cover as much literary ground as possible. By the way, one theory I have heard for covering much ground is that it is the last chance to tinge the poor engineer with a little culture! Thus the requisites I would specify are interesting subject matter, interesting class discussion, interesting essays.

Summarizing, I have thus outlined the nature of the program I would recommend as the social stem of the engineering curriculum. The educational values are as follows: All reading and study would be focused upon a definite, clearly visible objective; counsel of a mature mind; experience in pursuing independent critical study, in discriminating between the important and the trivial, in forming intelligent judgments, and in organizing thought logically and with purpose; the discipline of intelligent criticism by other minds; and the unmatched incentive to fruitful effort by the student of his "coming to bat" before, and in competition with, his associates. And I think I am justified in adding that it will create in many students the desire to continue reading and study after graduation. Experimentation for 4 years with such a program in junior and senior years gives me confidence that the outcomes implied in the proposed educational policy can be achieved reasonably; they certainly can be fully achieved with the better minds.

Is it worth while? Is America worth while? I do not suggest that this particular program is the final answer to the problem. It is still at experimental stage. And there may be many other ways to accomplish the purpose. But I do insist that we cannot escape the responsibility of striving toward the outcomes I have indicated, and insist, further, that the present typical educational programs do not achieve them. And even if adequate programs may cost slightly more, and require sacrifices in the specialized courses on the technical side, I repeat the question, Are they not worth while? For what is to be gained by preparing engineers to continue their building of a physically magnificent structure only to have it torn down ultimately by the uncontrolled, unintelligent forces of selfish interests and vandalism?

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# Electrical Accidents

By W. B. KOUWENHOVEN
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**Six factors influence the result of an electric shock: type of circuit, voltage, resistance, current, current pathway, and duration of contact. Preventive measures will reduce the hazard, and resuscitation will save many victims, according to information summarized in this article, which is based on reports previously published.**

MAN-MADE electric shocks are not modern. The first shock recorded in literature was reported by Galvani in 1780. The first fatal electrical accident occurred in France in 1879. In the United States the present death rate due to electrical accidents is one per 100,000 of the population. Approximately one-half of the electrical accidents reported result in fatalities. Some fatal accidents occur on low-voltage circuits and the house circuits account for the deaths of between 100 and 200 persons annually. With the increased availability of electric power and the new uses that are advocated, there is the possibility that electrical accidents may increase. It is the duty of engineers to acquaint the public with the dangers that do exist, so that undue hazard may be avoided.

Maclachlan[1] has published an excellent study of 479 cases of electric shock for which complete data are available. He showed that men are more commonly injured than women and that the ages of the greatest incidence of shock lie between 15 and 30, perhaps owing to the greater carelessness of youth. Accidents are more common in the summer months, as the result of the smaller protection offered by the clothing and the presence of perspiration, which lowers the skin resistance. Maclachlan found that accidents are more common at the end of the working day when fatigue is at a maximum. He reported that the current path through the body is generally from the right hand to the feet.

## Factors Involved

In every electrical accident there are 6 factors which influence the result. These are, first, the type of circuit with which contact is made; second, the voltage of the circuit; third, the resistance offered to the flow of current; fourth, the value of the current; fifth, the current pathway through the body; and sixth, the duration of the contact with the circuit.

### Type of Circuit

The type of circuit[2] with which contact is made affects the resulting injury. For example, low-voltage alternating current is more dangerous than the corresponding continuous voltages. On the contrary, d-c circuits above 1,000 volts are more dangerous than a-c circuits of the same voltage. Experimental studies[3] have shown that there is little if any difference between commercial 25- and 60-cycle circuits.

The tetanic contraction of the striated musculature of the body caused by contact with d-c circuits is not as severe as that produced by alternating current. The latter will sometimes throw the victim clear of the circuit. Experiments made with the lightning discharge of an impulse generator on animals showed no evidence of musculature contraction.

### Voltage

High-voltage circuits are recognized as dangerous and are carefully avoided by everyone. The public considers the low-voltage house circuits as perfectly safe; this, however, is not the case, as already has been stated. The contraction of the muscles when good contact is made with a low-voltage circuit is usually insufficient to throw the victim clear. He is held in contact with the circuit and death may result. Many of these low-voltage accidents could be avoided if the public appreciated the danger and realized that electricity, although a good servant, is a bad master.

### Resistance

Greatest protection against electric shocks, particularly those caused by low-voltage circuits, lies in the skin. The resistance that dry skin offers to the flow of electricity ranges from 70,000 to 100,000 ohms per square centimeter. Its value depends to a certain extent upon the callousness of the skin. Once the current enters the body, the tissues offer only a relatively low resistance to its flow.

When the skin is thoroughly moistened by washing or perspiration, its resistance falls to less than one one-hundredth of its dry value. It is under these conditions that contact with the low-voltage circuit is dangerous. Contact with electric circuits should be made impossible in kitchens, bathrooms, cellars, and industrial locations where moisture is present.

Considerable heat is generated in the epidermis at the points of contact with the circuit, because of its high resistance. If the victim cannot release his hold and contact with the circuit continues for even a short time,[4] the temperature may be raised to a sufficient degree to produce blisters. These break down the skin and destroy completely any protection that it had initially offered to the flow of current.

An address presented at the exercises commemorating the 25th anniversary of the engineering school of The Johns Hopkins University in February 1937.

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1. For all numbered references, see list at end of paper.

### Current

The sensitivity to electric currents varies widely. Some individuals can detect the presence of currents of one milliampere or less, while others require several times that amount in order to be certain that a circuit is alive. In any electrical accident, Ohm's law determines the current that flows, and it is the passage of this current through the body that determines the injury produced. The question naturally arises: What value of current is dangerous? The writer believes, because of the results of laboratory experiments and field data, that an alternating current of one-tenth of an ampere at commercial frequencies is sufficient to cause death provided it flows through the vital organs. This does not mean, however, that a current of 20 amperes will make death more certain. In fact the opposite is more often the case. The reason for this apparently anomalous statement is due to the fact that the flow of a small current through the chest may be sufficient to destroy the normal rhythm of the heart and to throw that organ into ventricular fibrillation. Under these conditions, the circulation of the blood ceases and death ensues as the human heart rarely recovers its regular beat spontaneously. A large current, however, produces a severe contraction of the body musculature including that of the heart and holds that organ at rest. Then when the circuit is broken, provided the duration of the contact is brief, the heart automatically resumes its activity.

### Current Pathway

The path that the current follows in its passage through the body is of great importance. In general, if no vital organ lies in the pathway, no serious injury results. For example, in experiments with rats when the electrodes were attached to the 2 hind legs, all but 2 of the animals survived a 2-second shock from a given circuit without injury. When, however, the electrodes were shifted to the forelegs all of the animals died. The currents and voltages were the same in both experiments. Once the current is inside the body, it spreads out in a more or less fusiform shape, assuming uniform specific resistance for the tissues. It is difficult to believe that any appreciable current passes through parts of the body that lie far outside of the main current pathway. There are, however, accident cases on record where unconsciousness followed the passage of a current between 2 fingers on the same hand or 2 points on the same leg. In such cases, no current flows through the central nervous system and the action must have been caused by the sudden shock and the resulting vasomotor changes.

The brain appears to be relatively easily injured by the passage of an electric current, and in legal electrocution one electrode is placed on the head. Fortunately, in most industrial accidents the brain does not lie in the current path; however, the heart and respiratory apparatus are often injured. In many electrical accidents the current in passing through the body produces a block in the nervous system. This prevents the normal stimuli from the brain reaching a given organ. If that organ is the breathing mechanism, the victim will die of asphyxia, unless artificial respiration is given promptly.

### Duration of Contact

The duration of the contact with the circuit is extremely important in determining whether an individual will survive or not. There is usually little data available in cases of human accidents as to the length of time that the current flowed through the body. In our first series[5] of experiments on animals in which they were subject to shocks of different voltages, the importance of the time factor was clearly demonstrated. In general, the higher the voltage, the shorter the time during which the circuit may remain closed and there be hope of resuscitation. Fortunately, due to the violent contraction of the muscles when contact is made with high-voltage circuits, the shock is usually of short duration.

## Preventive Measures

It is the duty of qualified persons to acquaint the public with the rules for the safe handling of electrical circuits and devices. It is the duty of the designing engineer and architect to reduce the low-voltage hazard by specifying highest grade equipment and so installing it as to make humanly impossible, as far as practicable, contact with a live circuit, especially in damp locations. The floors of such places are usually of concrete or similar electrically semiconducting material. Keeping in mind the fact that in most accidents the current flows from the hands to the feet, the building designer might well consider the question of providing an insulating floor covering. The manufacturer of power-operated hand tools and their accessories should use ample amounts of the best grades of insulation because the best is none too good.

## Resuscitation

The problem of the resuscitation of a shock victim divides itself into 2 fields, namely, the treatment of the fibrillating heart and of cases of paralysis of respiration due to nerve shock.

### Countershock

The statement has been made that small amounts of current are sufficient to throw the heart into ventricular fibrillation, but that when a large current flows, the heart is held quiet because of the strong musculature contraction. Experiments were carried out in which the heart was first thrown into ventricular fibrillation and then a larger current applied for a short time in order to ascertain if it were possible to arrest the fibrillation and recover normal heart action. These experiments[6] were successful. Ventricular fibrillation was stopped in dogs whose hearts had been left in that state for periods up to 5 minutes by the use of a "countershock" of 6 or 7 amperes at 330 volts applied by means of electrodes located on either side of the animals' chests. In these cases, the hearts have resumed normal operation and the animals have recovered. Ferris and Williams[7] have also experimented with the countershock method of resuscitating the fibrillating heart, and, using larger animals, have duplicated these results.

In the experiments carried on over a period of time at

The Johns Hopkins University, fibrillation has been stopped after having been allowed to continue for periods of more than 5 minutes. Although circulation has been re-established for a time in some of these cases, experimenters have not succeeded in saving the animals.

[**Editor's Note:** The method of countershock has not yet passed beyond a laboratory stage. Immediate application of artificial respiration is the recommended procedure.]

### Artificial Respiration

The most common result in electrical accidents is a physiological block or break in conduction in the nervous system controlling the operation of respiration. The victim will be apparently dead; he will not be breathing and his heart beat may be so faint as to make it impossible to detect the pulse. The nerves have been paralyzed by the current and no longer transmit the stimuli from the brain to the lungs. The block will often disappear in time if given a chance. Artificial respiration by the Schaeffer prone-pressure method should be applied at once and be continued either until the victim recovers or until rigor mortis sets in.

Remember that death from electric shock is often only apparent and that lives have been saved by the prolonged application of artificial respiration.

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# A Proposed Test Code for Apparatus Noise Measurement

## An Advance Report Presented for Purposes of Discussion

PREPARED under the auspices of the subcommittee on sound* of the AIEE standards committee, this preliminary report is intended to provide some basis for standardized technique in the relatively new field of apparatus noise measurement. Because of the newness of apparatus noise investigations, and the importance of the subject, the subcommittee anticipates some possible inadequacies in this report, and solicits criticisms and comments from readers. To facilitate specific discussions, paragraphs are numbered.

1. This test code is intended for use as a guide in the measurement of sound levels and the investigation of the various elements that contribute to the total noise produced.

2. Often, after apparatus is installed, questions arise as to the true causes of the observed sound level, and the best way in which to reduce it. Also, it is often desirable to design apparatus for a given installation to meet a specified sound level. These objectives require knowledge of the sound produced by the apparatus and of the effects on the sound level of reflections and absorption due to the ambient conditions. In this connection, it is necessary to make numerous measurements of sound levels, both in the factory and in the field.


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* Personnel of Subcommittee on Sound of AIEE Committee on Standards, 1936–37: P. L. Alger, *chairman;* A. P. Fugill, C. R. Hanna, H. B. Marvin, R. G. McCurdy, and H. M. Turner.

3. The purpose of this code is, therefore, to establish reasonably uniform methods of conducting and reporting such sound level tests, so that wherever or by whomever tests are made, the results will be of value for record and will be truly comparable with tests made at other times and places.

4. It is recognized that additional codes, sponsored by appropriate industry committees, may be desirable in the future for the conduct of sound level tests on specific types of apparatus, such as fans, motors, gears, etc. The present code contains only general recommendations, which will serve as a guide in the development of the technique of sound-level testing and a common foundation for future codes for specific types of apparatus.

## Scope

5. This test code contains general instructions for conducting and reporting sound-level tests on apparatus. It is based upon the 1936 American standards *Z*24.1 (Acoustical Terminology), *Z*24.2 (Noise Measurement), and *Z*-24.3 (Sound-Level Meters).

## General Considerations in Apparatus Noise Measurement

6. To appreciate the necessity of a test code for sound measurement, it is well to review a few of the important

physical phenomena attending the transmission and radiation of sound which have to be considered in formulating the code.

### Radiation of Sound

7. The distribution of sound about sources other than a few simple types is usually very complex. The out-of-phase as well as the multifrequency vibrations which exist on the surfaces of large sounding bodies such as transformers, motors, and generators, and other apparatus give rise to sound patterns that defy mathematical analysis. In practice, however, several simplifying assumptions can often be applied to help us understand the nature of sound radiation from apparatus. If the wave length of the emitted sound is large compared with the dimensions of the source the sound will be radiated quite uniformly in all directions. But if the wave length is short compared with the dimensions of the source, important directive effects will appear. This suggests that for large sound sources with complex radiating surfaces, a considerable number of sound measurements at different points about the source should be made and averaged to determine the sound level of the source.

8. Many small sound generators such as fractional horsepower motors, small contactors, electric clocks, etc., are inefficient and nondirective radiators of low-frequency sound, but they can be excellent radiators of sound of higher frequencies. Such sounding bodies can often produce marked increases in sound of lower frequency when their vibrational energy is transmitted to surfaces large enough to be efficient radiators. This principle, along with resonance, is often used to amplify the feeble tone of a tuning fork. A conventional horn-type loud speaker reproducing music outdoors provides an excellent example for illustrating directive radiation. The lower-frequency components of the music can be heard about equally well in all directions. The higher-frequency components, since they are effectively directed, can be heard best along the axis of the speaker.

9. A study of the radiation of single-frequency sounds from generators of simple shape reveals several interesting facts that should be kept in mind when noise measurements are made. If we assume a vibrating disk of dimensions such that the wave length of the emitted sound is short compared to the diameter of the disk, we find that for a range of distances along the axis, dependent upon the wave length and the distance, the intensity of the sound goes through a series of maxima and minima before a distance is reached beyond which the intensity decreases inversely as the square of the distance. If we assume a pulsating sphere which is small compared to the wave length of the emitted sound the intensity in free space will decrease inversely as the square of the distance. In this latter case, the sound level will decrease 6 decibels each time the distance is doubled.

### Room Effects

10. Particular attention should be given to sound radiated from room surfaces in response to vibrations transmitted through the apparatus supports. Sound produced in this way can be controlled by providing suitable vibration isolating supports for the apparatus.

11. When sound generators are placed within rooms the sound will usually be reflected back and forth many times from the surfaces, and so give rise to a complicated distribution of intensity within the space. At any point within the room the sound level is the resultant of 2 effects; namely, the direct sound which reaches the point without first being reflected, and the indirect sound which arrives after suffering one or more reflections from surrounding surfaces. In general, there will be little correlation between intensity and distance to the source. The intensity may not decrease inversely as the square of the distance; instead it may even be found that at certain points remote from the source the sound is more intense than at positions much closer.

12. The effect of room reflections upon sound measurements can usually be made small by placing the microphone close to the source, and by taking a number of measurements about the source. The use of effective sound-absorbent materials on the interior surfaces of the room will help materially in reducing the effect of indirect sound.

13. An analysis based on reverberation theory leads to the conclusion that if a given amount of sound is generated within a room, the average energy density due to diffusely reflected sound is inversely proportional to the total absorbing power of the room. Hence, assuming that a given absorbing power is constant with respect to the important frequencies in the sound, and converting the expressions relating the intensities at a point in the room where the sound is mostly indirect to the corresponding decibel expressions, the following relation approximately applies:

$$(SL)_1 - (SL)_2 = 10 \log_{10}\left(\frac{A_2}{A_1}\right)$$

where $(SL)_1$ is the sound level in decibels in a room having a total absorption of $A_1$, and $(SL)_2$ is the sound level when the absorption is $A_2$.

## Ambient Sound Levels

14. Measurements made in many locations have shown that the sound levels existing in factories, offices, and residences usually fall within the ranges given below:

| | Sound Level in Decibels |
|---|---|
| Factories† | 60–90 |
| Offices | 40–75 |
| Residences | 30–55 |

## Instrument Standards

15. A sound level meter in accordance with American tentative standards for sound-level meter Z24.3 should be used for measuring sound level.

16. Three response curves are provided for in the standards, curve *A* for a 40-decibel sound level, curve *B* for a 70-decibel level, and a flat response curve *C* for higher

**Table I. Correction for Ambient Sound Level**

| Difference in decibels between ambient plus apparatus sound level and ambient sound level | 2 | 3 | 4 | 6 | 8 | 10 |
|---|---|---|---|---|---|---|
| Correction to be applied to ambient plus apparatus sound level to obtain apparatus sound level | −4.3 | −3.0 | −2.2 | −1.3 | −0.8 | −0.4 |

levels. Each of these curves is desirable for use under proper conditions, but it is recommended that curve *A* be used for usual apparatus noise measurements, curve *C* for very high intensities where low frequency noise is predominant, and that curve *B* be used only in special cases.

17. This recommendation is supported by the fact that it is important to have sound-level readings representative of the level that is actually heard under operating conditions. If the apparatus sound level is high, the apparatus is usually placed remote from the point where quietness is desirable. Therefore, the sound level actually heard is much lower than that measured, and hence it is desirable to make the measurements with the scale corresponding to the lower level, that is, the *A* scale.

## Factory Tests

18. Factory noise measurements on apparatus are to be made under such conditions that the increase in the measured sound level produced by reflections from surrounding surfaces is small. Also, the microphone should be placed in a position free from disturbing air currents, vibration, electric or magnetic fields, or other external influences, which may affect the readings obtained. The ambient sound level at the test locations should be at least 6 decibels, preferably 10 decibels or more, lower than the sound level due to the apparatus. In general, this requires a special noise box or room with efficient sound-absorbing material placed on the floor, walls, and ceiling. Corrections for ambient levels in factory tests are not generally permissible due to the uncertainties introduced.

Note: Free field conditions for the test room should be attained in so far as it is practicable, but when reflections of importance cannot be avoided their effects upon the measured apparatus sound level may be checked by making a series of sound level measurements with the apparatus placed in various parts of the room, maintaining constant at all times the position of the microphone with respect to the apparatus. If the source is constant the variation in the magnitude of the sound level measured is an approximate measure of the effect of room reflections. The effect of room reflections may also be checked by comparing measurements made outdoors in an open space with measurements made inside of the room.

19. The apparatus under test may be mounted, at the manufacturer's discretion, so that the sound transmitted through the supports will be negligible.

20. Make measurements at several locations near the apparatus to obtain a close approximation to the average sound level produced by the apparatus under free field conditions. When a given type of apparatus consistently produces the same general sound pattern, it is often possible to make production tests at some one point which has proved to be representative of the sound level as determined by averaging the measurements about the machine. The arithmetic average value of the readings is usually satisfactory, but when point to point variations exceeding 10 decibels occur, the weighted energy average, or 10 times the logarithm of the average of the antilogarithms of $^1/_{10}$ the separate decibel values, should be employed.

Note: *Example*

| Microphone Position | Sound Level (Decibels) | Antilogarithm of 1/10-Decibel Sound Level |
|---|---|---|
| *A* | 60 | 1,000,000 |
| *B* | 50 | 100,000 |
| *C* | 40 | 10,000 |
| | | 3)1,110,000 total |
| | | 370,000 average |

$\log_{10} 370{,}000 = 5.54$

$10 \log_{10} 370{,}000 = 55.4$ or the desired decibel value

21. When reporting sound-level measurements, the dimensions of the room and the nature of the floor, walls, and ceiling, the sound level of the room, the condition of operation of apparatus under test, the position of the microphone, and the frequency response of the sound-level meter should be recorded. The type of mounting and other information indicative of the degree of transmission of sound to the supports should also be reported.

22. To promote uniformity and facilitate the comparison of measurements, it is suggested that one of 3 standard distances from the microphone to the apparatus be adopted in making factory noise measurements, these distances being 6 inches, one foot and 3 feet. For very small apparatus with a sound level of less than 35 decibels and major dimensions less than one foot over-all, the 6 inches distance is suggested. For fractional-horsepower motors in general and for measurements where the apparatus is large compared to the space in which measurements are made, the distance of one foot is suggested. For large rotating machines, office equipment, domestic applicances, etc., the 3-foot distance is suggested. In locating the microphone with respect to the apparatus, the distance should be measured to the nearest major surface, minor surface projection being disregarded. When directional microphones are used, the method of orientation with respect to the apparatus outlined in the introduction of the American tentative standards for sound level meters *Z*24.3 should be employed. It is recognized that definite values for these distances, the number of readings to be taken, etc., will ultimately be decided by those interested in formulating codes for sound-level measurements on each specific line of apparatus. The suggestions here are offered for consideration as a logical starting point in formulating such specific codes.

## Standard Factory Measurement Positions

23. When measurements at more than one position are made, and it is desired to obtain one over-all value to represent the noise produced by the apparatus, it is recom-

mended that the readings taken at several points be averaged in accordance with the method outlined under "Factory Tests," paragraph 20.

## Field Investigations

24. The first step should be to measure the sound level produced while the apparatus is in operation, with the microphone placed at the standard factory test positions, if possible. In any case, the positions should be chosen so near the apparatus producing the noise that the effects of wall reflections or other environmental conditions are a minimum. Then shut down the apparatus and measure the ambient sound level of the room.

25. Further procedure will depend on which of 4 different types of situations are encountered.

(*a*). Apparatus noise much lower than the ambient noise, indicated by no change in reading when the apparatus is shut down. The readings of the apparatus noise in this case are not correct, and indicate only that the apparatus noise does not exceed ambient noise level.

(*b*). Apparatus noise higher than ambient noise. If the apparatus noise is more than 6 decibels above the ambient level (as will be the case when the apparatus plus ambient, and the ambient, levels differ by more than 7 decibels) the apparatus noise is affected but slightly by ambient. In this case, it will be desirable to compare the ambient noise level in this particular location with the ambients of similar installations elsewhere, and also the apparatus noise level with that of similar apparatus when measured in the factory under standard test conditions.

(*c*). Apparatus noise of same order as ambient noise. Under these conditions the sound level of the apparatus may be approximated by the use of the following table which is based upon the fact that the sound level meter adds the weighted energies of the various sounds that reach the microphone.

(*d*). The effects of wall reflections and other environmental conditions may be determined by comparing readings at different positions in the vicinity of the apparatus with those at the standard positions. If the reduction of sound level with respect to distance deviates considerably from that obtained under free field conditions, or if marked variations in sound level occur from point to point, sufficient measurements should be made to establish the general character and location of local increases in sound level. These may be produced by reflecting surfaces, structure-borne noise transmission, focal points of reflections, etc.

# The American Engineering Council

## An Outline of Some of the Problems, Policies, and Activities of This Jointly Sponsored Engineering Agency

By A. A. POTTER

President, American Engineering Council

INTEREST in co-operation among different engineering groups and the need for an agency to provide, on behalf of our profession, tangible service to public agencies, prompted, in 1920, the organization of the American Engineering Council with Herbert Hoover, then Secretary of Commerce, as its first president. From its very beginning it has been an organization of organizations intended to aid the engineering profession in presenting a united front in matters of interest to our government and to the public. While the Founder and other major engineering societies have been aiding in professional development of the engineer, the American Engineering Council has been supplementing their efforts by relating the engineering profession to public welfare and by making our government, as well as the public at large, conscious of the value of the engineers' services and contributions. It has served during the past 16 years as a clearing house for questions of public nature which require technological knowledge and engineering experience, and it has acted as an advisory body for the various engineering societies in connection with problems of government. At the same time the American Engineering Council has been an agency of inquiry into economic and social problems as affected by technology.

A report to the Council of the American Society of Mechanical Engineers, read at its semi-annual meeting, Detroit, Mich., May 17, 1937. Published by permission A.S.M.E.

Doctor Potter, dean of the schools of engineering and director of the engineering experiment station, Purdue University, Lafayette, Ind., and past-president of the American Society of Mechanical Engineers and of the Society for the Promotion of Engineering Education, now is serving his second term as president of American Engineering Council.

## Four Major Functions

The major functions of the American Engineering Council are performed through four groups of committees, which are concerned with public affairs, engineering economics, operations within the Council, and united action of its member societies. These committees, through 17 subcommittees, are in close contact with trends in the conservation and utilization of our national resources, relation of the engineer in private practice to government, patent legislation, public works, aeronautics, surveys and maps, rural electrification, merit system in public service, inquiries in the fields of social and economic activities of

our country, and similar problems in which engineers may have opportunities for co-ordinated action.

The problems of the American Engineering Council have taken a new slant since 1934. Instead of the normal process of legislation on engineering matters, the AEC has had to work during the past 3 years with a group of administrative departments, whose legislative authority and funds had been established by administrative order. Government departments and bureaus had to be "reeducated" about the American Engineering Council, and its work had to be changed from an orderly process of committee reports and committee hearings and procedures to the specific acts of keeping up with rapidly changing conditions.

Much of the work of the American Engineering Council had to go unreported because it had to do with contacts and associations with individuals in the government, and one of its main tasks had been to make and keep friends with the constantly changing and greatly expanding agencies of the government. Much of the work had to be confidential and some intangible, but a few of the high points may be discussed.

The American Engineering Council has had a constant demand for engineers from government agencies and a large portion of the time of the staff had to be devoted to employment problems for the government bureaus and departments. This service included not only the recommendation of engineers to the various government agencies but also aid to administrative agencies in planning the handling of such work as emergency mapping under the WPA, Rural Electrification Administration programs, Rural Resettlement plans, and NRA codes.

The American Engineering Council is constantly being consulted as to salaries to be paid to engineers and is guided in such requests by the reports of the Founder member societies. It is also invited to suggest names of consultants for various enterprises.

The American Engineering Council has been instrumental in placing numerous engineers in important consulting and line engineering governmental positions, those appointed to such positions seldom knowing the part that the AEC has played in placing them, as it has always been careful to submit a number of names and not to promote the employment of any particular individual.

As part of this employment service, the American Engineering Council had attempted also to analyze and to make a survey of the employment of engineers by government, classified by divisions. Government bureau chiefs are fully appreciative of this service and realize that advice and recommendations by the American Engineering Council are based solely upon the ability and technical competence of engineers and not on questions of political preferment.

During the past few weeks, at a request of one of the national member societies, the American Engineering Council made an exhaustive examination of those laws, regulations, interpretations, and procedures affecting the engagement of technical talent and engineering service by the federal government outside of the civil service. Conditions in more than 30 of the principal agencies known to be using technical talent were investigated, and the results when finally compiled, should prove of great value to the engineering profession.

## Advice on Policy

The American Engineering Council has been called for service in connection with matters of policy affecting emergency government setups. A concrete illustration is its relation to the National Resources Committee. Immediately after this committee was set up, as the National Resources Board, the executive secretary made contact with its chairman and director. This was followed by a conference with the chairman, arranged by the American Engineering Council, at which were present the secretaries of the member national societies and from which grew out contacts which closely related engineers to the work of this committee.

Many of the earlier reports of the American Engineering Council on such questions as flood control and the policies for the development of water resources were transmitted to the National Resources Committee and the recommendation of this new agency of government has reflected, in part at least, the recommendations of the member organizations of the American Engineering Council and of its committees. Specifically, the proposal for improvement in collecting water-resources data and the whole question of the development of water resources on the basis of conception of the "water shed," rather than on the basis of states alone, were in the earlier reports of the American Engineering Council.

The authors of the number of reports issued by the National Resources Committee were recommended by the American Engineering Council. Even the most recent report, "Technological Trends and Their Social Implications," has been influenced by advice from the American Engineering Council.

## Mapping and Surveying

This is a matter which is having the active interest of the American Engineering Council and has been helpful in educating the Budget Bureau on the value of an adequate mapping program. The American Engineering Council has worked with the Federal Bureau of Surveys and Maps in rounding up the opinions of organizations with reference to this program. Its aid to individual states has resulted in definite progress. A concrete example is Indiana which has appropriated a considerable sum at the 1937 session of its legislature for mapping.

## Various Interests

The Upstream Engineering Conference, the Third World Power Conference, and the plans for the World Management Conference are examples of activitites by the American Engineering Council in the interest of united action.

The American Engineering Council, through a committee of which a secretary of a Founder society was chair-

man, was instrumental in this study by the Bureau of Labor Statistics of the United States Department of Labor. This study made available data regarding 60,000 engineers with reference to such questions as employment conditions, compensation, and distribution in different fields.

## Engineering Economics

The activities of the American Engineering Council in studies in engineering economics have been helpful in projecting the engineering profession into the fields of thinking and action relating to our national social, economic, and industrial questions. Among the early contributions of the Council in this field may be mentioned the reports on "Waste in Industry," which had a profound effect upon the conduct of industry the world over; the "Twelve-Hour Shift in Industry" (1921), which demonstrated the merits of the shorter working day; "Civil Aviation" (1924), which focused the national point of view upon the development of commercial aviation; "Radio Broadcasting," which was instrumental in bringing about present policies and practices; and "Water Resources," which was helpful in appropriations for the installation of the national hydraulic laboratory.

Among the recent engineering economic studies of major value may be mentioned the inquiry of the balancing of forces which has greatly influenced economic thought and action during recent years.

There is need for accurate knowledge to show the real effect of science and technology upon social security; such information should go a long way in overcoming the present tendency to make the engineer the major scapegoat of our social ills, by showing that engineers create employment, wealth, comfort, values, and other factors which definitely contribute to social security. The American Engineering Council is now endeavoring to ally itself with representative economists, sociologists, and statisticians in order to study questions of this type and to guide in the public interest some of the questions of larger policy which lie in the fields of both engineering and economics.

There is also need for factual reports, for the benefit of the public, by committees of leading engineers on the engineering projects of our government. Engineers have an opportunity to show, through nonpartisan and unbiased services, their competency and integrity, and to make the public more conscious of engineering contributions. The American Engineering Council hopes that before long it will be in a position to finance the preparation and distribution of more reports, on behalf of our profession, which bear upon public welfare.

## National Problems

The American Engineering Council is concerned with national questions to which engineers may contribute co-operatively and in problems in which the engineering societies may have opportunity for co-ordinated action. It is not a super organization intended to manage or to interfere with the autonomy or with the specialized fields of it member societies. It is striving to serve the public and to bring about a better appreciation on the part of all, and particularly of government agencies, of the importance and value of the engineer's contributions. It is endeavoring to bring about concerted action on the part of engineers in public questions of national scope, and a definite interest on the part of the engineering profession in a well-balanced social structure and good government. By representing the engineering profession in matters of public welfare, government, and of joint interest to all engineering societies, the American Engineering Council serves the engineer and the public.

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# The Making of Industrial Physicists

THE human material for the construction of an industrial scientist may be qualitatively described with considerable ease; but to write for it an engineering specification with inspection techniques and with prescribed tolerances is at present impossible. Unless, however, we would credit evolution with having changed human nature within the times of recorded history we will agree that, despite his specialized training, modern scientific point of view, and wealth of precise instruments, the industrial scientist of today is the man of yesterday and of yesteryear and so on back into prehistoric days. What did this type of human being do in the past? Was he king or priest? Captain or explorer? Medicine man or scribe? Trader or pirate? None of these. He was thinker and craftsman. His was the type that invented the wedge, the inclined plane, the lever, and the screw. He surveyed and built the pyramids; designed and constructed triremes, roads, and aqueducts; shaped the tools of his day; and led the way from stone to bronze to steel.

His urge was the instinct of workmanship, a pleasure in the act of creation or construction which is its own reward. Neither driven by acquisitive instinct nor maddened by lust for power or fame, his satisfaction was his work; he sought little reward; and died unknown. More practical than the philosophers; spending little of his time in teaching or writing; and no follower of the Muses, he burned with a quiet steady flame of the same divine fire that suffused the great teachers and poets of his time. The captains and the kings depart; but what he wrought is the hidden basis of our material grandeur.

From a paper presented by John Mills (A'11, F'23) director of publication, Bell Telephone Laboratories, Inc., at the annual meeting of the Society for Promotion of Engineering Education, Cambridge, Mass., July 1, 1937.

# The Selection and Training of Engineers

## A company may choose an engineer, or the engineer may choose a company; certain qualities should be sought in either instance

By A. M. MacCUTCHEON
PRESIDENT AIEE 1936–37

IN CONSIDERING this subject a clear, concise, definite, and comprehensive conception of an engineer is essential. The dictionary definition "one versed in or practicing any branch of engineering," does not meet the requirements. Several practicing engineers submitted definitions, the most amusing of which was, "an engineer is a man who can do with one dollar what any man can do with 2 dollars." An engineer's wife felt that "an engineer is one with whom it is rather difficult to live but quite impossible to live without." Of the definitions submitted, the following was the best: "an engineer is one who through training, study, and practice successfully adapts and controls the materials and forces of nature to the benefit and advantage of himself, his fellow engineers, and the rest of the human family." This is quite similar to that prepared by the American Engineering Council, "engineering is the science of controlling the forces and utilizing the materials of nature for the benefit of man and the art of organizing and directing human activities therewith."

Two young men were presenting to a general in the Army Engineering Corps the design of a new and novel pump, and hoping for its adoption. He was not interested because the pump had not been proved. In answer to their inquiry he assured them that he considered himself an engineer and one of the young men stated, "an engineer is one who can tell whether a thing will work before it has been tried, for any fool can tell afterwards."

Each young engineer in training and each engineer engaged in their training should have a clear conception of "an engineer" for that is what their combined effort is intended to produce. Engineers are often charged with being poor salesmen and in some cases this criticism is justified, since they are poor salesmen of themselves and their services. Their engineering should be to the advantage of themselves but this viewpoint should not be overemphasized. Today each engineer should ask himself whether his engineering is in the interest of the human family and if it is not, is he in the truest sense an engineer. Society should recognize that the engineer should be suitably rewarded for his engineering efforts and achievements, since otherwise able young men will not continue to enter the profession.

Selection is defined as the act of choosing. Shall the young engineer be chosen by the company, or the company chosen by the young engineer? This will depend upon the relative standing of each, compared with the others in their field. To a young engineer, it is most important whether he will select a job or whether he will seek one. If his standing and achievements among his fellows are high, he will usually have the privilege of selection. Following are the qualities which a company seeks in a young engineer, listed in approximately the relative order of importance: integrity, dependability, determination, resourcefulness, forcefulness, adaptability, co-operativeness, diplomacy, friendliness, broadmindedness, and knowledge. While the last quality is of great importance to a company selecting a man, the first 10 may be even more important. The more knowledge possessed by a man, the more valuable he will be but of all these 11 qualtities, a deficiency in knowledge is most easily remedied. If the young engineer has the privilege of selection, it is just as important that the company he selects should possess the first 10 qualifications and to these should be added: an able and experienced personnel and leadership, a good financial standing, and a definite record of accomplishment. In either case the decision should be based on the probable situation 10 years later. No young man should be satisfied to be an average engineer unless his definition is analogous to Sam's definition of an average tip.

A clergyman, unused to traveling, was making the trip from Birmingham to New York. He was pleased to find that the Pullman porter had, at one time, been the sexton of his church. Throughout the journey Sam took good care of the minister and as Sam was brushing him off, while crossing the Jersey meadows, he asked Sam about what was the average tip that a traveler gave in going from Birmingham to New York. Sam answered, "Well boss, the average tip is about $5." As the minister left the train he handed Sam a $5 bill. Sam's eyes popped and he said, "Boss, you is the first man what ever come up to the average."

When a company selects a young man, graduating from technical school, it should consider the record of his accomplishment even as far back as when he was in high school. It should consider his standing among his fellow students. If he is respected, admired, and followed it is likely that his business associates will respect him and follow him. During his time in college what did he do for his class, and what did he do for his college? This is of importance as an indication of what he is likely to do for his company. His scholastic standing is of much importance for he has gone to a technical college with a definite purpose and if his standing has not been good he has

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Essentially full text of an address presented before many AIEE Sections, and published in response to numerous requests.

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failed in his purpose. This is an indication that he will not be successful in his purpose after graduation. Membership in such societies as Tau Beta Pi or Eta Kappa Nu is of importance as an evidence of accomplishment but scholarship is not the only qualification to be considered for he may be an excellent scholar and definitely lack in the other 10 qualifications.

If the young man is to have the privilege of selection he should consider the accomplishment of the company in the business which it has been carrying on, and its standing with its competitors, for if the competitors do not think well of a company it is questionable whether it is truly successful. He should consider the company's activities in connection with the professional and trade societies having to do with and endeavoring to advance the interests of that class of business. If a company is not interested in such activities it is not doing its part in the development of the broad field of its activity. Lastly, he should consider the salary which is being offered by the company. While this is important it should not be overemphasized. Of far greater importance is the salary which he will receive 10 years later.

The company should offer a salary competitive with other companies in its line of activity. While many individuals give far too much consideration to the matter of salary, some give too little. The salary received is the most tangible evidence of accomplishment. While an engineer should receive a salary commensurate with the contribution that he makes to the success of the company, he should recognize that fair salaries cannot be paid unless the company is successful. A broadminded engineer may willingly accept a relatively low salary over a considerable period and without dissatisfaction because he believes in the ultimate success of the company and that when this success is achieved, the company will suitably recognize his contribution in making the company successful. If an individual is not satisfied with his financial return, and is convinced that the company is not and will not be fair to him, he should not stay with that company for one of the greatest deterrents to a man's success is a long continued dissatisfaction with his financial return, about which he does nothing constructive. If a young engineer selects the right company and makes himself so valuable that he cannot be replaced without a considerable penalty, he will usually have to give very little consideration to the matter of financial returns. Great weight should be given to the financial standing of a company, and of particular importance is the record during such a period of business depression as existed from 1930 to 1934.

In the selection of young engineers, company representatives should make trips to the educational institutions and study the young men in their student environment. Many companies have done this for years, and the practice is becoming almost universal. It is equally as desirable that the young engineer should visit companies in order to prepare himself for the making of an intelligent decision. Because of limited finances, university restrictions, and lack of experience, the young man is handicapped in such an investigation. Twenty years ago a technical graduate was not discouraged if he had not located, by the time of graduation. This time of selection has gradually moved backward. Those men and companies, whose records of accomplishment permit them to be the selectors, have usually made their decision prior to the first of April. Certain advantages would result from a mutual agreement between the technical schools and industrial organizations that December should be a period of contact and investigation with decision to be reached early in March. The Christmas holidays offer an opportunity for the visiting of plants and the period immediately before and during the midyear examinations should be free from interruption. Some specialization during the last semester would be possible. Several companies are now offering to the young engineer who is so fortunate as to be in that group which has the privilege of selecting, the opportunity of visiting the plant that he may familiarize himself with the activities and the personnel of the company, and decide whether the association would be mutually advantageous.

## Training Before Graduation

The larger part of the technical training of the young engineer is received in the technical school prior to his selection and necessarily independent of the company with which he is to be associated or the particular type of work in which he will engage. Such generalized training is broadening but not so immediately useful as training of a more specialized type. There should be a sufficient amount of specialized training as to develop a proper conception of the intimate relation between training and accomplishment. Broad technical training should be continued after graduation and still closer contact and co-operation between educators and industrial managements is most desirable that the training before and after graduation may be fully co-ordinated, the one supplementing the other.

Comments made by one connected with a manufacturing company, on the training prior to graduation, are made from a narrow viewpoint and are offered only as suggestions for the consideration of the engineer educators whose lives are devoted to the training of young engineers and who are intensively studying the technique of engineering education.

Admiral Sims, in his story, so effectively illustrates the influence of a varying viewpoint. A young American was ordered to England to take charge of the London office. He met and married a delightful English lady whose mother was strongly pro-British. Many arguments resulted between the young man and his mother-in-law as to the relative merits of the 2 countries. In the course of time a daughter was born and some 3 years later the father was ordered back to the States. On the evening before they sailed, the mother-in-law requested the privilege of putting her granddaughter to bed. She descended the stairs smiling broadly and said to her son-in-law, "You should have heard your little daughter's good-night prayer. 'Goodbye God, we're going to America tomorrow.'" "But," said the son-in-law, "what she meant was—'Good,

by God we're going to America tomorrow.' "

To one in manufacturing it sometimes seems that the technical schools still lay more emphasis on the giving and acquiring of information than on the methods of proper engineering attacks, engineering analysis, and the securing of engineering information. While the imparting of knowledge to the young engineer is of great importance, instruction in the proper application of the "engineering method" is of still greater importance. Because of the necessary generalization much of the information gained is not usable after graduation. Training in the engineering methods is most valuable no matter with what company the young engineer may be associated. As a simple example of a somewhat unusual training, consider the course given in Columbia by Professor Lucke to a group of electrical engineers who had requested a course on gas engines. Most of the work was done in the laboratory where there were 10 gas engines. Under Professor Lucke's direction the laboratory assistant did something to each of these gas engines so that they would not properly function. The students were divided into 10 squads; each squad assigned to a particular engine. The problem was to determine what was wrong with the engine, make the necessary correction, and leave the engine running properly. Text books, specifications, and diagrams were available for consultation. Both Professor Lucke and the laboratory attendant would answer any questions which might be asked with one exception, "What is wrong with this gas engine?" There was an intense competition as to which group would first have their engine functioning properly. These electrical men received an unusual training in how to attack an engineering problem, analyze it, and solve it. The qualities of determination, resourcefulness, forcefulness, adaptability, co-operation, diplomacy, and friendliness were being developed in each one of the students.

In each engineering school should there not be a course "how to get results. How to handle other people and get them to do what you wish them to do?" Such a course would give valuable training to any man, particularly to engineers; a course just as valuable to the design or research engineer as to the engineer who would later serve in an executive capacity. The ability to handle people and get results is subject to development through training and this training is greatly needed by all engineers. Such a course might be given by the case method so successfully used in the training of lawyers. Successful executives would undoubtedly co-operate by giving lectures, citing unusual instances of results secured through properly approaching, informing, and co-operating with others. The best engineering plan has little value unless the engineer can convince others of the soundness of the plan and persuade them to use it. The following is a simple illustration of securing results and properly handling other people. An important new machine was being designed. Successively the designer compelled himself to view the design as a member of the sales department, the manufacturing department, the service department, and, most important of all, as the user. He prepared a series of briefs summarizing the design from each viewpoint. He presented the appropriate brief to at least one in each of these groups and asked for criticism and suggestions. He adopted any suggestions that seemed to him practicable. He avoided any prolonged arguments, but stated in writing why certain suggestions could not be adopted. All of this was done before the routine delivery of drawings and specifications. Each interested group was prepared for and committed to solving their problems in connection with the design before the problems actually reached them. Throughout the manufacture, tests, installation, and final operation, the design engineer stood ready to give information, answer questions, and render assistance. The design was highly commended by all who came in contact with the machine. While this designer held an important position in the organization, he was not an executive. Often engineers have been handicapped by failure to recognize who should be consulted and who should receive information.

In most technical schools there are a certain number of shop courses and at least some of these should be retained. The young engineer should receive a training in manual dexterity and this can best be accomplished prior to the age of 23. The theoretical and the concrete should always be associated.

If such work is to be retained, should not the electrical department specify shop courses directly related to electrical equipment; and should not each electrical engineer in training experience the thrill of designing, building, and testing at least one piece of such equipment? While the primary purpose of the technical school is a thorough grounding in the technical fundamentals, and with only 4 years allowed for all that is to be accomplished, will not a certain number of shop courses, properly coordinated, so effectively supplement the technical training as to give a better result with the same effort?

The training of the young engineer by the company which he has selected or which has selected him, is equal in importance to the training while in the technical school. The course should be carefully planned before the young men enter the company's employ and in consultation with the professors in the technical schools who have given their lives to the training of engineers. The course should be open to modification upon suggestions from the young men in training. There should be a sympathetic interest on the part of all departments in the organization and to this end each department should clearly understand the value of such training in the interest of the company. Lectures should be given by the company executives acquainting the group in training with the history, the development, the ideals, and the policies of the company. Some time should be spent in every department and, in addition, there should be visits to the plants of customers where the young engineers can see machines which the company makes, in actual operation. In this way they can be acquainted with the customer's viewpoint.

Both the company and the group in training should recognize the necessary compromise between the theoretical and the practical. The primary purpose of the organization is the manufacture of the product and while the training of the young engineer is of importance there

are times when this training must suffer if it conflicts with the primary purpose of the organization.

The American Institute of Electrical Engineers effectively participates in the training of young engineers. In most of the engineering schools, student branches have been established and these are an integral part of the AIEE. Within the branch, technical papers are prepared and presented, affording valuable training to the young engineer who prepares the paper and valuable information to the other young engineers who hear the paper presented. To the student member of the Institute is available ELECTRICAL ENGINEERING, containing the technical articles presented before the national and regional conventions.

Engineers are sometimes prone to neglect the human relationships and one of the most delightful privileges of an engineer is to meet with other engineers and exchange ideas. This opportunity is offered through the AIEE Branches while the young man is in technical school and through the local Sections after he has joined a commercial organization.

The most effective agency in the training of a young engineer is the engineer himself. He has more to do with his training than the technical school or the company with which he is associated. The arranged training courses simply present an opportunity that he may effectively train himself. In accomplishing this training he should grasp every opportunity to become acquainted with all others in the organization, including the workman in the plant. He should accept every opportunity for contact with outside engineers. He should join in the work of the professional organization of engineers in the city where he lives. He should seek to find answers to every unanswered question in his mind about the company's product. He should never walk through the plant without asking himself what he can find out that he has not previously known. What a man learns for himself, he seldom forgets. He should feel free to make suggestions, for he has a fresh and uninfluenced viewpoint.

One of the most important phases in the training of an engineer is to develop in him the probability of being right. While no engineer will always be right, this is the limit which he should strive to approach. The closer he comes to the limit, the more successful he will be. In his endeavor to approach this limit, he should remember that there is a great value in what may be termed "secondary checks." A secondary check may be defined as a brief comparison between the solution of a new problem and the proved solution of a somewhat similar problem, which comparison will indicate, at least qualitatively if not always exactly quantitatively, whether the new solution is correct. Through a free use of secondary checks costly errors will often be avoided.

The young engineer should be trained in how to accept and delegate responsibility. He should recognize that no man should be asked to accept responsibility without having a corresponding authority. A leading executive once said, "the president of a company is responsible for the work of every man in that company; the chief engineer for the work of every engineer who reports to him; each engineering division head is responsible for the work of everyone in his division; the chief draftsman responsible for all the work of the drafting room including that of the blueprint boy." This is the correct theory of responsibility looking from above downward. On the other hand, looking from below upward, the blueprint boy should be trained to feel responsible for everything regarding blueprints and blueprint service. The draftsman should feel responsible for every drawing he makes. While he should accept advice from the man above him, he should consider the finished drawing as his, for which he alone is responsible. Accepting responsibility for the work of all the men under him, the chief engineer should not feel that the president above him is responsible for the engineering. He should ask for and welcome advice and guidance, but the finished engineering he should consider as his, and his responsibility. A close following of this theory of responsibility should produce unusually good results.

In any course of training there should be sincere co-operation between the technical school, the company, and the young engineer himself. From Columbus comes a story illustrating an unusual degree of co-operation between engineers.

A Columbus engineer was called to Dayton and advised his wife he would return about 11 o'clock that evening. His wife was tired and retired at 9 p.m. When she awoke in the morning she found that her husband had not returned. She became deeply concerned, made a list of 20 engineers living in Dayton and who were acquainted with her husband and to each one of the 20, sent an identical telegram, "Do you know where John is, or what he is doing?" John's automobile had given trouble so that he had stopped in Dayton for the night and had the necessary repairs made the following morning. He reached home about 10 a.m. About 11 o'clock the wife began to receive replies to her telegrams. Exactly 20 replies were received and each reply said the same thing, "Do not worry; John is spending the night with me."

A company which selects a young electrical engineer owes to him a deep responsibility for they are influencing his whole life. They should not invite him to join the organization unless there is likely to be an opportunity such as he deserves. They should never forget their responsibility to him. They should offer to him every opportunity for development and should endeavor to give him a suitable financial return. On the other hand, the young electrical engineer should also fully realize the measure of his responsibility. He has accepted a position which would have been offered to another man. He should use every effort to fully measure up to the opportunities which are open to him. He should recognize that no company should offer an opportunity to a man who does not earn it and that his opportunity with the company largely depends upon his contribution to the company. If there is the fullest co-operation between the company, the technical school, and the young engineer himself, the engineering profession should be carried to far greater heights than have ever been reached in the past.

# Engineering Income and Earnings, 1929–34

**In this, the fifth article[1] of a series reporting a survey of employment in the engineering profession by the United States Bureau of Labor Statistics, income data for engineers of various professional classes and ages are presented, based on information given for the years 1929, 1932, and 1934. Comparisons may be drawn among professional classes, ages, and educational backgrounds.**

REPORTS from 52,589 professional engineers to the Bureau of Labor Statistics, in its survey of the engineering profession,[1] undertaken at the request of the American Engineering Council, make it possible to relate the income data to many aspects of professional engineering activity. These income data are probably the most comprehensive ever presented in regard to a professional group. The following general findings appear from analysis of the reports.

In 1929, 50 per cent of the 30,032 reporting engineers earned more than $3,412, and 50 per cent earned less than that amount. Twenty-five per cent earned more than $5,012, but only 10 per cent had incomes in excess of $7,466 per annum. On the contrary, 25 and 10 per cent of the engineers earned, respectively, less than $2,509 and $1,878 per year.

Comparison of the incomes for 1932 and 1934 with those reported for 1929 shows that from 1929 to 1934, the sharpest absolute declines occurred in the 2 higher income groups. Their percentage decreases were least, however, averaging 31.2 and 31.6 per cent, whereas the middle values of income declined by 33 per cent, and the 2 lower levels by 41.3 and 53.6 per cent, respectively.

Almost two-thirds of these decreases in earned annual income occurred between 1929 and 1932. There were further decreases from 1932 to 1934.

Among the several professional classes, the divergences in earning capacities were most marked in the higher levels of income. Furthermore, the ranking of the profession on the basis of earnings opportunity was the same in the highest 10 and 25 per cent only.

In 1929, without regard to the age distributions of the different classes, 10 per cent of the mining and metallurgical engineers earned more than $9,912 per year, chemical and ceramic engineers ranked second with 10 per cent earning more than $9,103, and were followed in order by mechanical and industrial engineers ($8,508), electrical engineers ($7,185), and civil engineers ($6,507). At the upper 25 per cent level, mining and metallurgical engineers reported earnings of $6,301 per year, and those of the other professional classes ranged from 4 per cent lower for chemical and ceramic engineers, to 28 per cent lower for civil engineers. This order of professional classes was also maintained in 1932 and 1934.

In 1929, the earnings of the mining and metallurgical engineers were highest in the middle and 2 lower levels of income, while those of the electrical engineers were lowest. At these 3 levels, the earnings of the former were $4,010, $2,839, and $1,985; for the latter they were $3,277, $2,339, and $1,662, respectively. Over these 3 levels, the relative positions of the 3 remaining professional classes changed. There were further shifts in 1932 and 1934.

The data also show that, over the period 1929 to 1934, relatively the smallest shrinkages in earnings were reported by the civil engineers, while the chemical and ceramic engineers suffered the greatest reductions. Over the 5 income levels, the former ranged from 29.0 to 47.2 per cent, the latter from 35.6 to 63.8 per cent.

Analysis of the income data reported by all engineers in 1929, 1932, and 1934 shows that earnings advanced with age in 3 distinct phases, showing initial periods of exceptionally rapid rise, followed by 2 others of slower rates of increase. The age spans of these phases varied with the income level.

With advancing age, the spread in earnings became most accentuated beyond the age of 38. Thus, at the ages of 44 and 60, the incomes of the upper 25 per cent differed from the median or middle value by 41.0 and 51.0 per cent. The corresponding incomes of the upper 10 per cent at these ages were greater than the median by 116.0 and 157.0 per cent. Even in 1932 and 1934, this advantage in earning capacity was maintained.

The earnings of the engineers in the lower income levels ceased to increase at a relatively early age. These showed a level period before beginning to decline, whereas the higher levels of income showed continuous increases for a considerably longer period, after which, however, they declined at a much greater rate.

Over the period 1929 to 1934, a rise in earnings occurred for the youngest engineers who were in the profession in 1929 and who were 30 years of age or less in 1934. Thereafter there were progressively larger declines for the older engineers.

Comparison of the earnings of engineers of identical ages in 1929 and 1934 shows that the average income of engineers who had been out of college for 2 years declined 43 per cent. The income of those who had been out 5 years declined 35 per cent. For older engineers the decline approximated 30 per cent.

Consideration of the incomes reported by engineers of different educational backgrounds shows that those with a formal engineering education did receive a higher income. The differentials in earnings, however, did not accrue in equal measure for all 5 professional classes.

1. An article prepared by Andrew Fraser, Jr., of the Division of Hours, Wages, and Working Conditions, Bureau of Labor Statistics, United States Department of Labor, which article was published in the August 1937 issue of *Monthly Labor Review*. Articles reporting other phases of this survey were published in ELECTRICAL ENGINEERING as follows: "Professional Aspects of Engineering Education," August 1936, pages 863–7; "Unemployment in the Engineering Profession," February 1937, pages 216–23; "Employment in the Engineering Profession," May 1937, pages 524–31; "Security of Engineering Employment," June 1937, pages 655–61. A detailed report of the survey will be published later in bulletin form by the Bureau of Labor Statistics.

## Table I. Comparison of Gross and Net Numbers of Older* and Younger** Graduate and "Other" Engineers Reporting Annual Earnings in 1934

Without regard to employment status reported

| Professional Class | Graduate Engineers | | | | Other Engineers | | | |
|---|---|---|---|---|---|---|---|---|
| | Total | Older Group | Younger Group Graduated in— 1930–32 | 1933–34 | Total | Older Group | Younger Group Born in— 1907–09 | 1910–14 |
| | Number | | | | | | | |
| All classes: | | | | | | | | |
| Number reporting in survey | 43,288 | 24,837 | 11,039 | 7,412 | 9,301 | 8,440 | 575 | 286 |
| Gross number reporting income | 38,513 | 22,178 | 10,201 | 6,134 | 8,277 | 7,513 | 523 | 241 |
| Net number reporting income | 33,720 | 20,376 | 7,210 | 6,134 | 7,569 | 6,871 | 457 | 241 |
| Chemical and ceramic: | | | | | | | | |
| Number reporting in survey | 3,697 | 1,453 | 1,257 | 987 | 203 | 158 | 27 | 18 |
| Gross number reporting income | 3,270 | 1,285 | 1,169 | 816 | 177 | 137 | 27 | 13 |
| Net number reporting income | 2,749 | 1,150 | 783 | 816 | 156 | 124 | 19 | 13 |
| Civil, agricultural, and architectural: | | | | | | | | |
| Number reporting in survey | 16,114 | 10,318 | 3,598 | 2,198 | 4,712 | 4,341 | 256 | 115 |
| Gross number reporting income | 14,562 | 9,344 | 3,369 | 1,849 | 4,275 | 3,941 | 233 | 101 |
| Net number reporting income | 12,984 | 8,596 | 2,539 | 1,849 | 3,915 | 3,603 | 211 | 101 |
| Electrical: | | | | | | | | |
| Number reporting in survey | 9,924 | 5,184 | 2,947 | 1,793 | 1,519 | 1,285 | 156 | 78 |
| Gross number reporting income | 8,792 | 4,688 | 2,686 | 1,418 | 1,345 | 1,140 | 140 | 65 |
| Net number reporting income | 7,627 | 4,368 | 1,841 | 1,418 | 1,256 | 1,067 | 124 | 65 |
| Mechanical and industrial: | | | | | | | | |
| Number reporting in survey | 11,643 | 6,599 | 2,851 | 2,193 | 2,590 | 2,407 | 124 | 59 |
| Gross number reporting income | 10,236 | 5,785 | 2,620 | 1,831 | 2,246 | 2,082 | 113 | 51 |
| Net number reporting income | 8,923 | 5,271 | 1,821 | 1,831 | 2,035 | 1,889 | 95 | 51 |
| Mining and metallurgical: | | | | | | | | |
| Number reporting in survey | 1,910 | 1,283 | 386 | 241 | 277 | 249 | 12 | 16 |
| Gross number reporting income | 1,653 | 1,076 | 357 | 220 | 234 | 213 | 10 | 11 |
| Net number reporting income | 1,437 | 991 | 226 | 220 | 207 | 188 | 8 | 11 |
| | Per Cent of Number Reporting in Survey | | | | | | | |
| All classes: | | | | | | | | |
| Gross number reporting income | 89.0 | 89.3 | 92.4 | 82.8 | 89.0 | 89.0 | 91.0 | 84.3 |
| Net number reporting income | 77.9 | 82.0 | 65.3 | 82.8 | 81.4 | 81.4 | 79.5 | 84.3 |
| Chemical and ceramic: | | | | | | | | |
| Gross number reporting income | 88.5 | 88.4 | 93.0 | 82.7 | 87.2 | 86.7 | 100.0 | 72.2 |
| Net number reporting income | 74.4 | 79.1 | 62.3 | 82.7 | 76.8 | 78.5 | 70.4 | 72.2 |
| Civil, agricultural, and architectural: | | | | | | | | |
| Gross number reporting income | 90.4 | 90.6 | 93.6 | 84.1 | 90.7 | 90.8 | 91.0 | 87.8 |
| Net number reporting income | 80.6 | 83.3 | 70.6 | 84.1 | 83.1 | 83.0 | 82.4 | 87.8 |
| Electrical: | | | | | | | | |
| Gross number reporting income | 88.6 | 90.4 | 91.1 | 79.1 | 88.5 | 88.7 | 89.7 | 83.3 |
| Net number reporting income | 76.9 | 84.3 | 62.5 | 79.1 | 82.7 | 83.0 | 79.5 | 83.3 |
| Mechanical and industrial: | | | | | | | | |
| Gross number reporting income | 87.9 | 87.7 | 91.9 | 83.5 | 86.7 | 86.5 | 91.1 | 86.4 |
| Net number reporting income | 76.6 | 79.9 | 63.9 | 83.5 | 78.6 | 78.5 | 76.6 | 86.4 |
| Mining and metallurgical: | | | | | | | | |
| Gross number reporting income | 86.5 | 83.9 | 92.5 | 91.3 | 84.5 | 85.5 | 83.3 | 68.8 |
| Net number reporting income | 75.2 | 77.2 | 58.5 | 91.3 | 74.7 | 75.5 | 66.7 | 68.8 |

* Includes all engineers who were professionally active prior to 1930.
** Includes all engineers who entered the profession in the years 1930–32 and 1933–34.

At about 28 years of age the "other" engineers had lost an initial advantage in earning capacity. At that point, the 1929 earnings of the graduates ranged from $2,725 to $3,000 per year, those of the corresponding "other" engineers from $2,430 to $2,650.

With advancing age, the spreads in earnings in favor of the graduates became very marked indeed. For example, at 5, 20, and 37 years after graduation, the earnings of first-degree mechanical and industrial engineers exceeded by $175, $925, and $1,322 per year those of the engineers of the same professional class whose college course was incomplete, and surpassed by $225, $1,160, and $1,815 per year those of engineers with a noncollegiate technical school education.

Even among the graduate groups there was variation in the increase in earning capacity between the several professional classes. Thus, the 1929 earnings of first-degree civil engineers who had been out of college for 5 years were only $2,050 less than the earnings of those who had graduated 30 years before, whereas the corresponding difference for chemical and ceramic engineers was $3,600. The ranges in earnings of the remaining graduate groups fell between those reported by the civil and chemical and ceramic engineers.

In general, the earnings of the "other" engineers ceased to increase at an earlier age than those of the graduates.

## Scope and Method of Study

Analysis was made to determine the changes in the income and earnings of professional engineers during the period 1929 to 1934. The reports covered 2 distinct features of income for the years 1929, 1932, and 1934: (1) earned annual income received from all personal services and (2) average monthly compensation from engineering work only. The annual figures are a measure of what en-

## Table II. Comparison of Gross and Net Numbers of Older* and Younger** Graduate and "Other" Engineers Reporting Monthly Engineering Income† in 1934

Without regard to employment status reported

| Professional Class | Graduate Engineers | | | | Other Engineers | | | |
|---|---|---|---|---|---|---|---|---|
| | Total | Older Group | Younger Group Graduated in— 1930–32 | 1933–34 | Total | Older Group | Younger Group Born in— 1907–09 | 1910–14 |
| | Number | | | | | | | |
| All classes: | | | | | | | | |
| Number reporting in survey | 43,288 | 24,837 | 11,039 | 7,412 | 9,301 | 8,440 | 575 | 286 |
| Gross number reporting income | 31,574 | 19,814 | 7,405 | 4,355 | 7,504 | 6,860 | 447 | 197 |
| Net number reporting income | 26,680 | 17,686 | 4,639 | 4,355 | 6,639 | 6,070 | 372 | 197 |
| Chemical and ceramic: | | | | | | | | |
| Number reporting in survey | 3,697 | 1,453 | 1,257 | 987 | 203 | 158 | 27 | 18 |
| Gross number reporting income | 2,568 | 1,151 | 842 | 575 | 141 | 116 | 16 | 9 |
| Net number reporting income | 2,071 | 1,004 | 492 | 575 | 118 | 99 | 10 | 9 |
| Civil, agricultural, and architectural: | | | | | | | | |
| Number reporting in survey | 16,114 | 10,318 | 3,598 | 2,198 | 4,712 | 4,341 | 256 | 115 |
| Gross number reporting income | 12,929 | 8,593 | 2,817 | 1,519 | 3,996 | 3,691 | 212 | 93 |
| Net number reporting income | 11,073 | 7,647 | 1,907 | 1,519 | 3,538 | 3,260 | 185 | 93 |
| Electrical: | | | | | | | | |
| Number reporting in survey | 9,924 | 5,184 | 2,947 | 1,793 | 1,519 | 1,285 | 156 | 78 |
| Gross number reporting income | 6,307 | 4,003 | 1,524 | 780 | 1,138 | 980 | 109 | 49 |
| Net number reporting income | 5,376 | 3,678 | 918 | 780 | 1,041 | 898 | 94 | 49 |
| Mechanical and industrial: | | | | | | | | |
| Number reporting in survey | 11,643 | 6,599 | 2,851 | 2,193 | 2,590 | 2,407 | 124 | 59 |
| Gross number reporting income | 8,350 | 5,105 | 1,938 | 1,307 | 2,022 | 1,882 | 102 | 38 |
| Net number reporting income | 6,994 | 4,511 | 1,176 | 1,307 | 1,765 | 1,688 | 79 | 38 |
| Mining and metallurgical: | | | | | | | | |
| Number reporting in survey | 1,910 | 1,283 | 386 | 241 | 277 | 249 | 12 | 16 |
| Gross number reporting income | 1,420 | 962 | 284 | 174 | 207 | 191 | 8 | 8 |
| Net number reporting income | 1,166 | 846 | 146 | 174 | 177 | 165 | 4 | 8 |
| | Per Cent of Number Reporting in Survey | | | | | | | |
| All classes: | | | | | | | | |
| Gross number reporting income | 72.9 | 79.8 | 67.1 | 58.8 | 80.7 | 81.3 | 77.7 | 68.9 |
| Net number reporting income | 61.6 | 71.2 | 42.0 | 58.8 | 71.4 | 71.9 | 64.7 | 68.9 |
| Chemical and ceramic: | | | | | | | | |
| Gross number reporting income | 69.5 | 79.2 | 67.0 | 58.3 | 69.5 | 73.4 | 59.3 | 50.0 |
| Net number reporting income | 56.0 | 69.1 | 39.1 | 58.3 | 58.1 | 62.7 | 37.0 | 50.0 |
| Civil, agricultural, and architectural: | | | | | | | | |
| Gross number reporting income | 80.2 | 83.3 | 78.3 | 69.1 | 84.8 | 85.0 | 82.8 | 80.9 |
| Net number reporting income | 68.7 | 74.1 | 53.0 | 69.1 | 75.1 | 75.1 | 72.3 | 80.9 |
| Electrical: | | | | | | | | |
| Gross number reporting income | 63.6 | 77.2 | 51.7 | 43.5 | 74.9 | 76.3 | 69.9 | 62.8 |
| Net number reporting income | 54.2 | 70.9 | 31.2 | 43.5 | 68.5 | 69.9 | 60.3 | 62.8 |
| Mechanical and industrial: | | | | | | | | |
| Gross number reporting income | 71.7 | 77.4 | 68.0 | 59.6 | 78.1 | 78.2 | 82.3 | 64.4 |
| Net number reporting income | 60.1 | 68.4 | 41.2 | 59.6 | 68.1 | 68.5 | 63.7 | 64.4 |
| Mining and metallurgical: | | | | | | | | |
| Gross number reporting income | 74.3 | 75.0 | 73.6 | 72.2 | 74.7 | 76.7 | 66.7 | 50.0 |
| Net number reporting income | 61.0 | 65.9 | 37.8 | 72.2 | 63.9 | 66.3 | 33.3 | 50.0 |

* Includes all engineers who were professionally active prior to 1930.
** Includes all engineers who entered the profession in the years 1930–32 and 1933–34.
† In the text, "monthly engineering income" and "engineering income" are used interchangeably.

gineers were able to earn during each of the 3 years. This was determined not only by the rate of earnings but also by the volume of employment. The monthly figures are a measure of the rates at which engineering services were purchased.

Both income and earnings are shown in relation to (1) professional class, (2) age, (3) type of education, and (4) regional location. A discussion of earned annual income from all sources, by age, is included for engineers engaged in engineering work and also for those in nonengineering work, as well as annual income reported by those engineers who were unemployed at the end of 1929, 1932, and 1934. Monthly engineering earnings, while treated similarly to annual income, can only be shown for the various types of engineering employment. The earnings of those engaged in engineering work are also shown in relation to size of city.

From a consideration of certain pertinent aspects affecting the returns on income and earnings for 1929, 1932, and 1934, it is believed that these data are representative of the engineering profession as a whole. They have been shown to be representative as regards age, if allowance is made for the larger representation of engineers graduating in 1930 or later years. In analyzing the income data, as in the analysis of employment status, the samples of older and younger engineers[2] were combined on an adjusted basis to secure a cross section of the entire profession in 1932 and 1934.[3]

Without exception the several distributions of income follow a consistent pattern even when analyzed in detail.

2. Older engineers comprised 15 per cent of all those who were professionally active prior to 1930. The age composition of this group was consistently uniform with the corresponding data derived from the 1930 census on professional engineers. This was so for minor groupings of professional classes by 10 geographical regions and for the country as a whole. The younger engineers included the information furnished by all those who entered the profession in the years 1930–34 inclusive. The returns for each of these years covered the same proportions (32.0 per cent) of the total number of graduations reported by the Office of Education.

**Table III. Comparison of 5 Levels of Annual Earnings for All Professional Engineers Reporting in 1929, 1932, and 1934**

Figures derived from adjusted data as explained[3] and without regard to employment status reported or type of education

| Per Cent at Specified Income Level | Annual Earnings of More Than Specified Amount | | | Increase or Decrease | | | Per Cent of Change | | |
|---|---|---|---|---|---|---|---|---|---|
| | 1929 | 1932 | 1934 | 1929–34 | 1929–32 | 1932–34 | 1929–34 | 1929–32 | 1932–34 |
| 10 | $7,466 | $5,605 | $5,138 | −$2,328 | −$1,861 | −$467 | −31.2 | −24.9 | −8.3 |
| 25 | 5,012 | 3,827 | 3,429 | − 1,583 | − 1,185 | − 398 | −31.6 | −23.6 | −10.4 |
| 50 | 3,412 | 2,574 | 2,286 | − 1,126 | − 838 | − 288 | −33.0 | −24.6 | −11.2 |
| 75 | 2,509 | 1,698 | 1,473 | − 1,036 | − 811 | − 225 | −41.3 | −32.3 | −13.3 |
| 90 | 1,878 | 889 | 872 | − 1,006 | − 989 | − 17 | −53.6 | −52.7 | −1.9 |

Thus, the same type of distribution emerges when the data are analyzed by ages, by professional classes, or even on a regional basis. This is true of both annual income and monthly engineering income.

The averages proved to be essentially the same, whether derived from a "gross" or "net" number reporting. The "gross" number reporting income is the total number of engineers who reported income in any one year, irrespective of whether or not they reported in other years. The "net" number reporting income is the number who furnished information for all 3 years—1929, 1932, and 1934.[4] In the income tables averages are derived from the "gross" numbers reporting.

The "gross" numbers reporting earned annual income for 1934 and the "net" numbers are shown compared in table I. These numbers are the totals of those returning questionnaires before any adjustment is made in the number of the younger men.

In each case, the base for computing percentages was the number reporting in the survey, that is, those engineers who reported a type of education.[5] For all age groups, it will be noted that there were distinct differences between the "gross" and "net" percentages reporting income. The greatest divergences occurred among the 1930–32 graduate and the 1907–09 "other" engineers. For the country as a whole, these were respectively 27.1 and 11.5 per cent. On a national basis, older graduates differed by 7.3 per cent, older "other" engineers by 7.6 per cent. Despite these variations, a comparison of the corresponding measures of levels of annual income derived from the "gross" and "net" returns showed no significant differences. A similar situation was noted for the "gross" and "net" returns on monthly engineering income.

In the ensuing discussion, the middle values of income were computed for groups with at least 10 engineers reporting. For the upper and lower 25 per cent groups or levels, the measures were based on not less than 50, while the upper and lower 10 per cent groups embraced not less than 100 engineers.

3. The procedure of adjustment adopted was similar to that outlined in the discussion of the distributions of employment status. The numbers of younger engineers reporting in each income class for 1932 and 1934 were reduced in the ratio of 15 to 32, and added to the corresponding figures reported by the older engineers in 1932 and 1934.

4. In the case of the 1930–32 graduates and "other" engineers born in 1907–09, the net number reporting income is the number furnishing data for the 2 years, 1932 and 1934. In the case of the 1933–34 graduates and 1910–14 "other" engineers, income data for 1934 alone were relevant. Hence, there is no difference between "gross" and "net" data.

5. The use of type of education as a base was felt to be justified because only 104 of the 52,589 professional engineers reporting in this survey did not report their type of education. The 104 engineers however, did report their professional class; and either year of graduation or year of birth. They were, therefore, used for all purposes, except those dealing with type of education.

## Earned Annual Income

The income data for 1929 were furnished by 30,032 engineers, or slightly over 90 per cent of all reporting engineers who were professionally active prior to 1930. These data, together with the adjusted figures on earned annual income, without regard to employment status reported, for 1932 and 1934, are shown in table III.

In 1929 the range in earned annual incomes among professional engineers was great. Some 60 reported incomes less than $800 per year, while 162 earned more than $19,000 a year. In 1929, without regard to their age distribution, half of the engineers had annual incomes greater than $3,412, while half earned less than that figure. However, 25 per cent earned more than $5,012 per annum. Only 10 per cent of the 30,032 reporting engineers had incomes in excess of $7,466 per annum. On the contrary, one-quarter of all engineers reporting earned less than $2,509 per year, and one-tenth earned less than $1,878 per year.

From 1929 to 1934, marked decreases took place in the

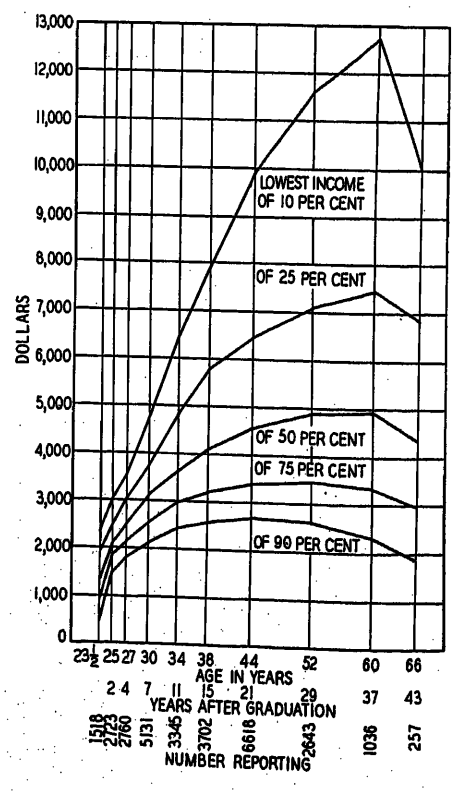



**Figure 1. Earned annual income of engineers according to age, 1929**

Income from engineering and non-engineering services, including full and part-time employment, all types of education

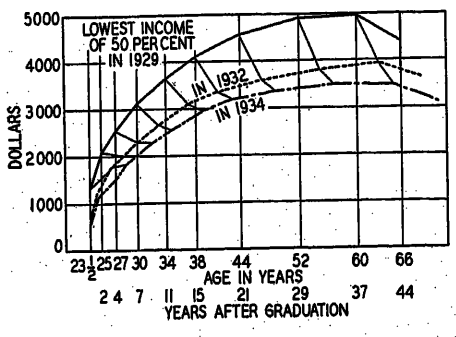
## Table IV. Comparison of 5 Levels of Annual Earnings for All Engineers Reporting in Each Professional Class in 1929, 1932, and 1934

Figures derived from adjusted data as explained[a] and without regard to employment status reported or type of education

| Per Cent of Professional Class at Specified Income Level* | Annual Earnings of More Than Specified Amount | | | Increase or Decrease | | | Per Cent of Change | | |
|---|---|---|---|---|---|---|---|---|---|
| | 1929 | 1932 | 1934 | 1929–34 | 1929–32 | 1932–34 | 1929–34 | 1929–32 | 1932–34 |
| 10 per cent: | | | | | | | | | |
| Mining and metallurgical | $9,912 | $7,011 | $6,486 | −$3,426 | −$2,901 | −$525 | −34.6 | −29.3 | − 7.5 |
| Chemical and ceramic | 9,103 | 6,525 | 5,860 | − 3,243 | − 2,578 | − 665 | −35.6 | −28.3 | −10.2 |
| Mechanical and industrial | 8,508 | 6,220 | 5,572 | − 2,936 | − 2,288 | − 648 | −34.5 | −26.9 | −10.4 |
| Electrical | 7,185 | 5,785 | 5,220 | − 1,965 | − 1,400 | − 565 | −27.3 | −19.5 | − 9.8 |
| Civil, agricultural, and architectural | 6,507 | 5,086 | 4,561 | − 1,946 | − 1,421 | − 525 | −29.9 | −21.8 | −10.3 |
| 25 per cent: | | | | | | | | | |
| Mining and metallurgical | 6,301 | 4,698 | 4,328 | − 1,973 | − 1,603 | − 370 | −31.3 | −25.4 | − 7.9 |
| Chemical and ceramic | 6,043 | 4,425 | 3,703 | − 2,340 | − 1,618 | − 722 | −38.7 | −26.8 | −16.3 |
| Mechanical and industrial | 5,582 | 4,123 | 3,662 | − 1,920 | − 1,459 | − 461 | −34.4 | −26.1 | −11.2 |
| Electrical | 4,806 | 3,770 | 3,410 | − 1,396 | − 1,036 | − 360 | −29.0 | −21.6 | − 9.5 |
| Civil, agricultural, and architectural | 4,508 | 3,579 | 3,266 | − 1,242 | − 929 | − 313 | −27.6 | −20.6 | − 8.7 |
| 50 per cent: | | | | | | | | | |
| Mining and metallurgical | 4,010 | 3,061 | 2,626 | − 1,384 | − 949 | − 435 | −34.5 | −23.7 | −14.2 |
| Chemical and ceramic | 3,803 | 2,625 | 2,047 | − 1,756 | − 1,178 | − 578 | −46.2 | −31.0 | −22.0 |
| Mechanical and industrial | 3,699 | 2,681 | 2,324 | − 1,375 | − 1,018 | − 357 | −37.2 | −27.5 | −13.3 |
| Civil, agricultural, and architectural | 3,291 | 2,545 | 2,297 | − 994 | − 746 | − 248 | −30.2 | −22.7 | − 9.7 |
| Electrical | 3,277 | 2,509 | 2,218 | − 1,059 | − 768 | − 291 | −32.3 | −23.4 | −11.6 |
| 75 per cent: | | | | | | | | | |
| Mining and metallurgical | 2,839 | 1,788 | 1,512 | − 1,327 | − 1,051 | − 276 | −46.7 | −37.0 | −15.4 |
| Mechanical and industrial | 2,626 | 1,676 | 1,424 | − 1,202 | − 950 | − 252 | −45.8 | −36.2 | −15.0 |
| Chemical and ceramic | 2,588 | 1,556 | 1,213 | − 1,325 | − 982 | − 343 | −52.2 | −38.7 | −22.0 |
| Civil, agricultural, and architectural | 2,499 | 1,770 | 1,596 | − 903 | − 729 | − 174 | −36.1 | −29.2 | − 9.8 |
| Electrical | 2,339 | 1,634 | 1,343 | − 996 | − 705 | − 291 | −42.6 | −30.1 | −17.8 |
| 90 per cent: | | | | | | | | | |
| Mining and metallurgical | 1,985 | 773 | 893 | − 1,092 | − 1,212 | + 120 | −55.0 | −61.1 | +15.5 |
| Mechanical and industrial | 1,956 | 919 | 853 | − 1,103 | − 1,037 | − 66 | −56.4 | −53.0 | − 7.2 |
| Civil, agricultural, and architectural | 1,926 | 909 | 1,016 | − 910 | − 1,017 | + 107 | −47.2 | −52.8 | +11.8 |
| Chemical and ceramic | 1,686 | 732 | 610 | − 1,076 | − 954 | − 122 | −63.8 | −56.6 | −16.7 |
| Electrical | 1,662 | 873 | 731 | − 931 | − 789 | − 142 | −56.0 | −47.5 | −16.3 |

* Arranged in ascending order of earned annual income for 1929.

earned annual incomes of professional engineers. The sharpest absolute declines occurred in the higher income levels. Thus, in 1929, while the highest one-tenth of the engineers had earned more than $7,466, in 1934 the earnings of this highest-paid tenth ranged down to $5,138. The middle income declined from $3,412 in 1929 to $2,286 in 1934. However, the percentages of decrease for the highest 10 and 25 per cent of reporting engineers were approximately the same, namely, 31.2 and 31.6 per cent, respectively. The middle or average values of all incomes declined by 33.0 per cent. At the lower income levels, the absolute declines were almost as great as was the decline of the median earnings; but the percentage decreases were greater. This decrease at the lower levels reflects not only salary cuts, but also the low earnings of those with long periods of unemployment. In 1929, while the yearly earnings reported by the lowest 25 and 10 per cent of the engineers were less than $2,509 and $1,878, respectively, by 1934 the former had decreased to $1,473, the latter to $872. The relative percentage decreases were greatest for these 2 lower income levels, namely, 41.3 and 53.6.[6]




Income from engineering and non-engineering services including full and part-time employment, all types of education

**Figure 2. Medians of earned annual income according to age, 1929, 1932, and 1934**

Almost two-thirds of the decrease in earned annual incomes occurred between 1929 and 1932. This, it will be recalled, was coincident with the greatest declines in employment. There were further declines in the period 1932 to 1934. In general, the order of the absolute decreases and the percentages of change followed those which took place in the period 1929 to 1934, the one exception being that, between 1932 and 1934, there was only a 1.9 per cent decline in the lowest income levels. The corresponding absolute decrease was $17.

When these adjusted data on annual income were compared for all engineers reporting in the 5 professional classes, marked divergences in their respective earning capacities were revealed.

These differences in earning capacity within the several professional classes were greatest at the higher income levels. Thus, in 1929, nine-tenths of all electrical engineers earned $1,662 or more, while a similar proportion of the mining and metallurgical engineers earned $1,985. The range was $323. For the middle values of income, a difference of $733 was noted between the extremes of

6. It must be noted that errors of reporting account for part of the decline, at least in the lowest brackets for which comparison is made. The questionnaire called for earnings during the calendar years 1929 and 1934. An engineer graduating from college in either year would usually have had only a half year in which he earned. In both years, there is some evidence that annual rates were occasionally reported. Such overreporting was more common for 1929 than 1934.

$4,010 for mining and metallurgical and $3,277 for electrical engineers. However, at the highest level, one-tenth of the mining and metallurgical engineers earned $9,912 or more, whereas a corresponding proportion of civil engineers earned only $6,507 or more. Clearly, it was in the higher income levels that the earning capacities of the several professional classes diverged the most, even in terms of percentages. Furthermore, this characteristic of greater variability among the professional classes at higher levels persisted in 1929, 1932, and 1934.

However, when the question is asked as to which professional class offers the greatest earnings, or which the lowest, the answer must be carefully qualified. In the first place, the averages shown in table IV relate to the total number in the professional class. For example, 1,319 mining and metallurgical engineers reported incomes for 1929, and of these one-tenth, or 132, had incomes of $10,000 or more. There were 13,424 civil, agricultural, and architectural engineers, of whom one-tenth, or 1,342, had incomes in excess of $6,507. Therefore, it may be concluded that of every 1,000 engineers in either professional class, a larger proportion will earn $10,000 in mining and metallurgical engineering than in civil engineering. But the total number of opportunities to earn $10,000 were greater in civil engineering, much the larger of the 2 professional classes. Among the civil engineers reporting to the Bureau for 1929, there were 469 who indicated incomes of $10,000 or more in 1929.

Again, the ranking of the profession on the basis of earnings opportunity relative to the number of engineers in the professional class was not the same at all levels and in all 3 periods. As regards the relative level of income for the highest 10 per cent, and also the highest 25 per cent, in each professional class, there was a constant relationship. Thus, in 1929, 10 per cent of the mining and metallurgical engineers earned more than $9,912. Chemical and ceramic engineers ranked second with 10 per cent earning more than $9,103, and were followed in order by mechanical and industrial engineers ($8,508), electrical engineers ($7,185), and civil engineers ($6,507). Relative to the mining and metallurgical engineers, the divergence was 8, 14, 27, and 33 per cent. A similar divergence was noted between the lower limit of $6,301 reported by the upper fourth of the mining and metallurgical engineers and those of the other professional classes. In 1929, these ranged from 4 per cent in the case of chemical and ceramic

**Table V. Comparison of 5 Levels of Annual Earnings on Age Basis for All Engineers Reporting in 1929, 1932, and 1934**

Without regard to employment status reported or type of education

| Age (Years) | Year of Graduation | Years After Graduation | Proportion With Annual Earnings of More Than Specified Amount (Per Cent) | | | | |
|---|---|---|---|---|---|---|---|
| | | | 10 | 25 | 50 | 75 | 90 |
| | | | 1929 | | | | |
| 64 and over | Prior to 1889 | 41 and over | $ 9,999 | $6,942 | $4,427 | $3,005 | $1,904 |
| 56—63 | 1889–96 | 33–40 | 12,749 | 7,493 | 4,968 | 3,378 | 2,328 |
| 48–55 | 1897–1904 | 25–32 | 11,701 | 7,129 | 4,918 | 3,471 | 2,621 |
| 40–47 | 1905–12 | 17–24 | 9,913 | 6,473 | 4,588 | 3,403 | 2,683 |
| 36–39 | 1913–16 | 13–16 | 7,936 | 5,802 | 4,121 | 3,210 | 2,563 |
| 32–35 | 1917–20 | 9–12 | 6,520 | 4,850 | 3,674 | 3,004 | 2,448 |
| 28–31 | 1921–24 | 5–8 | 4,797 | 3,786 | 3,145 | 2,567 | 2,130 |
| 26–27 | 1925–26 | 3–4 | 3,621 | 3,099 | 2,550 | 2,149 | 1,827 |
| 24–25 | 1927–28 | 1–2 | 3,049 | 2,497 | 2,098 | 1,822 | 1,462 |
| 23 | 1929 | 0 | 2,330 | 1,922 | 1,313 | 882 | 478 |
| | | | 1932 | | | | |
| 67 and over | Prior to 1889 | 44 and over | 8,940 | 5,931 | 3,650 | 2,104 | 953 |
| 59–66 | 1889–96 | 36–43 | 9,318 | 6,167 | 3,959 | 2,462 | 964 |
| 51–58 | 1897–1904 | 28–35 | 8,350 | 5,753 | 3,832 | 2,525 | 1,219 |
| 43–50 | 1905–12 | 20–27 | 7,570 | 5,192 | 3,619 | 2,520 | 1,410 |
| 39–42 | 1913–16 | 16–19 | 6,395 | 4,592 | 3,385 | 2,475 | 1,478 |
| 35–38 | 1917–20 | 12–15 | 5,519 | 4,115 | 3,135 | 2,307 | 1,355 |
| 31–34 | 1921–24 | 8–11 | 4,287 | 3,386 | 2,677 | 2,025 | 1,229 |
| 29–30 | 1925–26 | 6–7 | 3,428 | 2,862 | 2,314 | 1,810 | 1,110 |
| 27–28 | 1927–28 | 4–5 | 2,970 | 2,452 | 2,020 | 1,504 | 876 |
| 26 | 1929 | 3 | 2,451 | 2,075 | 1,772 | 1,271 | 735 |
| 25 | 1930 | 2 | 2,139 | 1,898 | 1,540 | 1,007 | 577 |
| 24 | 1931 | 1 | 1,960 | 1,605 | 1,224 | 733 | 293 |
| 23 | 1932 | 0 | 1,673 | 1,097 | 645 | 322 | 129 |
| | | | 1934 | | | | |
| 69 and over | Prior to 1889 | 46 and over | 7,360 | 5,182 | 3,188 | 1,470 | 787 |
| 61–68 | 1889–96 | 38–45 | 8,280 | 5,391 | 3,497 | 1,800 | 770 |
| 53–60 | 1897–1904 | 30–37 | 7,720 | 5,264 | 3,502 | 2,165 | 1,157 |
| 45–52 | 1905–12 | 22–29 | 7,226 | 4,907 | 3,380 | 2,364 | 1,441 |
| 41–44 | 1913–16 | 18–21 | 6,204 | 4,441 | 3,211 | 2,256 | 1,491 |
| 37–40 | 1917–20 | 14–17 | 5,336 | 3,953 | 2,977 | 2,173 | 1,463 |
| 33–36 | 1921–24 | 10–13 | 4,259 | 3,334 | 2,569 | 1,958 | 1,358 |
| 31–32 | 1925–26 | 8–9 | 3,496 | 2,840 | 2,294 | 1,817 | 1,276 |
| 29–30 | 1927–28 | 6–7 | 3,004 | 2,467 | 2,023 | 1,568 | 1,061 |
| 28 | 1929 | 5 | 2,567 | 2,162 | 1,858 | 1,431 | 998 |
| 27 | 1930 | 4 | 2,318 | 1,987 | 1,666 | 1,256 | 865 |
| 26 | 1931 | 3 | 2,100 | 1,816 | 1,441 | 1,067 | 631 |
| 25 | 1932 | 2 | 1,952 | 1,581 | 1,275 | 945 | 495 |
| 24 | 1933 | 1 | 1,801 | 1,454 | 1,139 | 813 | 333 |
| 23 | 1934 | 0 | 1,810 | 927 | 598 | 299 | 120 |

## Table VI. Comparison of 5 Levels of Annual Earnings for 5 Age Groups of Older* Engineers Reporting in 1929, 1932, and 1934

Without regard to employment status reported or type of education

| Per Cent at Specified Income Level | Engineers, With Annual Earnings of More Than Specified Amount, Whose Age Was— | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 60 in 1929 | 63 in 1923 | 65 in 1934 | 38 in 1929 | 41 in 1932 | 43 in 1934 | 30 in 1929 | 33 in 1932 | 35 in 1934 | 25 in 1929 | 28 in 1932 | 30 in 1934 | 23½ in 1929 | 26½ in 1932 | 28½ in 1934 |
| 10 | $12,749 | $9,318 | $8,280 | $7,936 | $6,395 | $6,204 | $4,797 | $4,287 | $4,259 | $3,049 | $2,970 | $3,004 | $2,330 | $2,451 | $2,567 |
| 20 | 7,493 | 6,167 | 5,391 | 5,802 | 4,592 | 4,441 | 3,786 | 3,386 | 3,334 | 2,497 | 2,452 | 2,467 | 1,922 | 2,075 | 2,162 |
| 50 | 4,968 | 3,959 | 3,497 | 4,121 | 3,385 | 3,211 | 3,145 | 2,677 | 2,569 | 2,098 | 2,020 | 2,023 | 1,313 | 1,772 | 1,858 |
| 75 | 3,378 | 2,462 | 1,800 | 3,210 | 2,475 | 2,256 | 2,567 | 2,025 | 1,958 | 1,822 | 1,504 | 1,568 | 882 | 1,271 | 1,431 |
| 90 | 2,328 | 964 | 770 | 2,563 | 1,478 | 1,491 | 2,130 | 1,229 | 1,358 | 1,462 | 876 | 1,061 | 478 | 735 | 998 |
| | Per Cent of Increase or Decrease | | | | | | | | | | | | | | |
| | 1929–34 | 1929–32 | 1932–34 | 1929–34 | 1929–32 | 1932–34 | 1929–34 | 1929–32 | 1932–34 | 1929–34 | 1929–32 | 1932–34 | 1929–34 | 1929–32 | 1932–34 |
| 10 | −35 | −27 | −11 | −22 | −19 | −3 | −11 | −11 | − 1 | − 1 | − 3 | + 1 | + 10 | + 5 | + 5 |
| 25 | −28 | −18 | −13 | −23 | −21 | −3 | −12 | −11 | − 2 | − 1 | − 2 | + 1 | + 12 | + 8 | + 4 |
| 50 | −30 | −20 | −12 | −22 | −18 | −5 | −18 | −15 | − 4 | − 4 | − 4 | 0 | + 42 | +35 | + 5 |
| 75 | −47 | −27 | −27 | −30 | −23 | −9 | −24 | −21 | − 3 | −14 | −17 | + 4 | + 62 | +44 | +13 |
| 90 | −67 | −59 | −20 | −42 | −42 | +1 | −36 | −42 | +10 | −27 | −40 | +21 | +109 | +54 | +36 |

* Includes those engineers who were professionally active prior to 1930.

engineers ($6,034) to 28 per cent for the civil engineers ($4,508). This order of professional classes was also maintained in 1932 and 1934.

In 1929, the relative order of the median professional incomes was the same as that just described, as regards mining, chemical, and mechanical engineers. But whereas the upper limit of the earnings of the lowest 25 per cent of the electrical engineers exceeded that of a similar proportion of the civil engineers by 6.6 per cent, at the median level the situation was reversed—half the civil engineers earned $3,291 or more, whereas half the electrical engineers earned $3,277 or more. This change in order persisted in 1932 and 1934.

In 1932 and 1934, the median earnings of mining and mechanical engineers led all the others. Chemical engineers were below mechanical engineers in 1932. The median earnings of chemical engineers were lower than the median of every other professional class in 1934.

At the lower levels the most marked shift in rank was that of civil engineers and chemical engineers. In 1929, one-quarter of the civil engineers earned less than $2,499, exceeding only the comparable earnings of electrical engineers. But in 1932, civil engineers were in second place as regards the level of earnings of the lowest quarter of the profession, and in 1934 they were in first place. Even in 1929, the lowest 10 per cent of the civil engineers had earned almost as much as the lowest 10 per cent of the mining and mechanical engineers, and substantially exceeded the level of the lowest 10 per cent of the chemical and electrical engineers. With reference to both the lowest 25 and 10 per cent groups, chemical engineers' earnings came in last place in 1932 and 1934.

Further examination of the adjusted data in table IV, given without regard to age, demonstrates not only differences in earning capacity but also variations in the decreases in earned annual income over the period 1929 to 1934. Without exception, the greater part of all contractions in income reported occurred between 1929 and 1932, though there were further declines in the period 1932 and 1934.

## Annual Income Related to Age

The effects of age upon earned annual incomes, for all professional engineers combined are presented in table V.

This table makes it plain that the engineers' earnings advanced with age. In 1929, the income level of half of the engineers who had graduated in 1927 or 1928, or were from 24 to 25 years of age, exceeded $2,098, whereas that of half of the engineers in the age group 56–63 exceeded $4,968. Similarly, in 1932 and 1934, there was a continuous advance. But apparently age 60 represented a turning point in the average earnings of professional engineers. Furthermore, the increase in earnings with age comprised 3 distinct phases: Initial periods of exceptionally rapid rise which contain the maximum average yearly increase, followed by 2 others in which the rates of increase were progressively slower up to the respective maxima of the 5 income groups or levels. The age spans of these phases differed with the income level. Thus, for the middle and 2 lower levels of income in 1929, the maximum yearly increase of $450 was reached at the age of 25. On the other hand, the initial periods of rapid rise for the upper 25 and 10 per cent levels were not reached until the ages of 27 and 34, respectively. The subsequent periods of increase for

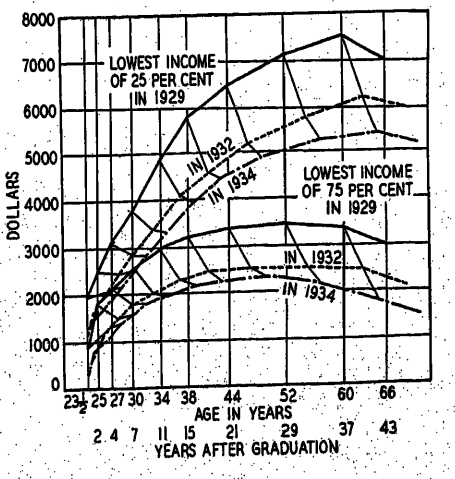



**Figure 3. Upper and lower quartiles of earned annual income according to age, 1929, 1932, and 1934**

Income from engineering and non-engineering services including full and part-time employment, all types of education

the upper 10 per cent embraced the age spans of 34 to 44, and 44 to 60, whereas those for the next highest income level extended from 27 to 38, and 38 to 60 years of age. The 3 remaining income levels increased at practically the same rate between 25 and 34 years. But while the age span for the third phase of increase was from 34 to 52 for the middle level, it only extended from 34 to 44 in the case of the 2 lower levels of income.

There was also an increased spread of earnings with advancing age. Even in the early ages there was a fairly considerable range. Thus, in 1929, among those who graduated in 1927 or 1928, the lowest quarter earned less than $1,822, whereas the earnings of the highest quarter were about 1/3 higher than this amount, or $2,497 per annum. It is also true that the highest 10 per cent of these ages earned at least twice as much as the lowest 10 per cent. But among engineers who were about 52 in 1929, the highest-paid quarter earned at least twice as much as the lowest-paid quarter, and the highest 10 per cent earned more than 4 times as much as the lowest 10 per cent. Similar relationships existed in 1932 and 1934, although the range of increases was due in large part to the influence of unemployment on the earnings in the lower levels of income.

The spread in earnings was accentuated beyond the age of 38. At that point, the income curve of the upper 10 per cent diverged upward and continued thus to the age of 60. On the other hand, the remaining curves ran consistently parallel up to their respective maxima. For example, at the ages of 25, 44, 52, and 60 the incomes of the upper 25 per cent differed from the median by 19, 41, 45, and 51 per cent, while the order of differences for the lower 25 per cent was 13, 26, 29, and 32 per cent. By contrast, the corresponding incomes of the upper 10 per cent at these ages were greater than the median by 45, 116, 138, and 157 per cent. Clearly, beyond the age of 44, the earned annual incomes reported in 1929 by the upper 10 per cent of all engineers differed very greatly from those in the other income levels, and this advantage in earning capacity was maintained in the years 1932 and 1934 also.

The earnings of engineers in the lower income brackets ceased to increase at a relatively early age. It is only approximately correct to assume that ability and income are in direct proportion. By and large, however, it is perhaps safe to assume that the engineers at any age in the lowest 10 per cent income group are less able than the average at that age; and that the highest 10 per cent are substantially more able than the average. The Bureau's data reveal that the maximum earnings of the lowest 10 and 25 per cent were reached in 1929 at about 44 years of age, and the average engineer reached his maximum earnings at about 52. The same relationship held in 1932 and 1934.

In the 2 later years the maximum for the average engineer occurred at about 60, but it is evident that earning power for engineers above the average continued to rise beyond this age. Thus, the average earnings of engineers 53 to 60 years of age in 1934 exceeded $3,502, whereas the average earnings of those 61 to 68 years were more than $3,497. But the highest 10 per cent of the first group earned over $7,720, whereas the same class of the second group earned more than $8,280.

Table V discloses differences in the age-income cycles beyond the points of maximum earnings, that is, at the end of the third phases of increase. In any case of the 2 higher income levels, the fourth and last phase in 1929 was one of decrease. This was not so for the 3 lower income levels. For them, there was a fourth phase of no change in income which covered a span of approximately 8 years: 52 to 60 for the middle group, and from 44 to 52 in the case of the 2 lower levels. The fifth phases were ones of decrease. Relatively, however, the steepest declines occurred in the 2 higher income levels.

Changes in income brought about by the depression in various years may be considered from the point of view of particular individuals whose age and experience was increasing, or from the point of view of the expectations of men with comparable periods of experience. For example, the average earnings of engineers who graduated in

**Table VII. Comparison of 5 Levels of Annual Earnings for Corresponding Years After Graduation in 1929, 1932, and 1934**

Without regard to employment status reported or type of education

| Age of Engineers (Years) | Years After Graduation | Proportion With Annual Earnings of More Than Specified Amount (Per Cent) | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 10 | | | 25 | | | 50 | | | 75 | | | 90 | | |
| | | 1929 | 1932 | 1934 | 1929 | 1932 | 1934 | 1929 | 1932 | 1934 | 1929 | 1932 | 1934 | 1929 | 1932 | 1934 |
| 23 1/2 | 1/2 | $ 2,330 | $1,673 | $1,310 | $1,922 | $1,097 | $ 927 | $1,313 | $ 645 | $ 598 | $ 882 | $ 322 | $ 299 | $ 478 | $ 129 | $ 120 |
| 25 | 2 | 3,049 | 2,150 | 1,880 | 2,497 | 1,750 | 1,500 | 2,098 | 1,399 | 1,190 | 1,822 | 840 | 860 | 1,462 | 420 | 410 |
| 28 | 5 | 3,980 | 2,970 | 2,410 | 3,300 | 2,452 | 2,080 | 2,710 | 2,020 | 1,750 | 2,275 | 1,504 | 1,340 | 1,925 | 876 | 940 |
| 33 | 10 | 6,000 | 4,287 | 3,700 | 4,560 | 3,386 | 2,990 | 3,500 | 2,677 | 2,380 | 2,890 | 2,025 | 1,850 | 2,375 | 1,229 | 1,299 |
| 43 | 20 | 9,450 | 6,680 | 6,204 | 6,350 | 4,750 | 4,441 | 4,450 | 3,420 | 3,211 | 3,380 | 2,490 | 2,256 | 2,650 | 1,460 | 1,491 |
| 53 | 30 | 11,700 | 8,000 | 7,450 | 7,190 | 5,580 | 5,050 | 4,900 | 3,780 | 3,420 | 3,480 | 2,520 | 2,240 | 2,590 | 1,285 | 1,286 |
| 60 | 37 | 12,749 | 8,900 | 7,900 | 7,493 | 5,960 | 5,250 | 4,968 | 3,900 | 3,500 | 3,378 | 2,490 | 2,010 | 2,328 | 1,050 | 980 |

| Age of Engineers (Years) | Years After Graduation | Per Cent of Increase or Decrease | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 1929–34 | 1929–32 | 1932–34 | 1929–34 | 1929–32 | 1932–34 | 1929–34 | 1929–32 | 1932–34 | 1929–34 | 1929–32 | 1932–34 | 1929–34 | 1929–32 | 1932–34 |
| 23 1/2 | 1/2 | −44 | −28 | −22 | −52 | − 43 | −15 | −54 | −51 | − 7 | −66 | −63 | − 1 | −75 | −73 | −1 |
| 25 | 2 | −38 | −29 | −13 | −40 | −30 | −14 | −43 | −33 | −13 | −53 | −54 | + 2 | −72 | −71 | −2 |
| 28 | 5 | −39 | −25 | −19 | −37 | −26 | −15 | −35 | −25 | −13 | −41 | −34 | −11 | −51 | −54 | +7 |
| 33 | 10 | −38 | −29 | −14 | −34 | −26 | −12 | −32 | −24 | −11 | −36 | −30 | − 9 | −45 | −48 | +6 |
| 43 | 20 | −34 | −29 | − 7 | −30 | −25 | − 7 | −28 | −23 | − 6 | −33 | −26 | − 9 | −44 | −45 | +2 |
| 53 | 30 | −36 | −32 | − 7 | −30 | −22 | − 9 | −30 | −23 | −10 | −35 | −27 | −11 | −50 | −50 | 0 |
| 60 | 37 | −38 | −30 | −11 | −30 | −20 | −12 | −30 | −21 | −10 | −40 | −26 | −19 | −58 | −55 | −7 |

## Table VIII. Comparison of 5 Levels of Earned Annual Income for Older,* Graduate,** and "Other"† Engineers Reporting in Each Professional Class at End of 1929, 1932, and 1934

Without regard to employment status reported

| Per Cent of Professional Class‡ at Specified Income Level | Annual Earnings of More Than Specified Amount | | | | | | Per Cent Income of "Other" Engineers Formed of That of Graduate Engineers— | | |
|---|---|---|---|---|---|---|---|---|---|
| | Graduate Engineers** | | | "Other" Engineers† | | | | | |
| | 1929 | 1932 | 1934 | 1929 | 1932 | 1934 | 1929 | 1932 | 1934 |
| 10 per cent: | | | | | | | | | |
| Mining and metallurgical | $10,015 | $7,413 | $7,530 | $8,940 | $6,370 | $6,263 | 89 | 86 | 83 |
| Chemical and ceramic | 9,173 | 7,432 | 7,414 | 8,100 | 6,435 | 6,795 | 88 | 87 | 92 |
| Mechanical and industrial | 8,715 | 6,481 | 6,269 | 8,161 | 6,273 | 5,997 | 94 | 97 | 96 |
| Electrical | 7,301 | 6,263 | 6,084 | 6,654 | 5,943 | 5,670 | 91 | 95 | 93 |
| Civil, agricultural, and architectural | 6,853 | 5,478 | 5,133 | 5,745 | 4,470 | 4,222 | 84 | 82 | 82 |
| 25 per cent: | | | | | | | | | |
| Mining and metallurgical | 6,349 | 4,973 | 4,833 | 6,025 | 4,640 | 4,587 | 95 | 93 | 95 |
| Chemical and ceramic | 6,111 | 5,116 | 4,976 | 5,210 | 4,540 | 4,335 | 85 | 89 | 87 |
| Mechanical and industrial | 5,603 | 4,414 | 4,262 | 5,536 | 4,269 | 3,972 | 99 | 97 | 93 |
| Electrical | 4,886 | 4,175 | 4,062 | 4,497 | 3,762 | 3,654 | 92 | 90 | 90 |
| Civil, agricultural, and architectural | 4,732 | 3,923 | 3,671 | 4,036 | 3,349 | 3,163 | 85 | 85 | 86 |
| 50 per cent: | | | | | | | | | |
| Mining and metallurgical | 4,053 | 3,299 | 3,227 | 3,762 | 3,082 | 3,072 | 93 | 93 | 95 |
| Chemical and ceramic | 3,839 | 3,368 | 3,308 | 3,525 | 3,050 | 2,857 | 92 | 91 | 86 |
| Mechanical and industrial | 3,663 | 3,025 | 2,848 | 3,777 | 2,929 | 2,645 | 103 | 97 | 93 |
| Civil, agricultural, and architectural | 3,375 | 2,834 | 2,636 | 3,099 | 2,530 | 2,362 | 92 | 89 | 90 |
| Electrical | 3,296 | 2,863 | 2,821 | 3,218 | 2,627 | 2,517 | 97 | 92 | 89 |
| 75 per cent: | | | | | | | | | |
| Mining and metallurgical | 2,841 | 2,013 | 2,029 | 2,829 | 2,013 | 1,947 | 99 | 100 | 96 |
| Mechanical and industrial | 2,556 | 1,981 | 1,952 | 2,902 | 1,930 | 1,837 | 114 | 97 | 94 |
| Civil, agricultural, and architectural | 2,541 | 2,009 | 1,956 | 2,429 | 1,860 | 1,747 | 96 | 93 | 89 |
| Chemical and ceramic | 2,538 | 2,178 | 2,195 | 2,540 | 1,885 | 1,834 | 100 | 87 | 84 |
| Electrical | 2,317 | 1,997 | 2,003 | 2,400 | 1,883 | 1,792 | 104 | 94 | 89 |
| 90 per cent: | | | | | | | | | |
| Mining and metallurgical | 1,977 | 1,052 | 1,279 | 2,030 | 1,210 | 1,283 | 103 | 115 | 100 |
| Civil, agricultural, and architectural | 1,935 | 1,136 | 1,361 | 1,910 | 1,028 | 1,152 | 99 | 90 | 85 |
| Mechanical and industrial | 1,888 | 1,212 | 1,245 | 2,170 | 1,040 | 1,169 | 115 | 86 | 94 |
| Chemical and ceramic | 1,657 | 1,443 | 1,458 | 1,820 | 699 | 783 | 110 | 48 | 54 |
| Electrical | 1,609 | 1,311 | 1,308 | 1,860 | 1,185 | 1,088 | 116 | 90 | 83 |

* Includes all engineers who were professionally active prior to 1930. ** Graduate engineers embrace all postgraduates, nonengineering graduates, and first degree engineering graduates. † "Other" engineers embrace all engineers with college course incomplete, noncollegiate technical school course, and secondary school education. ‡ Arranged in ascension of graduate earned annual income for 1929.

1927–28 declined only from $2,098 in 1929 to $2,020 in 1932, and increased slightly to $2,023 in 1934. On the other hand, those who graduated in 1897–1904 averaged $4,918 in 1929, $3,832 in 1932, and $3,502 in 1934. Such comparisons for each group of engineers over the period 1929–34 may be made from table V. They are, more conveniently arranged for direct comparison in table VI.

This table shows a rise in earnings for the youngest engineers in the profession in 1929, who were near to 30 years of age in 1934. The advance in earning capacity in the first 5 years of engineering experience was so great that it offset the influence of the depression in the case of the youngest engineers. At higher ages, when an added year's experience influenced income less, the incomes of particular engineers declined by as much as 30 per cent for the average graduate of the classes of 1889–96.

In order to trace the influence of the depression on professional opportunity and on the normal expectations of members of the profession, table VII compares the earnings for identical ages in each of the 3 years.[7]

For each level of experience, incomes declined from 1929 to 1934, and two-thirds to three-quarters of this decline occurred from 1929 to 1932. Over the entire period the average income of those who had been out of college for 2 years declined 43 per cent. Those who had been out 5 years had, on the average, 35 per cent less income in 1934 than the corresponding group in 1929. For older engineers the decline approximated 30 per cent, being slightly more than this for those with 10 years' experience, and slightly less for those with 20 years' experience.

The most significant differences brought about by the depression were in the spread of incomes at various ages.

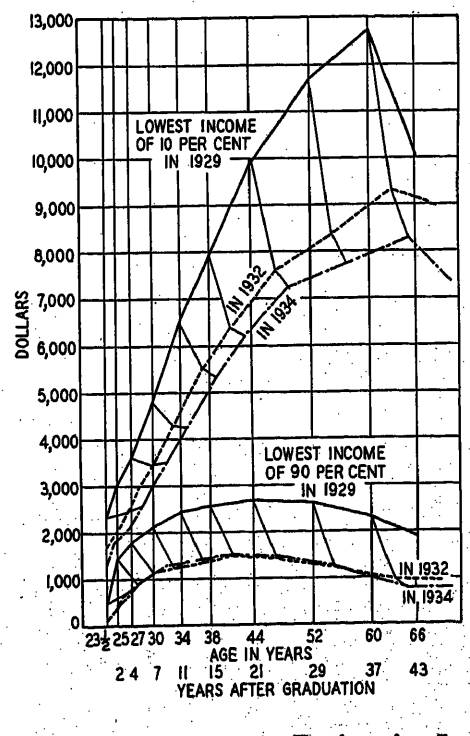



**Figure 4. Upper and lower deciles of earned annual income according to age, 1929, 1932, and 1934**

Income from engineering and nonengineering services including full and part-time employment, all types of education

7. The figures are not derived from direct tabulations which were made on the basis of the same combinations of years of birth or graduation in each of the 3 years, but the movements of earnings proved to be sufficiently regular to justify reading the values for particular ages from the chart.

In all cases, primarily because of the influence of unemployment, annual income for the lowest 25 per cent and the lowest 10 per cent declined more than the average income at a given age. Thus, 2 years after graduation, 10 per cent of the engineers earned less than $1,462 in 1929 as compared with a corresponding group earning less than $410 in 1934. This was a decline of 72 per cent as compared with a 43 per cent decline for the average of this age. Similarly, the average for engineers 30 years after graduation declined 30 per cent from 1929 to 1934, while the level below which the earnings of 10 per cent of such engineers were found fell by 50 per cent.

There was comparatively little difference for the various ages in the decline of the median income or in the decline of the level of income above which only 25 per cent of the engineers of corresponding ages were found. The highest level of income (that achieved by only 10 per cent at each age) declined more than the average in the case of all groups of engineers with 5 years' or more experience. Thus this select group among engineers 60 years of age lost 38 per cent from 1929 to 1934, whereas the average decline at that age was 30 per cent.

## Annual Income and Education

The foregoing analysis of annual incomes reported by professional engineers for 1929, 1932, and 1934 took no account of differences in educational background. In 1929, some 22,386, or 86 per cent, of the 24,837 older graduates in engineering courses in the sample reported income and 7,646, or 90 per cent, of the 8,440 older "other" engineers who were in the profession in 1929 reported. The 5 income levels for these 2 groups are shown in table VIII.

Consideration of the ratios derived from the 1929 earnings reported by the "other" and graduate engineers clearly indicates that those with a formal engineering education had higher incomes. Thus, in the highest 10 and 25 per cent income groups, the earnings of the graduates in each professional class exceeded those of the "other" engineers. It will, however, be noted that there were wide variations in the ratios in the earnings of the 2 groups, indicating that the differentials in earnings do not accrue in equal measure for all 5 professional classes. In the upper 25 per cent level, the order of yearly differences in favor of the graduates was $901, $696, $389, $324, and $67, the 3 smallest of these being in the electrical, mining and metallurgical, and mechanical and industrial classes. In the highest income level, differences of $647 and $554 per year were reported by the graduate electrical and mechanical and industrial engineers; in the 3 remaining professional classes none of the graduate groups reported differentials of less than $1,000 per year. In general, from 1929 to 1934, the earnings of the upper 25 per cent of the older graduates and of the "other" engineers declined by similar amounts.

The advantage enjoyed by engineers with college degrees is less marked at the lower levels. The average income of mechanical engineers in the profession in 1929 reporting income for 1929 was actually higher for noncollege graduates than for graduates. This was the only professional class of which this was true for the average, but, in general, the lowest 25 per cent and the lowest 10 per cent among the "other" engineers had higher incomes than among the graduates. But even at these levels, it will be seen that an advantage accrued over the period 1929 to 1934 to the college graduates. The income of the lowest 25 per cent of those graduating prior to 1929 declined less than the income of the lowest 25 per cent of the corresponding group of "other" engineers and by 1934, college graduates had the higher incomes even at this level.

The apparent advantage enjoyed in 1929 by the "other" engineers at the lower levels of income may best be explained in conjunction with the data in tables IX and X. The data for the median values[8] only of earned annual income of all engineers classified by age in the 3 years, 1929, 1932, and 1934 are presented in table IX.[9]

The first observation to be made has regard to the fact that the "other" engineers, at a very early age, lose the advantage in earning capacity, arising from practical experience gained, while the college graduate is in school. This loss of advantage is best exemplified by considering the ranking order of the 12 groups of engineers at corresponding years after graduation (table X).

At the end of 2 years after graduation[10] in 1929, the "other" engineers held ranks 1, 2, 4, 5, and 6, the first-degree civil graduates were third, and the remaining graduate groups occupied positions 7 to 12, inclusive. Five years after graduation, however, there was a complete reversal of this situation, which placed all graduates ahead of the "other" engineers.

Relatively, the greatest shifts in position occurred between the second and fifth years after graduation. Secondary-school engineers dropped from sixth to twelfth place. The noncollegiate civil engineers declined from second to eleventh place, while the civil engineers whose college course was incomplete declined from fifth to tenth place. Positions 8 and 9, respectively, were occupied by the mechanical engineers whose college course was incomplete and those who were graduates of noncollegiate technical schools; 2 years after graduation they had held first and fourth places. Among the engineering graduates, the greatest shift in position occurred among the first-degree chemical and ceramic engineers, who moved from tenth to first place at 5 years after graduation, and maintained that position throughout the 1929 age cycle. It will also be noted that the 1929 earnings reported by the first-degree civil engineers were greater at 5 years after graduation than those of both postgraduates and first-degree electrical engineers. On the other hand, the earnings of these 3 groups were less than those reported by first-degree mining and metallurgical, and mechanical and industrial engineers, and nonengineering graduates.

Thus, it follows that the greater decline from 1929 to 1934 in the incomes of the lower 10 and 25 per cent of the "other" engineers reflects in part the greater advantage of

8. I.e., the middle value of earned annual income—50 per cent earning more and 50 per cent earning less than the figure shown.
9. Insufficient data were furnished for the 2 lower and higher income levels to enable a complete comparison for all age groups and all types of education.
10. The incomes reported just after graduation are not compared. These are invalidated by the fact that, while the graduates could have reported incomes for 6 months only, it was possible for the "other" engineers to have reported an income for a full year or more.

## Table IX. Median Annual Earnings in 1929, 1932, and 1934, for All Engineers Reporting by Age and Type of Education

Without regard to employment status reported

| Age (Years) | Year of Graduation | Years After Graduation | Postgraduates | Nonengineering Graduates | First-Degree Engineering Graduates | | | | | Others With— College Course Incomplete | | Others With— Noncollegiate Technical Course | | Secondary School Education |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | Chemical and Ceramic | Civil, Agricultural, and Architectural | Electrical | Mechanical and Industrial | Mining and Metallurgical | Civil, Agricultural, and Architectural | Mechanical and Others | Civil, agricultural, and architectural | Mechanical and Others | |
| | | | 1929 Income (Dollars) | | | | | | | | | | | |
| 64 and over | * | 41+ | ** | 6,000 | ** | 4,460 | ** | 5,100 | 4,800 | 3,400 | 5,700 | ** | ** | 3,800 |
| 56–63 | 1889–96 | 33–40 | 6,030 | 5,500 | 6,450 | 4,981 | 5,580 | 6,255 | 6,180 | 3,733 | 4,933 | 3,657 | 4,440 | 4,120 |
| 48–55 | 1897–1904 | 25–32 | 5,320 | 5,663 | 6,600 | 4,804 | 5,460 | 5,793 | 5,200 | 3,774 | 5,179 | 3,514 | 4,714 | 4,333 |
| 40–47 | 1905–12 | 17–24 | 5,000 | 5,000 | 6,429 | 4,411 | 5,239 | 5,434 | 5,400 | 3,565 | 4,579 | 3,500 | 4,246 | 3,708 |
| 36–39 | 1913–16 | 13–16 | 4,286 | 4,933 | 6,021 | 3,964 | 4,480 | 4,878 | 4,825 | 3,328 | 4,031 | 3,168 | 3,889 | 3,625 |
| 32–35 | 1917–20 | 9–12 | 4,608 | 4,086 | 4,523 | 3,616 | 4,048 | 4,057 | 4,600 | 3,036 | 3,793 | 3,121 | 3,448 | 3,267 |
| 28–31 | 1921–24 | 5–8 | 3,164 | 3,072 | 3,544 | 3,122 | 3,190 | 3,354 | 3,306 | 2,614 | 3,200 | 2,574 | 2,925 | 2,814 |
| 26–27 | 1925–26 | 3–4 | 2,565 | 2,675 | 2,729 | 2,579 | 2,505 | 2,616 | 2,840 | 2,410 | 2,468 | 2,400 | 2,482 | 2,250 |
| 24–25 | 1927–28 | 1–2 | 2,008 | 1,978 | 2,007 | 2,150 | 1,977 | 2,099 | 2,086 | 2,127 | 2,232 | 2,200 | 2,144 | 2,100 |
| 23 | 1929 | 0 | 1,040 | 1,500 | 1,200 | 1,256 | 996 | 1,146 | 1,175 | 2,062 | 2,129 | 1,780 | 1,950 | 1,900 |
| | | | 1932 Income (Dollars) | | | | | | | | | | | |
| 67 and over | * | 44+ | ** | 3,000 | ** | 3,600 | ** | 5,200 | 1,100 | 2,600 | 4,600 | ** | ** | 3,467 |
| 59–66 | 1889–96 | 36–43 | 5,160 | 4,600 | ** | 4,090 | 4,733 | 4,700 | 5,000 | 2,950 | 3,600 | 2,933 | 3,400 | 3,433 |
| 51–58 | 1897–1904 | 28–35 | 4,757 | 5,000 | 5,200 | 3,761 | 4,677 | 4,189 | 3,940 | 2,969 | 3,688 | 2,846 | 3,550 | 3,650 |
| 43–50 | 1905–12 | 20–27 | 4,155 | 4,475 | 5,320 | 3,533 | 4,214 | 4,070 | 4,222 | 3,038 | 3,631 | 2,777 | 3,241 | 3,178 |
| 39–42 | 1913–16 | 16–19 | 3,745 | 4,222 | 4,657 | 3,318 | 3,877 | 3,800 | 3,700 | 2,702 | 3,162 | 2,709 | 2,968 | 3,173 |
| 35–38 | 1917–20 | 12–15 | 3,377 | 3,600 | 3,773 | 3,048 | 3,509 | 3,470 | 3,444 | 2,518 | 3,029 | 2,475 | 2,682 | 2,720 |
| 31–34 | 1921–24 | 8–11 | 2,882 | 2,945 | 3,167 | 2,628 | 2,807 | 2,861 | 2,744 | 2,406 | 2,563 | 2,173 | 2,310 | 2,488 |
| 29–30 | 1925–26 | 6–7 | 2,472 | 2,655 | 2,580 | 2,343 | 2,309 | 2,403 | 2,200 | 2,090 | 2,105 | 1,971 | 2,000 | 2,057 |
| 27–28 | 1927–28 | 4–5 | 2,029 | 2,167 | 2,064 | 2,124 | 1,992 | 1,985 | 1,940 | 1,932 | 1,906 | 1,836 | 1,686 | 1,840 |
| 26 | 1929 | 3 | 1,794 | 1,800 | 1,773 | 1,896 | 1,660 | 1,716 | 1,560 | 1,657 | 1,638 | 1,900 | 1,600 | 1,350 |
| 25 | 1930 | 2 | 1,378 | 1,575 | 1,628 | 1,709 | 1,451 | 1,495 | 1,492 | 1,709 | 1,373 | 1,700 | 1,450 | 1,633 |
| 24 | 1931 | 1 | 948 | 1,367 | 1,208 | 1,349 | 1,032 | 1,247 | 1,147 | 1,620 | 1,390 | ** | 1,600 | 1,700 |
| 23 | 1932 | 0 | 687 | 1,800 | 606 | 629 | 586 | 645 | 480 | 1,433 | 1,183 | ** | 1,400 | ** |
| | | | 1934 Income (Dollars) | | | | | | | | | | | |
| 69 and over | * | 46+ | ** | 3,100 | ** | 3,200 | ** | 3,933 | 1,200 | 2,000 | 3,400 | ** | 2,000 | 3,100 |
| 61–68 | 1889–96 | 38–45 | 4,333 | 4,400 | ** | 3,567 | 4,143 | 4,100 | 4,333 | 2,800 | 2,900 | 2,600 | 2,460 | 3,133 |
| 53–60 | 1897–1904 | 30–37 | 4,488 | 4,400 | 5,100 | 3,337 | 4,400 | 3,731 | 3,900 | 2,787 | 3,493 | 2,429 | 3,364 | 3,508 |
| 45–52 | 1905–12 | 22–29 | 3,923 | 4,088 | 5,000 | 3,311 | 4,089 | 3,875 | 4,086 | 2,780 | 3,497 | 2,533 | 2,974 | 2,940 |
| 41–44 | 1913–16 | 18–21 | 3,517 | 4,467 | 4,111 | 3,129 | 3,917 | 3,538 | 3,588 | 2,496 | 2,990 | 2,420 | 2,713 | 3,031 |
| 37–40 | 1917–20 | 14–19 | 3,250 | 3,575 | 3,850 | 2,826 | 3,393 | 3,278 | 3,567 | 2,354 | 2,890 | 2,286 | 2,543 | 2,711 |
| 33–36 | 1921–24 | 10–13 | 2,864 | 2,857 | 3,244 | 2,516 | 2,801 | 2,704 | 2,811 | 2,147 | 2,432 | 2,036 | 2,161 | 2,356 |
| 31–32 | 1925–26 | 8–9 | 2,513 | 2,475 | 2,586 | 2,263 | 2,364 | 2,378 | 2,463 | 1,974 | 2,093 | 1,863 | 1,957 | 1,900 |
| 29–30 | 1927–28 | 6–7 | 2,072 | 2,200 | 2,225 | 2,069 | 2,021 | 2,058 | 2,100 | 1,875 | 1,911 | 1,567 | 1,738 | 1,860 |
| 28 | 1929 | 5 | 1,888 | 1,871 | 1,982 | 1,892 | 1,759 | 1,908 | 1,809 | 1,678 | 1,808 | 1,867 | 1,525 | 1,575 |
| 27 | 1930 | 4 | 1,563 | 1,800 | 1,795 | 1,762 | 1,527 | 1,719 | 1,542 | 1,518 | 1,500 | 1,800 | 1,433 | 1,660 |
| 26 | 1931 | 3 | 1,437 | 1,457 | 1,426 | 1,545 | 1,263 | 1,433 | 1,479 | 1,567 | 1,633 | 1,400 | 1,467 | 1,800 |
| 25 | 1932 | 2 | 1,255 | 1,233 | 1,286 | 1,384 | 1,138 | 1,261 | 1,241 | 1,388 | 1,400 | ** | 1,367 | ** |
| 24 | 1933 | 1 | 840 | 1,314 | 1,162 | 1,249 | 1,047 | 1,126 | 1,159 | 1,283 | 1,267 | ** | 1,600 | ** |
| 23 | 1934 | 0 | 612 | 1,000 | 567 | 638 | 540 | 560 | 564 | 1,200 | 1,089 | ** | 1,263 | 1,325 |

* Prior to 1889. ** Less than 10 persons reported.

5 years additional experience among the younger college graduates.

Between 5 and 10 years after graduation, there were but slight changes in relative position. At the latter period, however, all first-degree and nonengineering graduates were ahead of the postgraduate engineers. The secondary-school engineers reported earnings greater than either of the 2 groups of "other" civil engineers. The "other" mechanical engineers trained in noncollegiate technical schools followed ninth in order, after the postgraduates.

At 20 years after graduation, the first-degree civil engineers ranked below both the "other" mechanical engineers whose college course was incomplete and the postgraduate engineers; between 20 and 37 years after graduation, the relative standing of the several groups remained comparatively stable. It will also be noted that even in 1934 the order of the groups shows no marked departure from the situation which prevailed in 1929.

A further explanation may be given of the apparent advantage of "other" engineers in the lower income levels, as shown in table VIII. There are too few cases to warrant showing text tables of income for the lowest 10 and 25 per cent of the engineers classified simultaneously by professional classifications, age, and type of education.

## Table X. Rank of Engineers of Specified Education According to Median Annual Earnings in 1929 and 1934, for Corresponding Years After Graduation

Without regard to employment status reported

| Type of Education | Years After Graduation | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 2 | 5 | 10 | 20 | 30 | 37 | 2 | 5 | 10 | 20 | 30 | 37 |
| | Rank in 1929 | | | | | | Annual Earnings in 1929 | | | | | |
| College course incomplete: Mechanical and others* | 1 | 8 | 6 | 7 | 7 | 8 | $2,232 | $2,650 | $3,580 | $4,425 | $5,100 | $4,933 |
| Noncollegiate technical course: Civil, agricultural, and architectural | 2 | 11 | 11 | 12 | 12 | 12 | 2,200 | 2,450 | 2,950 | 3,425 | 3,550 | 3,657 |
| First-degree engineering graduates: Civil, agricultural, and architectural | 3 | 5 | 7 | 8 | 8 | 7 | 2,150 | 2,750 | 3,490 | 4,300 | 4,800 | 4,981 |
| Noncollegiate technical course: Mechanical and others* | 4 | 9 | 9 | 9 | 9 | 9 | 2,144 | 2,600 | 3,300 | 4,190 | 4,650 | 4,440 |
| College course incomplete: Civil, agricultural, and architectural | 5 | 10 | 12 | 11 | 11 | 11 | 2,127 | 2,475 | 2,900 | 3,500 | 3,750 | 3,733 |
| Secondary school education | 6 | 12 | 10 | 10 | 10 | 10 | 2,100 | 2,430 | 3,150 | 3,700 | 4,275 | 4,120 |
| First-degree engineering graduates: | | | | | | | | | | | | |
| Mechanical and industrial | 7 | 3 | 3 | 2 | 2 | 2 | 2,099 | 2,825 | 3,875 | 5,350 | 5,800 | 6,255 |
| Mining and metallurgical | 8 | 2 | 2 | 3 | 6 | 3 | 2,086 | 2,975 | 4,200 | 5,300 | 5,350 | 6,180 |
| Postgraduates | 9 | 6 | 8 | 6 | 5 | 4 | 2,008 | 2,750 | 3,475 | 4,850 | 5,375 | 6,030 |
| First-degree engineering graduates: Chemical and ceramic | 10 | 1 | 1 | 1 | 1 | 1 | 2,007 | 3,000 | 4,250 | 6,350 | 6,600 | 6,450 |
| Nonengineering graduates | 11 | 4 | 5 | 5 | 3 | 6 | 1,978 | 2,800 | 3,800 | 4,990 | 5,600 | 5,500 |
| First-degree engineering graduates: Electrical | 12 | 7 | 4 | 4 | 4 | 5 | 1,977 | 2,725 | 3,800 | 5,075 | 5,450 | 5,580 |
| | Rank in 1934 | | | | | | Annual Earnings in 1934 | | | | | |
| Secondary school education | 1 | 9 | 9 | 8 | 9 | 8 | $1,550 | $1,625 | $2,025 | $3,031 | $3,200 | $3,350 |
| Noncollegiate technical course: Mechanical and others* | 2 | 12 | 10 | 10 | 10 | 10 | 1,475 | 1,475 | 2,010 | 2,713 | 3,150 | 2,980 |
| College course incomplete: Mechanical and others* | 3 | 10 | 8 | 9 | 7 | 9 | 1,350 | 1,600 | 2,200 | 2,990 | 3,490 | 3,200 |
| Noncollegiate technical course: Civil, agricultural, and architectural | 4 | 2 | 12 | 12 | 12 | 12 | ** | 1,330 | 1,900 | 2,420 | 2,490 | 2,490 |
| First-degree engineering graduates: Civil, agricultural, and architectural | 5 | 5 | 7 | 7 | 8 | 7 | 1,325 | 1,800 | 2,350 | 3,129 | 3,300 | 3,400 |
| College course incomplete: Civil, agricultural, and architectural | 6 | 11 | 11 | 11 | 11 | 11 | 1,300 | 1,600 | 2,000 | 2,496 | 2,780 | 2,790 |
| Nonengineering graduates | 7 | 3 | 3 | 1 | 2 | 3 | 1,275 | 1,825 | 2,600 | 4,467 | 4,250 | 4,400 |
| First-degree engineering graduates: | | | | | | | | | | | | |
| Chemical and ceramic | 8 | 1 | 1 | 2 | 1 | 1 | 1,250 | 1,875 | 2,750 | 4,111 | 5,050 | ** |
| Mining and metallurgical | 9 | 7 | 4 | 4 | 5 | 5 | 1,200 | 1,700 | 2,550 | 3,588 | 3,980 | 4,050 |
| Mechanical and industrial | 10 | 4 | 6 | 5 | 6 | 6 | 1,180 | 1,825 | 2,490 | 3,538 | 3,780 | 3,880 |
| Electrical | 11 | 8 | 5 | 3 | 3 | 4 | 1,080 | 1,650 | 2,500 | 3,917 | 4,250 | 4,325 |
| Postgraduates | 12 | 6 | 2 | 6 | 4 | 2 | 940 | 1,750 | 2,610 | 3,517 | 4,175 | 4,425 |

* Includes chemical, ceramic, electrical, industrial, mining, and metallurgical engineers.
** Less than 10 engineers reported.

But such values have been computed for every such classification embracing more than 100 reports and the results may be summarized. In 1929, at every age the lowest 10 per cent of the civil engineers with incomplete college courses had lower incomes than the lowest 10 per cent of those with completed college courses. This continued to be true in 1934 for engineers who graduated prior to 1928, the last year with an adequate number of reports to warrant this particular comparison. For the 5 age groups from 28 to 47, for which comparisons can be made, the lowest 10 per cent of civil engineers with noncollegiate technical school courses had lower incomes than those with incomplete college courses. These statements hold, not only for the lowest 10 per cent of the civil engineers but also for the lowest 25 per cent. There are not enough cases of engineers in the professional classes, other than civil engineers, to warrant a detailed analysis of nongraduates on an age basis for the separate classes. But the income of the lowest 10 and 25 per cent of the nongraduates of the 4 classes combined is less than the corresponding level of income for graduates in any of the professional classes at almost all ages for which comparisons can be made. It seems highly probable, in the light of these facts, that part of the advantage shown by "other" engineers in table VIII is due to a higher age among the nongraduates in the groups compared.

Table X also shows that, although the earnings reported in 1929 by the "other" engineers at 2 years after graduation were higher than those of the graduates, the differentials were not great. For the former, the 1929 median earnings ranged from $2,100 in the case of secondary-school engineers to $2,232 for mechanical engineers who had not completed their college course, while the range for the latter was from $1,977 for electrical to $2,099 for mechanical and industrial engineers. At 5 years after graduation, when the positions were reversed, the differentials were still slight. The earnings of the graduates ranged from $2,725 to $3,000 per year and those of the "other" engineers from $2,430 to $2,650. With advancing age, however, the spreads in earnings in favor of the graduates became very marked. In the case of mechanical engineers, for instance, the difference in earnings between the first-degree engineers and those who did not complete their college course was $175, $295, $925, $700, and $1,322 per year, and between first-degree and noncollegiate mechanical engineers it was $225, $575, $1,160 $1,150, and $1,815 per annum. Similarly, for the civil engineers, the difference in earnings between those with first-degrees and whose college course was incomplete was $275, $590, $800, $1,050, and $1,248 per year, while between first-degree civil and noncollegiate technical school engineers, the order was $300, $540, $875, $1,250, and $1,324 per annum.

Even among the graduate groups there was variation in earning capacity. Thus, while the earnings of first-degree civil engineers ranged from $2,750 to $4,800 per year between 5 and 30 years after graduation, the range for the first-degree chemical and ceramic engineers was from

$3,000 to $6,600 per year. In other words, over a period of 25 years, the civil engineers' earnings increased by only $2,050, whereas those of engineers in the chemical and ceramic field increased by $3,600. The ranges in earnings of the remaining graduate groups fell between those reported by the civil and the chemical and ceramic engineers.

Earnings of the "other" engineers cease to increase several years before those of the graduates. Their earnings began to decline after 55 years of age in 1929, whereas the earnings of the graduates continued to increase even at 64 years of age and over (table IX).

When consideration is given to the changes in income status between 1929 and 1934 of selected age groups of engineers in each type of education, it appears, again, that the depression bore hardest upon the older engineers.

As indicated in table XI, over the period 1929–34 the decreases in earnings of engineers who were 60 years of age in 1929 and 65 in 1934 ranged from 20 to 45 per cent. The smallest range, however, occurred among the graduate engineers. This is explained by the fact that for the "other" engineers, the earnings reported at the age of 60 in 1929 were those for the period of decline, since they were less than those reported for engineers who were 52 in 1929. When, however, comparison is made of the earnings for the 2 age groups of engineers who were 52 and 44, respectively, in 1929 and 5 years older in 1934, it will be noted that the decreases in their earnings over the period 1929–34 show little variation. The important thing to note is that the effect of the depression was approximately the same on both graduates and "other" engineers. On the other hand, for the 2 younger groups shown in table XI, the graduate engineers who were 25 in 1929, practically all showed increases in their earnings by 1934, whereas the "other" engineers showed further decreases. This situation was even more pronounced in favor of the graduate engineers who were 23½ years of age in 1929.

Throughout the whole of this analysis of differences in earnings by type of education, there have only been incidental references to the changes which occurred over the period 1929–34 and in the intervening periods, 1929–32 and 1932–34. It will be recalled, however, that the percentage decreases in the incomes for all engineers at corresponding years after graduation were practically the same. This was also the case for the 12 groups of engineers when segregated by type of education, as is evidenced by a consideration of the data shown in table XII.

**Table XI. Comparison of Median Annual Earnings in 1929, 1932, and 1934 of Selected Age Groups of Engineers Reporting by Type of Education**

Without regard to employment status reported

| Type of Education | Engineers Whose Age Was— 60 in 1929 | 63 in 1932 | 65 in 1934 | 52 in 1929 | 55 in 1932 | 57 in 1934 | 44 in 1929 | 47 in 1932 | 49 in 1934 | 25 in 1929 | 28 in 1932 | 30 in 1934 | 23½ in 1929 | 26½ in 1932 | 28½ in 1934 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Median Annual Earnings | | | | | | | | | | | | | | |
| Postgraduates | $6,030 | $5,160 | $4,333 | $5,320 | $4,757 | $4,488 | $5,000 | $4,155 | $3,923 | $2,008 | $2,029 | $2,072 | $1,040 | $1,794 | $1,888 |
| Nonengineering graduates | 5,500 | 4,600 | 4,400 | 5,663 | 5,000 | 4,400 | 5,000 | 4,475 | 4,088 | 1,978 | 2,167 | 2,200 | 1,500 | 1,800 | 1,871 |
| First-degree engineering graduates: | | | | | | | | | | | | | | | |
| Chemical and ceramic | 6,450 | ** | ** | 6,600 | 5,200 | 5,100 | 6,429 | 5,320 | 5,000 | 2,007 | 2,064 | 2,225 | 1,200 | 1,773 | 1,982 |
| Civil, agricultural and architectural | 4,981 | 4,090 | 3,567 | 4,804 | 3,761 | 3,337 | 4,411 | 3,533 | 3,311 | 2,150 | 2,124 | 2,069 | 1,256 | 1,896 | 1,892 |
| Electrical | 5,580 | 4,733 | 4,143 | 5,460 | 4,677 | 4,400 | 5,239 | 4,214 | 4,089 | 1,977 | 1,992 | 2,021 | 996 | 1,660 | 1,759 |
| Mechanical and industrial | 6,255 | 4,700 | 4,100 | 5,793 | 4,189 | 3,731 | 5,434 | 4,070 | 3,875 | 2,099 | 1,985 | 2,058 | 1,146 | 1,716 | 1,908 |
| Mining and metallurgical | 6,180 | 5,000 | 4,333 | 5,200 | 3,940 | 3,900 | 5,400 | 4,222 | 4,086 | 2,086 | 1,940 | 2,100 | 1,175 | 1,560 | 1,809 |
| College course incomplete: | | | | | | | | | | | | | | | |
| Civil, agricultural, and architectural | 3,733 | 2,950 | 2,800 | 3,774 | 2,969 | 2,787 | 3,565 | 3,038 | 2,780 | 2,127 | 1,932 | 1,875 | 2,062 | 1,657 | 1,678 |
| Mechanical and others* | 4,933 | 3,600 | 2,900 | 5,179 | 3,688 | 3,493 | 4,579 | 3,631 | 3,497 | 2,232 | 1,906 | 1,911 | 2,129 | 1,638 | 1,808 |
| Noncollegiate technical course: | | | | | | | | | | | | | | | |
| Civil, agricultural, and architectural | 3,657 | 2,933 | 2,600 | 3,514 | 2,846 | 2,429 | 3,500 | 2,777 | 2,533 | 2,200 | 1,836 | 1,567 | 1,780 | 1,900 | 1,867 |
| Mechanical and others* | 4,440 | 3,400 | 2,460 | 4,714 | 3,550 | 3,364 | 4,246 | 3,241 | 2,974 | 2,144 | 1,686 | 1,738 | 1,950 | 1,600 | 1,525 |
| Secondary school education | 4,120 | 3,433 | 3,133 | 4,333 | 3,650 | 3,508 | 3,708 | 3,178 | 2,940 | 2,100 | 1,840 | 1,860 | 1,900 | 1,350 | 1,575 |
| | Per Cent of Change | | | | | | | | | | | | | | |
| | 1929–34 | 1929–32 | 1932–34 | 1929–34 | 1929–32 | 1932–34 | 1929–34 | 1929–32 | 1932–34 | 1929–34 | 1929–32 | 1932–34 | 1929–34 | 1929–32 | 1932–34 |
| Postgraduates | −28 | −14 | −16 | −16 | −11 | − 6 | −22 | −17 | − 6 | + 3 | + 1 | + 2 | +82 | +73 | + 5 |
| Nonengineering graduates | −20 | −16 | − 4 | −22 | −12 | −12 | −18 | −11 | − 9 | +11 | +10 | + 2 | +25 | +20 | + 4 |
| First-degree engineering graduates: | | | | | | | | | | | | | | | |
| Chemical and ceramic | ** | ** | ** | −23 | −21 | − 2 | −22 | −17 | − 6 | +11 | + 3 | + 8 | +65 | +43 | +12 |
| Civil, agricultural, and architectural | −28 | −18 | −13 | −31 | −22 | −11 | −25 | −20 | − 6 | − 4 | − 1 | − 3 | +51 | +51 | 0 |
| Electrical | −26 | −15 | −12 | −19 | −14 | − 6 | −22 | −20 | − 3 | + 2 | + 1 | + 1 | +77 | +67 | + 6 |
| Mechanical and industrial | −34 | −25 | −13 | −36 | −28 | −11 | −29 | −25 | − 5 | − 2 | − 5 | + 4 | +66 | +50 | +11 |
| Mining and metallurgical | −30 | −19 | −13 | −25 | −24 | − 1 | −24 | −22 | − 3 | + 1 | − 7 | + 8 | +54 | +33 | +16 |
| College course incomplete: | | | | | | | | | | | | | | | |
| Civil, agricultural, and architectural | −25 | −21 | − 5 | −26 | −21 | − 6 | −22 | −15 | − 8 | −12 | − 9 | − 3 | −19 | −20 | + 1 |
| Mechanical and others* | −41 | −27 | −19 | −33 | −29 | − 5 | −24 | −21 | − 4 | −14 | −15 | 0 | −15 | −23 | +10 |
| Noncollegiate technical course: | | | | | | | | | | | | | | | |
| Civil, agricultural, and architectural | −29 | −20 | −11 | −31 | −19 | −15 | −28 | −21 | − 9 | −29 | −17 | −15 | + 5 | + 7 | − 2 |
| Mechanical and others* | −45 | −23 | −28 | −29 | −25 | − 5 | −30 | −24 | − 8 | −19 | −21 | + 3 | −22 | −18 | − 5 |
| Secondary school education | −24 | −17 | − 9 | −19 | −16 | − 4 | −21 | −14 | − 7 | −11 | −12 | + 1 | −17 | −29 | +17 |

* Includes chemical, ceramic, electrical, industrial, mining, and metallurgical engineers. ** Less than 10 engineers reported.

At 5 years after graduation the range of decreases of earnings over the period 1929–34 was from 25 to 43 per cent. At 10 years after graduation, the range was from 25 to 39 per cent, while even at 30 years after graduation the percentage decreases ranged only from 22 to 35 per cent. It will, however, be noted that the extremes of the ranges are the exception, indicating that regardless of type of education, the incomes of engineers of identical ages in 1929 and 1934 suffered about the same from the depression.

It cannot be too strongly emphasized that these data relate only to what engineers of various ages were earning in 1929, 1932, and 1934. Since there are no better data available it is almost inevitable that the figures will be used to predict what young engineers may expect to earn 10 or 15 years hence. For that reason, it is important to emphasize the severe limitations which attach to the data in this connection.

The first point—that the general level of engineering income fluctuates from year to year—needs merely to be mentioned in passing. Therefore, the absolute level of incomes for engineers with any given amount of experience cannot be forecast for any future year.

The chief danger to be guarded against is the assumption that the income relationships for 1934 will hold in some future year. A cautious use of such information may add to the value of the advice of those who are directing young men into the various fields of specialization. A careless assumption that this same relationship will hold 20 years hence for future graduates will make the resulting advice dangerous.

The tabulations show merely the facts of the income distribution in 1934 or some other particular year. For example, chemical and ceramic engineers 20 years after graduation averaged $4,100 and one-quarter of such engineers earned more than $6,000. On the contrary, civil engineers 20 years after graduation averaged $3,100 and the best-paid quarter averaged only $4,100 or more. It is evident, therefore, that men graduating from college in 1914 advanced on the whole to higher levels of income if their college work had been in the field of chemical or ceramic engineering rather than if it had been in the field of civil engineering. This much is fact.

But it must not be concluded from these data on income alone that it is wise to encourage men entering college in 1937 to specialize in chemical and ceramic engineering and to discourage their entering the field of civil engineering. Such advice will be sound only if the conditions surrounding the two fields of engineering and their prospects for the next 20 years are similar to the conditions of 1914 to 1934. Years of experience are themselves a factor in determining what kind of engineers are available. It is quite possible that there may be a relative scarcity of engineers with a given type of academic background and with 20 years of experience, while at the same time the supply of younger engineers with that same type of formal education may have become excessive. It is quite easy to see that a special scarcity value may have attached in 1934 to chemical engineers that did not accrue to civil engineers graduating in 1914. There was a tremendous expansion of the chemical industry in the United States during and following the war. It is a matter of common knowledge that such enterprises had the greatest difficulty in finding sufficient men with the requisite education and experience. On the other hand, while there are more civil engineers and more jobs for civil engineers than in 1914, a decrease in certain types of civil engineering work—as, for example, the construction of new railroads—has acted to restrain the development of relative scarcity values such as may have attached to chemical engineers.

At the same time it is impossible to make a comparison of the earnings of the younger engineers in the several professional classes and to conclude that the relationship between the professional groups will hold when they have had 20 years' experience. Thus in 1934 we find that chemical and ceramic engineers who graduated in 1932 averaged $1,286, whereas civil and mechanical engineers averaged $1,384. The statistics do not preclude the possibility that there is a longer period of apprenticeship for some types of engineering work than for others and that, following such a period of apprenticeship, there may be a more rapid advancement in the one line than in the other, ultimately to a higher level of income.

Conclusions as to the relative desirability of entering one type of engineering rather than another should be drawn only by those with an intimate acquaintance with all fields of engineering. Available statistics are probably a less satisfactory basis for advice than would be the pooled nonstatistical judgments of a number of people

**Table XII. Percentage Decreases in Median Annual Earnings Over Period 1929–34, for Corresponding Years After Graduation Among Engineers Reporting by Type of Education**

Without regard to employment status reported

| Type of Education | Per Cent of Decrease in Income, at End of Specified Period After Graduation | | | | | |
|---|---|---|---|---|---|---|
| | 2 Years | 5 Years | 10 Years | 20 Years | 30 Years | 37 Years |
| Postgraduates | —53 | —36 | —25 | —27 | —22 | —27 |
| Nonengineering graduates | —36 | —35 | —32 | —10 | —24 | —20 |
| First-degree engineering graduates: | | | | | | |
| Chemical and ceramic | —38 | —38 | —35 | —35 | —23 | ** |
| Civil, agricultural, and architectural | —38 | —35 | —33 | —27 | —31 | —32 |
| Electrical | —45 | —39 | —34 | —23 | —22 | —22 |
| Mechanical and industrial | —44 | —35 | —36 | —34 | —35 | —38 |
| Mining and metallurgical | —42 | —43 | —39 | —32 | —26 | —34 |
| College course incomplete: | | | | | | |
| Civil, agricultural, and architectural | —39 | —35 | —31 | —29 | —26 | —25 |
| Mechanical and others* | —40 | —40 | —39 | —32 | —32 | —35 |
| Noncollegiate technical course: | | | | | | |
| Civil, agricultural, and architectural | ** | —25 | —36 | —29 | —30 | —32 |
| Mechanical and others* | —31 | —43 | —39 | —35 | —32 | —33 |
| Secondary-school education | —26 | —33 | —36 | —18 | —25 | —19 |

* Includes chemical, ceramic, electrical, industrial, mining, and metallurgical engineers.
** Less than 10 engineers reported in 1934.

with a wide knowledge of the engineering profession and its opportunities. The statistical materials of this study can be used safely in projection only to fortify the judgments and forecasts of such individuals. To those who know not only the present situation of the various professional groups, but also the changing background of those professions over the past few decades, the income data will have particular significance. One who knows how the supply of and demand for particular types of engineering training has changed can make allowances and may attempt to estimate the most probable changes in future relationships. He will be helped to appraise the state of the current market for engineering services by earlier articles in which has been indicated the extent to which recent engineering graduates have been able to find engineering jobs.

The statistics which are presented here have a value that varies with the richness of the background of the user. Educational advisers and directors are performing specialized work and by the very nature of their work must guess what the future holds in store for various professions. Their prognosis becomes better if it is based on an extensive and accurate knowledge of existing conditions. This basis of knowledge the Bureau supplies on a hitherto unprecedented scale. The Bureau has attempted as comprehensive an analysis of recently existing relationships as its resources permit, and will welcome further critical analysis from any source of the detailed materials.

The Bureau has carefully refrained in this article from describing differences in the average incomes of graduate and nongraduate engineers as a measure of the value of a completed college course in engineering. From the data in hand, it is impossible to determine whether the differences are due to the fact that given individuals have received a college education or to other factors. It is possible that the differences in income arise from an initial process of selection. It is also possible that a prejudice in favor of the college graduate affords him better opportunities to acquire valuable experience than are given to the noncollege graduate. In such case, the advantages would arise not from formal education which the man had received but from his status as a college graduate.

It is a matter of common belief that college training has economic value for the prospective engineer. The figures in this study support this belief but cannot be taken as conclusive proof. Rather more conclusively they prove the great importance of other factors in addition to formal education. If formal education is an asset, the young graduate engineer should advance more rapidly than the nongraduate of corresponding age. This does happen. The data thus furnish supporting evidence as to the value of a formal education. But were formal education an all-important element in determining income in these early years, there should come a point at which no further relative spread developed between the average earnings of college graduates and nongraduates.

The facts show that the spread does increase. The difference is greater both in absolute terms and in relative terms after 30 or 40 years of experience than it is after 10 or 15 years of experience. This increased spread is noted

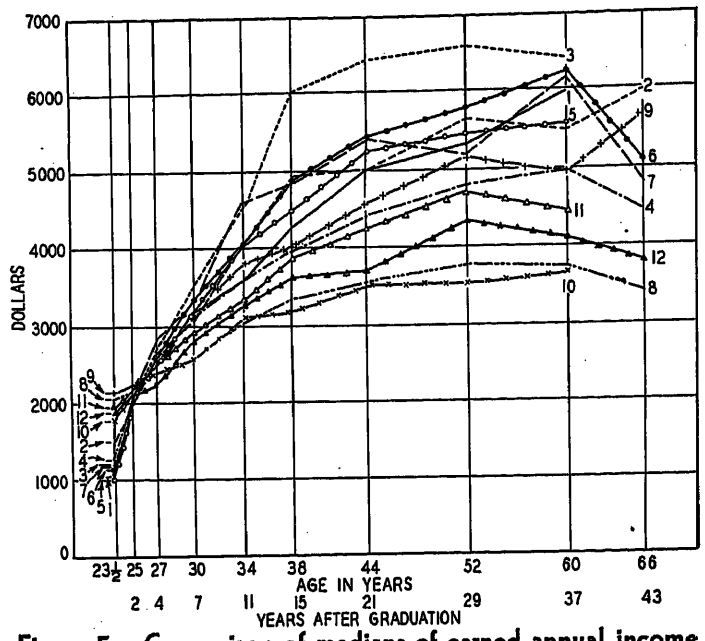



**Figure 5. Comparison of medians of earned annual income according to age, 1929**

Income from engineering and nonengineering services, including full and part-time employment for specific types of education

1—Postgraduates
2—Nonengineering graduates

*First-degree engineering graduates*

3—Chemical and ceramic
4—Civil, agricultural, and architectural
5—Electrical
6—Mechanical and industrial
7—Mining and metallurgical

*College course incomplete*

8—Civil, agricultural, and architectural
9—Mechanical and others

*Noncollegiate technical course*

10—Civil, agricultural, and architectural
11—Mechanical and others
12—Secondary school education

not only with reference to the average of the 2 classes but applies at the 5 levels that have been studied. It was found not only in 1929 but also in 1932 and 1934.

It can hardly be argued that the scholastic background of engineers who entered the profession in 1900 is a controlling factor with reference to their earnings in 1929 and 1934. Certainly, the value of their services is no longer primarily dependent upon the odds and ends of information which they acquired in college, although it is possible that habits of thinking and study which the engineer received in his college days constitute a permanent legacy. By and large the factors controlling the value of a man's engineering services after 30 years or more of experience must be primarily his native capacity and the training which he has received on the various jobs that he has performed.

As regards native capacity, there is reason to believe that, on the average, better material will be found among college graduates than among those who failed to complete a college course. There are, of course, many individuals who are unable to complete an engineering course for financial reasons. There are also many individuals of limited capacity who receive degrees. But there is also a wholesale process of weeding out that goes on in the engineering schools. Thus even the differences in income shown in

the earliest years of experience may reflect differences in capacity rather than differences arising from the value of the formal training.

Whether ability is more important than the differences in the kinds of experience that are open to the college graduate and the nongraduate, it is impossible to tell. It is a matter of common knowledge that for a number of years college education has been thought of as a normal prerequisite to engineering work. Some large employers of engineers deliberately differentiate between the college graduate and the nongraduate, offering the young engineer with a college education opportunities for training on the job which either are not available to the nongraduate or which are open to him after special consideration rather than as a matter of routine.

It must be noted that this latter type of advantage will tend increasingly to accrue to the status of the graduate as opposed to the nongraduate. In this sense status is gained by graduation, to some extent no longer with regard to the value of the formal education as such. The more common a college education becomes, the more widespread the assumption of a difference in capacity between the college graduate and the nongraduate becomes, the more certain it is that employers will discriminate in favor of the college graduate. Such discrimination means that the college graduate will generally be given more favorable opportunites for training on the job than the nongraduate of equal capacity.

It is known, however, that many large employers of young engineers have already developed a highly selective process of employment in interviewing candidates from engineering colleges. They may assume that in general college graduates are more promising material than nongraduates. They no longer recognize the mere fact of graduation as evidence of employability and give special status only to those who graduate with a standing substantially better than the average of the class. Thus the advantage of status which may have accrued a number of years ago through the fact of college graduation alone now accrues in equal measure only to graduation with exceptional standing.

The candidate for a position in the engineering profession should study carefully the tables which will be presented in the final bulletin[1] not only for average earnings (as in table IX) but also for the upper and lower 10 and 25 per cent of the engineers. Table IX showed clearly enough that a young man is well advised to enter the profession after successfully completing a period of formal education beyond the high-school level. An earlier chapter on education indicated that college training was coming to be a prerequisite for entrance to the profession. But it is unwise to rely heavily on the value of a college education per se.

The present study gives conclusive demonstration of differences of income which generally reflect different degrees of capacity. The lot of the college graduate may be somewhat easier than that of the nongraduate. But even in 1929 the lowest 10 per cent of the college graduates in civil engineering were earning less than $2,500 after 10 years of experience and $2,700 after 20 years of experience. These figures are to be compared with the average earnings of $3,600 and $4,400 for these respective groups. On the other hand, the upper 10 per cent of the civil engineers whose college course was incomplete earned $5,200 or more after 10 years of experience and $7,600 or more after 20 years of experience. The upper 10 per cent of the engineers with only a secondary-school education similarly show earnings substantially above those of the average college graduate. In other words, graduation from an engineering school is no guaranty of a satisfactory income, while there is still apparently an opportunity for a man of outstanding capacity to secure far better than an average engineering income even though he has not attended college.

The most significant differences in income revealed by the present survey are not the differences in the average income received by individuals who have received a college degree and those who have not. Nor are they the differences as between individuals who have entered one professional class rather than another. These differences on the whole are moderate, though they are large enough to prove the desirability of choosing well both the field of endeavor and the type of training best adapted to advancement in that field. The most striking differences are those which exist within each profession and within each group classified on the basis of its educational background. One out of 10 of the engineers in each such group secures an income several times as great as the average for the group as a whole. At least one out of 10 at the bottom of each such group, whether a college graduate or not, whether a chemical engineer or a civil engineer, whether a man with many years of service or freshly out of college, is hardly to be distinguished as regards income from a skilled wage earner.

We [of the Bureau] do not feel ourselves competent to project from these data what the future holds in store for the high-school boy who must be advised as to what type of training will be most advantageous. We hope he may be fortunate enough to encounter wise advice. We dare do no more than point out that in 1929 the average income of graduate engineers with 10 years' experience ranged from $3,600 to $4,600 in the various professional classes. In 1929 only 6.4 per cent of the incomes in the United States exceeded $4,000. Furthermore, engineering is a profession in which earning capacity advances and is sustained until late in life. But if in these respects the profession appears attractive on the average, its rewards are not particularly attractive to the poorer or less fortunate engineers. Even in 1929 the lowest-paid 10 per cent of the engineers could hope for no more than $2,500 to $3,000, though they might stay in the profession for 40 years. In 1934, exposed as the profession was to the risks of unemployment, the lowest-paid 10 per cent of the engineers with less than 5 years' experience after graduation earned less than $1,000. Even with 10 to 30 years' experience they earned no more than $1,000 to $1,500. Judged from the basis of money income, there can be no question but that the best of a group of skilled wage earners are in better economic position than those who struggle to maintain a position on the fringes of the engineering profession.

# Electrical Applications in Bethlehem's 72-Inch Strip Mill

By F. D. EGAN
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THE RAPIDLY increasing demand for flat-rolled sheet steel and strip products has made necessary the application of electrical apparatus to modern developments in rolling-mill machinery and caused the rapid construction of many wide continuous hot- and cold-strip mills in every section of the country. A comprehensive picture of a strip mill, and the application of electricity to the production of sheet steel can be seen in Bethlehem Steel Company's hot- and cold-strip mill.

This mill is built on a plot of 67 acres adjacent to, and across the highway from the main plant, acquired for the purpose of providing ample space for the best arrangement of buildings, in order that the most economic routing of materials and product through its 22 acres of floor space could be obtained.

This mill, which has an annual hot-rolled capacity of strip, sheet, and light plate of 800,000 tons, of which 360,000 tons can be converted into cold-rolled finished product, is capable of producing wide strip up to 60 inches in width by 0.0625 inch in thickness, and 72 inches in width by 0.078 inch in thickness, with a minimum width of 18 inches by 0.05 inch thick; as well as light plates up to $1/2$ inch in thickness. Cold-rolled strip is produced ranging from $18 1/2$ inches to 72 inches wide and from 0.0125 inch in thickness up to 0.109 inch in thickness, and by cross rolling in a 93-inch 4-high skin pass mill, sheets may be rolled up to 84 inches in width.

All possible refinements for hot-rolled products, as well as for cold-rolled sheet and strip for which there is a commercial demand, are provided in the finishing departments.

The mill's location gives it a nearby source of its basic material; namely, the slab, the steel made at the open hearth furnaces, and the ingots rolled to required sizes in the main plant. Its location enables it to use electricity, water, and gas from the main plant; also permits service, controlled to meet its needs by the South Buffalo Railroad, connecting with 13 trunk line railroads entering Buffalo, provides the advantages of shipping facilities on the Great Lakes for raw and finished materials, as well as the advantage of a location, central in relation to the consumers of sheet product.

The slab storage building (figure 1) comes first in the sequence of rolling operation; this building is 925 feet long and 85 feet wide, and has a capacity of approximately 10,000 tons of slabs. The stock of slabs varies in widths from 20 inches to 48 inches, in thicknesses from 3 inches to 6 inches, and in lengths from 5 feet to 15 feet. These slabs, of various chemical composition, are ready for heating and rolling as needed.

The slabs are removed from storage by an overhead traveling crane and piled on a magazine pusher, which is driven by a 35-horsepower motor through a rack and pinion arrangement. Each operation of the machine lifts the magazine so that a chain drive can carry but one slab at a time, onto the furnace charging table. This 3-section roller table carries the slab to a position in front of one of 3 heating furnaces, from where a pusher forces it into the furnace. These furnaces are of the recuperative type, 3 zone and triple fired. They have an effective heating length of 80 feet and can be either gas or oil fired. Each is capable of heating 55 gross tons of slabs per hour, giving a total furnace hourly capacity of 165 gross tons. At a signal from the head roller, the pulpit *A* operator, located in the slab yard, opens the furnace door, and then pushes a slab into the rear of the furnace; this causes one of the heated slabs to drop out of the furnace at the other end onto the 3-section furnace delivery table. These tables are duplicates of the charging tables.

The slab leaves the furnaces at approximately 2,250 degrees Fahrenheit and proceeds down the roller table to number 1 scale breaker, which precedes a series of 4 mill stands in the roughing train. The scale breaker is a 2-high mill, having 24-inch diameter by 76-inch long rolls, through which the slab passes and is given a slight reduction in thickness to break up any scale that may have formed on the surface of the slab as it is leaving the furnace. As the slab leaves the scale breaker, water at 1,000 pounds pressure is sprayed upon it to remove the loosened scale.

The slab now enters a 4-high broadside mill, which has 2 36-inch diameter working rolls, and 2 49-inch diameter backup rolls, all 96 inches long. Slabs which are to be finished as strip less than 48 inches, pass straight through this broadside mill; but, for a strip width of greater than 48 inches, the slab is turned crosswise on the turntable and is cross rolled to the desired strip width, after which it is turned back 90 degrees for rolling lengthwise in the remaining mill stands. On cross roll passes, a 150-horsepower motor-driven pusher is provided to force the slab into the stand.

Before the slab enters the remaining mills of the roughing group, a slab squeezer, driven by a 275-horsepower motor, squeezes the slab sideways to true and square its edges. The remaining 3 roughing stands are 4-high universal mills, each has $24 1/2$-inch diameter working rolls and 49-inch diameter backup rolls 79 inches long, as well as 2 vertical edging rolls, the latter driven by a 150-horsepower motor. These rolls are used to maintain the required slab width.

After leaving the last universal mill, the slab emerges onto a long, 2-section approach table. Each section is

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Figure 1. Slab storage building

driven by 2 35-horsepower motors operated in either series or parallel, to give 2 table speeds. Since the finishing temperature of the hot strip is a prime factor in the quality of the product produced, this roller line serves as a special cooling place between the roughing and finishing stands. When the thin slab has reached the proper temperature, which is automatically indicated by a photoelectric pyrometer, it enters the second scale breaker, which breaks up the secondary scale, formed on the cooling table. As the slab leaves the scale breaker, water at 1,000 pounds pressure removes the scale.

The cleaned slab now enters the 6-stand finishing train (figure 2). However, unlike the roughing mill, the strip is in all of these stands at the same time; thus, the speed of successive mill stands must be increased to compensate for the elongation in the preceding stand. This, together with the loopers, provide a means of keeping the slack out of the sheet throughout the finishing mill.

As in the roughing mills, so in the finishing mill, every precaution is taken during the rolling to eliminate scale and dirt. Here, steam instead of water is sprayed on the rapidly thinning strip just after it passes through each set of rolls. As it leaves the last finishing stand, the rapidly moving strip may be cut to any predetermined length from 11 to 22 feet, by a flying shear, synchronized with the speed of the strip, or the shear may be used to cut off the front and rear crop of the strip to be coiled.

On the front of each mill, there is a screwdown dial resembling a clock face, the hands of which indicate the movement of each end of the top roll. The rolls are roughly set up with a feeler gauge to produce a definite gauge of product. Then, to obtain perfectly accurate adjustments, either one or both ends of the top roll can be moved as small as $^{1}/_{1,000}$ of an inch by the screwdown motors, these movements being indicated by the hands on the screwdown dial. These screws are driven by 70-horsepower motors, which are coupled by a magnetic clutch when the screws are moved together.

Throughout the whole series of mill stands, grease is automatically pumped into the roll neck bearings at intervals of a few seconds, and a constant flow of oil is maintained to all motor bearings, gear and pinion housings, and backup roll bearings. These automatic lubrication systems help to insure a smooth operating mill.

In the production of hot-rolled strip it is important to secure the desired grain structure, which is controlled by the temperature of the strip as it leaves the finishing mill train. The finishing temperature is regulated by the length of time that the plate is held on the cooling tables ahead of the finishing stands. To indicate the finishing temperature, a recording Speedomax has been installed and placed within view of the finishing mill operator.

The finishing end of the hot-strip mill, designed to dispose of the various products rolled by the hot mill proper, consists of runout tables, cooling beds, trimming line, and other processing equipment. The runout table equipment serves to transport the steel from the mill to the coilers in a continuous strip, and to transport sheets, cut to length, by the flying shear, to the pilers.

That part of the runout table *A* between number 10 stand of the mill and the coilers is made up of 125 16-inch-diameter rollers, direct connected to gear head motors through flexible couplings. The motors are 2.25/7.5-horsepower 600/1,800-rpm 147/440-volt 20/60-cycle squirrel-cage induction motors, with a 5 to 1 gear ratio output shaft. The remainder of *A* table run, from the coilers to the piler, is made up of 216 rollers, 12 inches in diameter, arranged for flange-mounted motors with one motor driving 2 rollers. These motors are 1.37/5-horsepower 560/1,770-rpm 147/440-volt 3-phase 20/60-cycle induction motors.

As the continuous strip approaches the coiler, a door is opened in the table roller line, to direct the strip down into the coiler, where it is wound around a mandrel to a compact coil by individual-motor-driven revolving rolls. The finished coil is deposited on a chain conveyor and

either carried through an underground tunnel to storage space in the continuous-pickler building of the cold mill, or taken from the conveyor in the hot-mill shipping building to be delivered as hot-rolled coils, or further processed in shearing, trimming, and leveling lines.

These continuous trimming lines consist of a coil box, a trimmer, a leveler, and a shear with interconnecting roller lines. The strip passes through these machines and emerges as cut-to-length flat sheets, ready for shipment or storage. The cut-to-length strip from the flying shear is collected by automatic pilers and transported to temporary storage for self-annealing. Part of these sheets are delivered as self-annealed black sheets; however, if deep drawing qualities are required by the customer, the sheets are normalized in a 150-foot-long gas-fired furnace.

The normalized sheets may be further processed by passing through a roller leveler and a skin pass mill. However, other finished product specifications may require that the normalized sheets be first taken through a sheet pickling process. This pickling process consists primarily of dipping the sheets into a sulphuric-acid bath and a hot-water rinse and then a cold-water rinse. The sheet next passes through a scrubber and dryer for final cleaning.

For handling and processing plates, 3 additional roller tables, designated as *B*, *C*, and *D* lines, have been provided south of, and parallel to, *A* table line. When plate is being rolled it is routed from *A* to *B* table line by a chain transfer, driven by 3 70-horsepower motors. The *B* table run is made up of 434 12-inch-diameter rollers, arranged for flange-mounted 0.66/2-horsepower 147/440-volt 3-phase 20/60-cycle motors, with each motor driving 2 rollers. For flexibility of control, this *B* table run is divided into 3 major divisions. The first section, consisting of 174 rollers, delivers the plate to a leveler. The second section of 172 rollers carries the plate from the leveler and feeds it into a shear, which cuts it to desired lengths. The third section of 88 rollers carries the plate from the shear to the *B* to *C* table transfer.

*C* table, used entirely as a transfer and cooling table, is made up of 436 12-inch-diameter rollers, arranged for flange-mounted 0.5/1.5-horsepower 240/720-rpm 147/440-volt 3-phase 20/60-cycle motors, with each motor driving 2 rollers.

For convenience in plate handling, this *C* table is divided into 5 separately controlled sections. The last section of this table delivers plate to the *C* to *D* table transfer. The *D* table run, utilized as a $^1/_2$-inch-plate processing line, consists of 480 12-inch-diameter rollers, geared to flange-mounted motors duplicate of those driving *C* table. This table is divided into 7 sections. The first 2 sections are used either to spot material already processed on *B* table for removal by plate handling equipment, or to deliver material requiring further processing to the third section of this line which serves as an approach to a rotary side-trimming shear. Section number 4 is used to convey the material from this shear to a leveler from where it is




**Figure 2. Side view of number 9 and number 10 stands rolling wide strip**

delivered by section number 5 to an up-cut shear. The sheared plate is carried by sections number 6 and number 7 to piling skids, for transfer to storage and shipment or transferred to the $^5/_{16}$-inch trimmer line, or $^1/_2$-inch re-squaring shears for further processing.

All of the motors (figure 3), driving *A* table rollers and both coilers, the motors driving the second section of *B* table, and the motors driving the fourth and fifth sections of *D* table, receive their power from 6 166/500-kva 147/-440-volt 3-phase 20/60-cycle synchronous generators, each driven by 2 125/250-horsepower 300-volt 400/1,200-rpm shunt-wound, separately excited at 250 volts, adjustable-speed d-c motors connected in series to operate from the 600-volt d-c hot-mill bus. The table sections and coilers are arranged to be driven from the 6 alternator sets as follows:

Number 1 motor-alternator drives section number 1 of *A* table.
Number 2 motor-alternator drives section number 2 of *A* table.
Number 3 motor-alternator drives either number 1 coiler or section number 3 of *A* table.
Number 4 motor-alternator drives either number 2 coiler or section number 4 of *A* table.
Number 5 motor-alternator drives section number 2 of *B* table.
Number 6 motor-alternator drives section number 4 and number 5 of *D* table.

The motors driven from these alternators are started at base speed, 20 cycles at 147 volts on the line and increased to full speed, 60 cycles at 440 volts by field weakening of the d-c motors driving the alternators. In reverse manner the table drives are decelerated to base frequency and voltage by field strengthening of the driving motors, which pump regenerated energy into the 600-volt system. At base speed the motors are cut free from the alternators and brought to rest by d-c dynamic braking. This direct current is supplied by a 200-kw 75-volt separately excited shunt-wound generator driven by a 300-horsepower 440-volt motor. Excitation for this dynamic braking machine and the motor-alternator sets is supplied by a 100-kw self-excited 250-volt generator driven by a 150-horsepower 440-volt motor.

The motors driving the remaining sections of *B*, *C*, and *D* tables are operated at a fixed frequency of 25 cycles at about 187 volts, supplied by 2 banks of 3 100-kva single-phase, 440-volt primary, 170/200-volt secondary, transformers.

Coils of strip rolled in the hot mill are carried underground by 3 motor-driven coil conveyors to coil storage in the continuous pickler building. From here the hot-rolled coils definitely start on their journey through the cold mill for the process of becoming full-finished cold-rolled sheets.

The coils are taken from storage with a lifting magnet suspended from a traveling crane, to one of the continuous pickling lines, in vertical position. An up-ender tilts this coil to a horizontal position, from where it is rolled down an incline to the feed reel. The coil is lifted into position in this feed reel by an electric hoist, where motor-adjusted heads clamp it into place. The strip is threaded into a combination processor and straightener, which unwinds the coil and levels the sheet. The end of the strip continues to a shear where it is cropped square, so that it can be fastened to the squared end of the preceding strip by a stitcher to form a continuous ribbon of steel.

A looping pit is provided between the stitcher and the acid tanks, where sufficient slack can be kept in the strip to allow time for the stitching and shearing processes and still maintain a continuous passage of steel through the pickle tanks. The strip is then pulled by pinch rolls, out of the looping pit and through 4 60-foot acid tanks, a 25-foot cold-water-rinse tank, and a 25-foot hot-water-rinse tank, which helps to dry it. Emerging from the latter it moves over a roller table, under which is a hot-air dryer, designed to remove all traces of moisture. The pickling solution normally consists of a sulphuric-acid bath, kept at a temperature of 180 degrees Fahrenheit by pyrometrically controlled steam heat.

As the sheet is pulled from the drying table by the third pinch roll, it is recut to original coil lengths by a double-cut shear which removes the stitch. A recoiler located at the end of the line, coils the strip, from which it is discharged to a gravity conveyor, weighed, and delivered to the storage space adjacent to the tandem cold-rolling mills.

The next step after pickling is to reduce the strips' thickness to such gauges as may have been ordered by customers. This is accomplished by rolling the metal cold in the 3-stand 4-high tandem mills, there being 2 sets. One set of mills is designed to roll coils up to 48 inches maximum width, while the other will roll them up to a width of 72 inches.

The tandem arrangement of 3 mills in series makes possible 3 cumulative reductions at one pass of the strip through the mill train. Synchronizing the series of mills to the proper speed and reduction is accomplished by an elaborate electrical control system. The gauge or thickness of the strip on its passage through the mill stands is indicated to the operator by a flying micrometer which automatically indicates on a dial any variations in the thickness in increments of 0.0002 of an inch. The dial is located within view of the operator, and enables him quickly to adjust the pressure on the rolls to maintain uniform gauge.

Each mill stand is driven by a 1,250-horsepower motor, sufficient power being available to give a delivery speed at the last stand of 660 feet per minute. From the stand (figure 4), the strip is wound by a reel with a collapsible core, which maintains a predetermined strip tension during recoiling. After the strip is coiled the reel is stopped, then a pneumatic pusher discharges the coil from the reel, and the coil is either sent to storage for shipment, or subsequent treatment.

Preparatory to annealing, the coils from the tandem cold mills are cut into sheets, or especially processed in coil form. If the steel is to be annealed in sheet form, the coils are taken to a group of 3 cutting up lines. Each of these lines consists of a feed reel, a side trimming shear, roller leveler, and flying shear, arranged in tandem. From these lines the strip, now flattened sheets, are delivered in packs by gravity conveyors to the annealing department. Strip, to be annealed in coil form, is taken to a loose

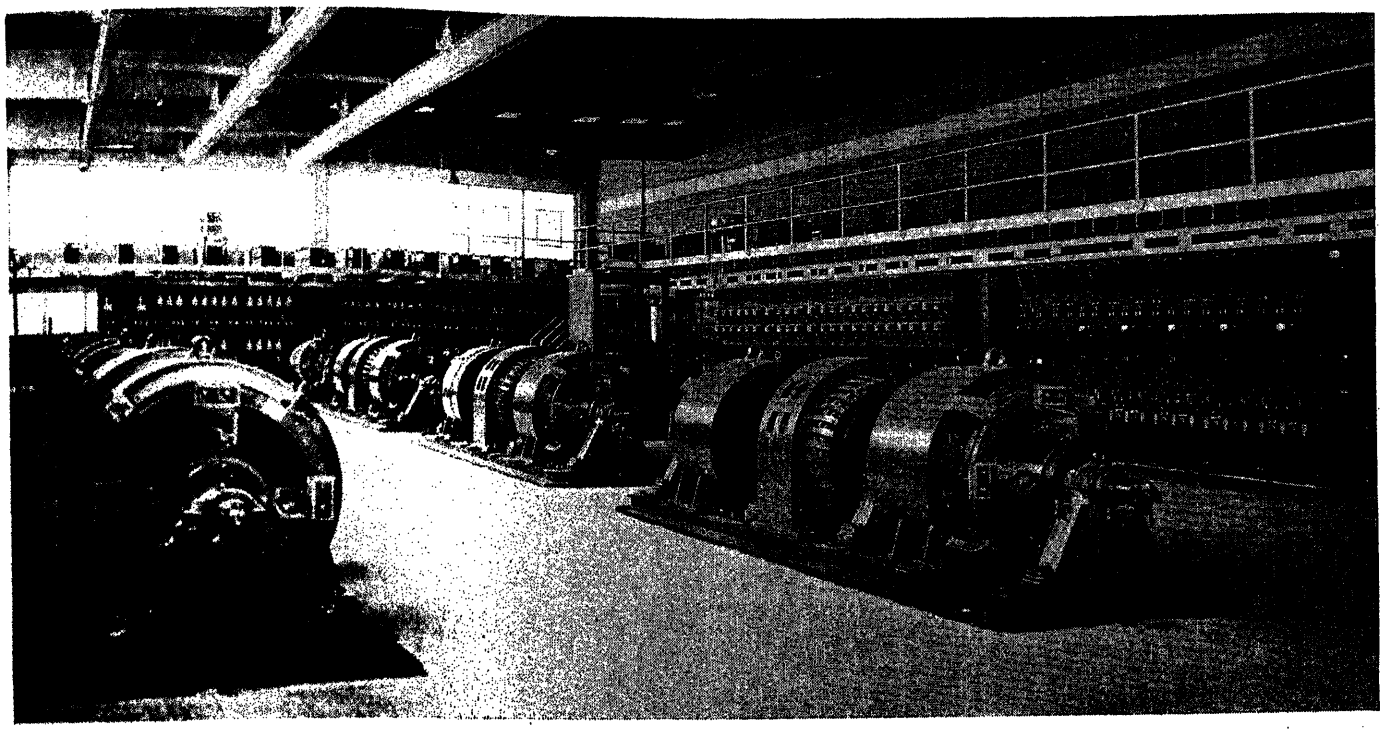


**Figure 3. Variable-frequency-motor room**

winding machine, which rewinds the tightly coiled strip as it comes from the tension reel of the tandem mills. This is done to permit a more thorough annealing and to eliminate the possibility of the smooth surface of the coils adhering to each other under the high annealing temperature.

The annealing equipment consists of 44 gas-fired radiant-tube furnaces. Thirty-one of these furnaces, provided with 91 bases and inner covers, will handle sheets up to 75 inches in width by 220 inches in length or coils up to 59 inches in width; 5 furnaces, provided with 14 bases and inner covers, are capable of taking sheets up to 84 inches by 186 inches, or coils up to 72 inches in width; and 8 furnaces, provided with 28 bases and inner covers, size 90 inches by 250 inches, are now being installed. The use of several bases to one furnace has secured maximum efficiency of furnace capacity.

In the sequence of the annealing operation, sheets are piled on a base, the inner cover placed over the pile, and the furnace lowered over this cover. The lower edges of both the inner cover and the furnace are sand sealed. During the annealing operation, an atmosphere of deoxidized gas is introduced under the inside of the inner cover at a slight positive pressure. The temperature in the furnace is slowly brought up, until it is a little above the predetermined annealing point. To reach this temperature requires from 30 to 40 hours on sheets, and about 20 hours on coils. The furnace temperature is maintained at this level by automatic control, while the pack of sheets is soaked for about 22 hours, or in the case of coils, 6 hours. The furnace is then removed by an overhead crane to another base that has been charged in a manner similar to the first. The annealed pile, enclosed in its inner cover, is allowed to cool to about 200 degrees Fahrenheit. The inner cover is then removed and after the pile has cooled to atmospheric temperature, it is removed. The base is now ready for another cycle of annealing operations.

Strip steel, when annealed in coils, is placed upright on the bases and covered by the inner cover, and furnace. The same method of annealing processes pertains to coils as to sheets, except that, due to the separation between coil turns, the soaking period can be reduced, making possible a shorter annealing cycle.

Four individual mills have been provided to skin pass the annealed sheets, namely: 2 4-high 76-inch mills; one 4-high 90-inch mill; and one 2-high 54-inch mill. In addition to skin rolling single sheets, one of the 76-inch 4-high mills and the 2-high 54-inch mill are equipped with feed and tension reels for skin passing strip in coil form. The slight reduction of one to 3 per cent, not only smoothens and polishes the sheet but also affects the hardness and ductility of the sheet. These qualities can be modified by varying the amount of reduction, depending upon the draw required in the sheet.

Strip, in coil form, can be delivered in widths, ranging from one inch to 72 inches, and in varying thicknesses from 0.0125 inch to 0.125 inch. To supply the narrow widths of 18 inches and under, the hot- and cold-rolled coils are slit to required widths by especially designed slitting units. One of these machines is capable of handling strip up to 36 inches in width and the other up to 72 inches in width. The machines may also be used to trim wide strip in coil or sheet form to accurate widths.

Typical uses of sheet and strip products, rolled by this mill, are as follows:

Hot-rolled sheets are used in the manufacture of tacks, large steel tanks, concrete forms, brick pallets, perforated screens, range boilers, and similar articles.

Hot-rolled annealed sheets are used in the manufacture of steel drums, barrels, metal flasks, coiling stock, stove parts, low price cabinets, lockers, and shelving, and other products, which do not have very rigid forming or surface requirements.

Blued sheets are used for the manufacture of stove pipe, stove parts, and other articles that are finished with a smooth unpainted surface.

Extra-smooth hot-rolled annealed sheets, also called japanning steel, are used principally for steel cabinets, shelving, stove parts, and various metal novelties that require a smooth surface suitable for lacquer or enamel finish and which do not have severe forming requirements.

Hot-rolled annealed sheets-pickled, have a clean, porous surface and are suitable for products that have drawing or electric welding requirements, but they are not recommended for articles on which a smooth finished surface is required. They are used by the automobile industry for inside body and chassis parts, such as: inside door panels, seat backs and bottoms, floor pans, and pillar posts.

Cold-rolled sheets are used in the automobile industry for turret tops, doors, panels, hoods, fenders, radiator shells, and side aprons; in the container industry for milk, paint, ink, grease, and oil cans; in the refrigerator industry for panels and doors; in the radio industry for chassis parts; and in the furniture industry for filing cabinets, desks, chairs, partitions, hot-air registor and radiator covers; in the electrical industry, cold-rolled stretcher-leveled sheets are used for control panels, metal-clad switchgear, instrument panels, breaker panels, and for other products which require perfectly flat, non-resilient steel.

Due to the distance between the main plant and the strip mill, it became necessary to erect an independent boiler plant to provide steam for processing and heating. This station is equipped with 4 500-horsepower boilers, 150 pounds pressure, 200 degrees superheat, capable of operating at 200 per cent rating. The units are designed to use coke breeze for fuel; this fuel is handled from cars to bunkers over the boilers by an automatic skip hoist and belt conveyor. The fuel is fed into the boilers by chain-grate stokers, and the ash removed by dumping directly into hopper cars. Three of the 4 boilers are equipped with steam-driven auxiliaries, the fourth being equipped with motor-driven auxiliaries. The boiler feed pumps, water-softening plant, and 3 2,000-cubic-feet-per-minute air compressors for general plant service, are located in a room adjoining the boiler house proper.

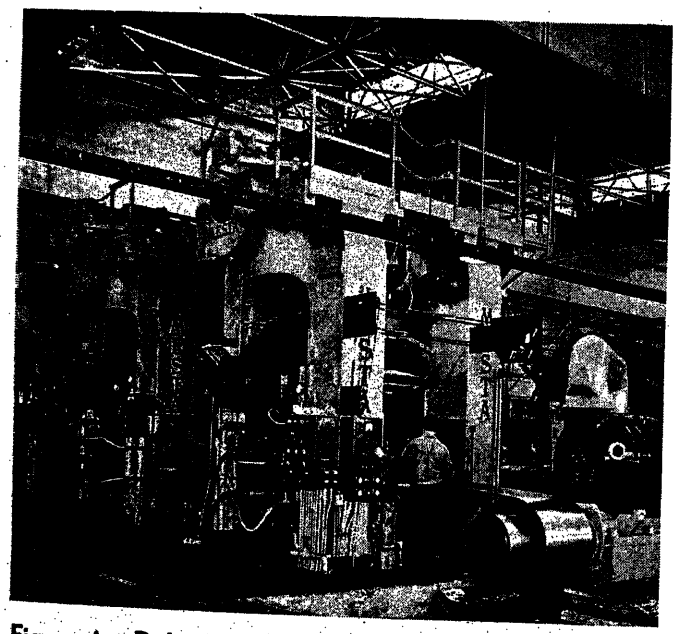


**Figure 4. Delivery side of 54-inch tandem mill, showing tension reel**

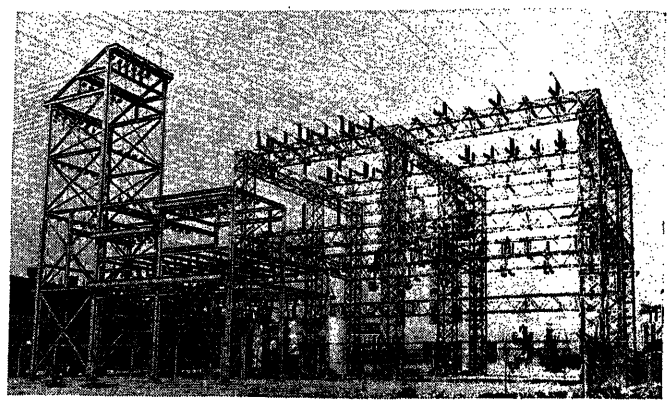


**Figure 5. Number 5 substation**

A roll shop is provided as a continuation of the cold-mill building, for grinding both the hot- and cold-mill rolls. This shop is equipped with 2 53-inch by 20-foot and 2 36-inch by 18-foot grinders, together with bearing changing blocks, roll racks, and sandblasting equipment for surfacing the cold-mill rolls.

A service building located central to the hot and cold mill, contains an electric shop, machine shop, and storehouse for small machines and tools required for general plant maintenance.

For the convenience of the large number of workmen a welfare building was built between the hot and cold mills to provide shower baths, washing basins, and individual lockers for the workmen. This building is steel brick construction, with glazed tile interior; covered walkways have been provided between this building and the various departments for the convenience of the workmen.

As the steel industry has developed, electricity has played an increasingly important part in the production of steel. Thus, with the large investment in the modern strip mill, it becomes most important that provision be made to supply adequate power with minimum interruption to service.

The power for this strip mill is supplied from 3 different sources over 6 lines from 2 different directions. The main source of supply is number 5 substation (figure 5). This station is located approximately 600 feet east of the hot-mill motor room, and consists of a 2-bay outdoor high-voltage switching structure, 56 feet by 80 feet. This station is fed from the power company over 2 3-phase 25-cycle 60,000-volt lines, each rated at 40,000 kva. These lines pass through this structure and continue to another substation feeding the main plant.

Each of the power company's lines occupy one bay of the high-voltage structure and with the use of a cross bus and tie switch, it is possible to feed this station from either or both of these lines. The structure is designed to accommodate 2 15,000-kva 60,000/6,600-volt 25-cycle 3-

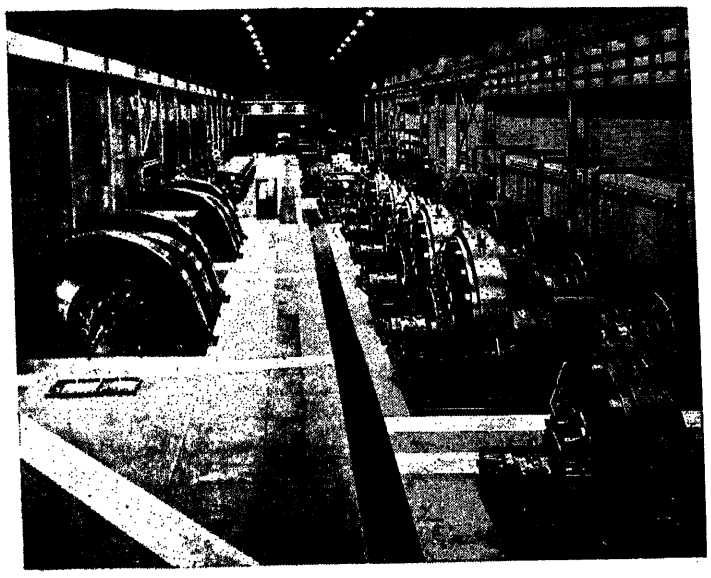


**Figure 6. General view of motor room**

phase water-cooled banks of transformers, one of which is installed at present.

A secondary bus structure, 20 feet deep by 40 feet long, is provided to accommodate the bus work, oil switch on the secondary side of the transformer, and the disconnect switches on the outgoing lines. Provision is made to add a duplicate secondary structure for the future bank of transformers.

The secondary bus structure and the towers between the substation and the motor room are designed for 6 500,000-circular-mil circuits, 4 of which are installed at present. These lines are tied to the secondary bus of the transformers through 1,200-ampere high-pressure-contact outdoor disconnect switches and 2 circuits are paralleled on the other end to feed the motor-room bus through a 1,200-ampere 500,000-kva metal-clad oil circuit breaker.

The 2 power company lines that pass through station number 5, continue to the main plant to feed station number 3 through 2 400-ampere 1,000,000-kva oil circuit breakers. This station is very similar in design to station number 5, including the cross bus and transformer layout for 2 15,000-kva 60,000/6,600-volt 3-phase 25-cycle air-cooled banks of transformers, both of which are installed and operating. Space is available at this station for the installation of a third 15,000-kva bank, duplicate of above. This station is located about one mile north of the strip mill, with a 6,600-volt tower line connecting the substation with the mill, designed for 4 500,000-circular-mil circuits, 2 of which are installed at the present time. Each line is tied to the substation bus through a 1,200-ampere 25,000-volt outdoor-type oil circuit breaker and each is tied to the motor-room bus through a 1,200-ampere 500,000-kva metal-clad oil circuit breaker.

(Figure 6) this is a general view of the motor room with the d-c motors driving the finishing mill in the right foreground, the 2 1,500-kw auxiliary motor-generator sets in the right center, and the 6,600-volt a-c roughing-mill induction motors in the right background. The 2 6,000-kw motor-generator sets driving the finishing-mill motors are shown in the left foreground and the 6,600-volt metal-clad bus structure in the left center.

This metal-clad bus structure consists of 22 high-speed 1,200-ampere 500,000-kva oil switches, complete with sealed-in bus compartment. A 250-volt storage battery is located in the basement to provide closing and tripping power for these switches.

The main bus in this metal-clad structure is separated into 2 parts which are tied together through a 2,000-ampere nonautomatic 500,000-kva oil circuit breaker. The incoming lines from number 3 substation feed into the west end of this bus and the incoming lines from number 5 substation feed into the east end of this bus. The roughing-mill induction motors, the 3 cold-mill motor-generator sets, and one of the auxiliary motor-generator sets feed off the west bus and the finishing-mill motor-generator sets, auxiliary transformers, spray pumps, and one of the auxiliary motor-generator sets feed off the east bus. The normal operation of the power system is to have the east and west busses tied together with the lines from both number 3 and number 5 substations operating in parallel.

The bus at number 3 substation that feeds the 2 500,000-circular-mil lines to the strip mill is tied in with a 25,000-kva generating station through the plant network.

The roughing-mill motors driving number 1 scale breaker and stands numbers 1 to 4, inclusive, are 6,600-volt 3-phase 25-cycle induction motors equipped with automatic liquid slip regulators for starting and regulating the load, with the exception of the 1,000-horsepower squirrel-cage motor driving number 1 scale breaker, which starts across the line. Each motor has 6 leads brought out of the stator, with current transformers ahead of the motor and in the neutral for differential protection.

These motors are stopped by applying direct current to the motor windings, which results in a modified form of

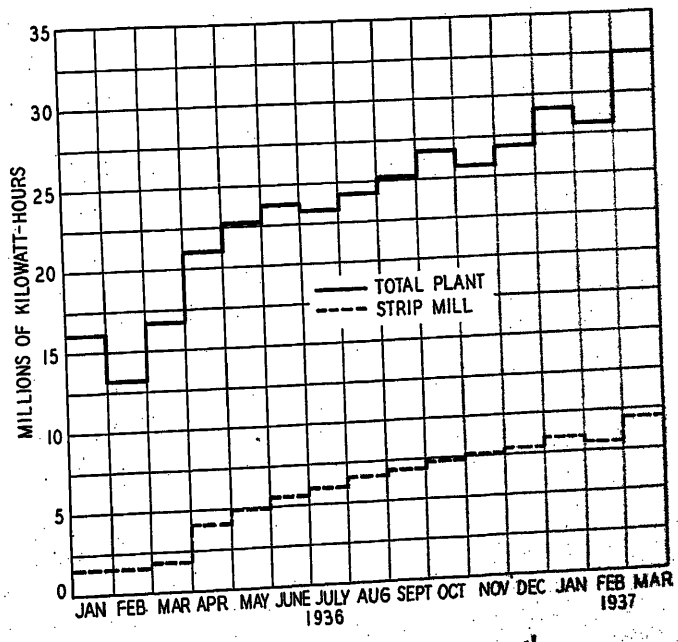



**Figure 7. Kilowatt-hours per month**

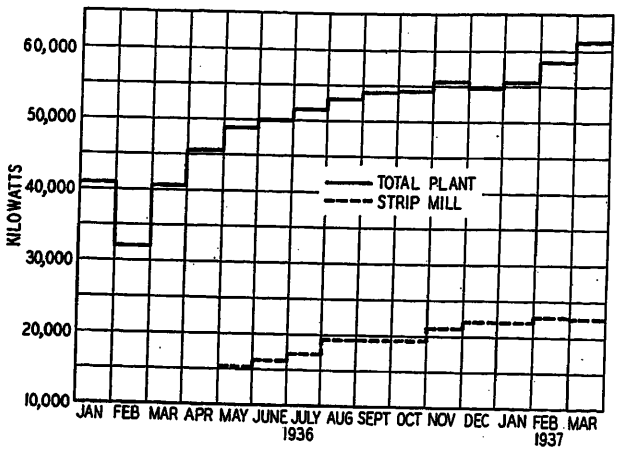



**Figure 8. Maximum 15-minute demands**

dynamic braking. The ratings of these motors are as follows:

| | | | |
|---|---|---|---|
| Number 1 scale breaker | 1,000 horsepower | Squirrel cage | 375 rpm |
| Number 1 stand | 3,000 horsepower | Wound rotor | 150 rpm |
| Number 2 stand | 3,000 horsepower | Wound rotor | 500 rpm |
| Number 3 stand | 3,000 horsepower | Wound rotor | 500 rpm |
| Number 4 stand | 3,000 horsepower | Wound rotor | 500 rpm |

Number 1 stand has a flywheel mounted on the motor shaft and numbers 2, 3, and 4 stands have 2 flywheels mounted on the pinion shaft of the gear unit.

The 600-volt direct current, to operate the finishing-mill motors, is supplied by 2 6,000-kw motor-generator sets, each set consisting of one motor and 2 generators. The motor driving these sets is a 7,200-kva 6,600-volt 3-phase 25-cycle 375-rpm synchronous motor, connected for differential protection, the same as roughing-mill induction motors. The motors are started through the 1,200-ampere metal-clad switchgear and are brought up to speed as an induction motor, the current being limited by the starting reactor to 165 per cent in terms of normal rating. At approximately 90 per cent speed, a light field is applied to the motor to pull the machine in step with proper polarity on field poles. After the machine pulls into step, the reactor is shorted out of the circuit, placing the machine across the line, and at the same time full field is applied. The d-c generators are rated 3,000-kw 600-volt d-c continuous rated, open, compensated, shunt wound, separately excited with 250 volts, direct current.

The 4 generators feed into a common bus, from which, the 7 d-c finishing-mill motors and the variable-frequency motor-generator sets obtain their power. The ratings of these motors are as follows:

| | | | |
|---|---|---|---|
| Number 2 scale breaker | 1 | 500 horsepower | 150/600 rpm |
| Numbers 5, 6, 7 stands | 3 | 3,500 horsepower | 175/300 rpm |
| Numbers 8, 9 stands | 2 | 4,500 horsepower | 125/250 rpm |
| Number 10 stand | 1 | 2,500 horsepower | 175/350 rpm |

making a total connected load of 22,500 horsepower for finishing stands.

These 22,500 horsepower of d-c motors, together with the 4 3,000-kw generators, form an extremely heavy concentration of d-c power on the 600-volt d-c bus. In the case of a short circuit on this bus, there would be developed a current in the nature of 300,000 amperes, which would produce an estimated separating force of several tons per running foot for ordinary bus spacing. Since the force is inversely proportional to the distance between the busses, this installation was made with busses placed at several times normal spacing. The positive and negative busses were placed on opposite sides of the bus room, to give this wide spacing. Aluminum channel, placed back to back, was used to increase the lateral stiffness and in addition, the bus was firmly braced against the walls of the room. Each motor and generator and the 600-volt bus to the variable-frequency room are tied to the main bus through 2 single-pole high-speed d-c circuit breakers, incorporating the "rate of rise" feature of instantaneous trip on direct short circuits. These breakers are located in both the positive and negative legs of each machine and spaced on opposite sides of the room each being firmly braced to the back walls. This entire construction of bus, circuit

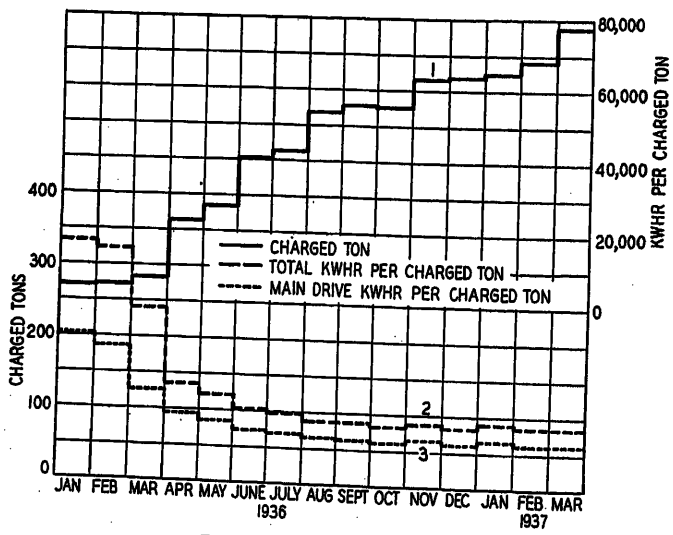



**Figure 9. Hot-strip mill**

breakers, and feeder bus was designed to withstand heavy short-circuit stresses.

The d-c motors and generators are connected to the bus at zero voltage and motors brought up to speed by building up the generator voltage by the use of a motor-operated potentiometer rheostat. Each individual motor is adjusted to the required speed by weakening or strengthening the field of the motor with the use of a motor-operated coarse rheostat and a hand-operated vernier rheostat, both located in the mill pulpit *C*, from which point the finishing-mill motors are controlled. Six meters, calibrated in horsepower, are located in the face of *C* pulpit, in view of the roller, to indicate load on the 6 finishing stands.

A great deal of heat is generated through the heavy loads imposed on the main drive equipment. To dissipate this heat a recirculating system of ventilation is provided. The finishing-mill motor foundations are so arranged that all 6 motor pits are connected with each other forming a tunnel, closed on each side and open at the ends. The 2 6,000-kw motor-generator sets, located

directly across the room have a similar layout in the foundation arrangement. The rotating motors and generators pick up cool, clean air in the motor room by their natural fan action, which ventilates the machines and is then discharged into the foundation tunnel. At each end of these 2 foundation tunnels is a surface cooler through which the heated air from the machines must pass, to be recooled to normal temperature. A blower is located near the discharge of each of these coolers, the sucking action of which draws the air through the coolers and discharges it into the motor room for recirculation. As the 4 blowers are not connected direct to the coolers, any one of the units can be shut down without affecting the coolers. Under normal operation the blowers operating depends upon the temperature in the motor room. To offset air losses, as well as to maintain a slight positive pressure in the motor room, makeup fans are provided at each end of the room. These fans draw fresh air from the outside, through a filter cleaning equipment and discharge it into the motor-room basement.

The 2 hydraulic spray pumps are driven by 2 1,000-horsepower 6,600-volt wound-rotor induction motors, the pumps deliver 1,000 gallons per minute at 1,000 pounds pressure to the spray nozzles.

The cold-mill substation contains the motor-generator sets and auxiliary units for driving the tandem and skin pass mills. A 3-unit 6,000-kw motor-generator set, duplicate of the hot-mill main drive sets, is provided to furnish 600-volt direct current to the 76-inch tandem mill from one generator to the 54-inch tandem mill from the other generator. A 2,500-kw motor-generator set driven by a 3,750-horsepower 6,600-volt synchronous motor, direct connected to 2 1,250-kw 600-volt generators, furnishes power to the 2 76-inch skin pass mills. A 1,300-kw motor-generator set driven by a 2,000-horsepower 6,600-volt synchronous motor, is direct connected to 3 generators. Two of these generators are 500-kw 300-volt capacity and one generator is 300-kw 250-volt capacity. The 2 500-kw generators are normally connected in series to provide 600 volts to drive the 90-inch skin pass mill. However, they can be connected in parallel to provide emergency 250-volt direct current for plant auxiliaries at reduced capacity. The 300-kw generator furnishes power to drive the 54-inch skin pass mill. The ventilating scheme of the substation is duplicate of the hot-mill motor room, described earlier in this paper.

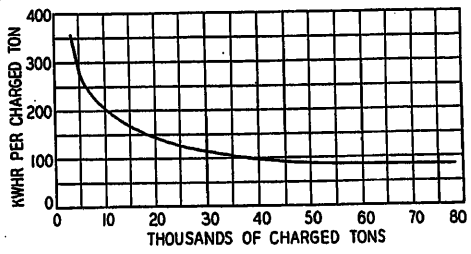



**Figure 10. Hot-strip mill**

A bus tunnel is provided to connect the cold mill substation with the various cold-mill control rooms, which are located in the basement. The top of this tunnel houses the bus runs between the generators and the tandem and skin pass mill motors and the tunnel proper is used to provide makeup air for the ventilation of the cold-mill drive motors. The makeup air equipment consists of an air washer and blower located at the end of the tunnel, the blower discharging into the tunnel to maintain a slight positive pressure in the tunnel and control rooms. Each of the cold-mill drive motors has its own recirculating ventilation system, taking air from the tunnel, circulating it through the motors and coolers to discharge into the tunnel again. In this manner, each motor is cooled with fresh clean air.

The d-c auxiliary power for both hot and cold mill is supplied by 2 1,500-kw motor-generator sets, each driven by a 2,100-kva 6,600-volt 500-rpm 80-per-cent-power-factor synchronous motor with 250-volt d-c field excitation from the d-c end. The motor is designed for full-voltage starting, requiring 500 per cent kilovolt-ampere inrush, in terms of normal rating. The generator is rated 1,500 kw at 250 volts, and is self-excited and flat compound wound. The 2 generators are arranged to operate in parallel, but only one set is required to furnish both hot- and cold-mill power.

The 2 1,500-kw generators tie into the 250-volt bus through 2 8,000-ampere single-pole 600-volt air circuit breakers, each equipped with overload, under voltage, and reverse-current features. The d-c power is fed into the various sections of both hot and cold mill over 6 feeder circuits, each connected to the bus with a 4,000-ampere single-pole 600-volt air circuit breaker with inverse time overload protection.

The a-c auxiliary power is supplied by 3 1,000-kva 6,600/440-volts ingle-phase 25-cycle air-cooled transformers connected delta-delta. The power is distributed to the mill over 3 3-phase circuits, each protected with a 1,600-ampere 3-pole 600-volt air circuit breaker.

The entire lighting for the mill is supplied by a bank of 3 500-kva 6,600/440-volt single-phase 25-cycle air-cooled transformers, connected delta-delta. The primary side of this bank is connected in parallel with the primary side of the power transformers, and both are fed through a common oil circuit breaker from the station bus. The

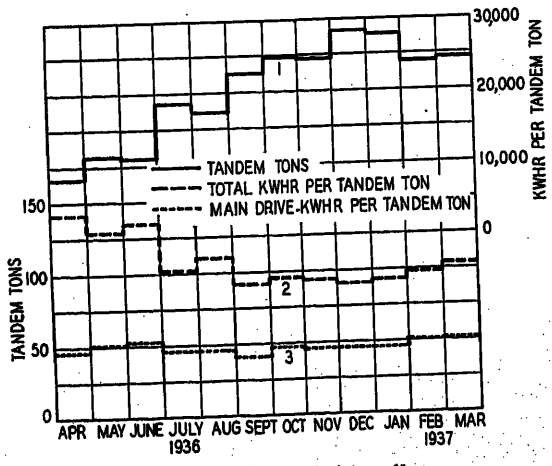



**Figure 11. Cold mill**

secondary side of this bank feeds through a 4,000-ampere 3-pole 600-volt air circuit breaker, to the various distribution points throughout the mill. At these points, the 440-volt power is stepped down to 3 phase, 110-volts, through $7\frac{1}{2}$- and 10-kva single-phase oil-insulated air-cooled transformer banks, to sectionalized 110-volt feeder circuits.

The overhead lighting consists of 300 porcelain-enamel reflectors, 225 silver-backed glass reflectors with steel covers, and 450 prismatic glass reflectors with spun-on steel covers. All of these units are of the high-bay type of 750 watts capacity. The low-bay lighting, control house and pulpit lighting, and various scattered units, consists of over 700 units, varying in capacity from 50 to 500 watts. The tunnel lighting consists of 220 units, built into the side walls, each of 200 watt capacity.

### Summary of 6,600-Volt Connected Load

| | Kilovolt-Amperes |
|---|---|
| Number 1 scale breaker | 860 |
| Number 1 stand | 2,650 |
| Numbers 2, 3, 4 stands | 7,260 |
| Finishing mill—motor-generator sets | 14,400 |
| Spray pumps | 1,640 |
| Auxiliary motor-generator sets | 4,200 |
| Cold-mill motor-generator sets (1) | 7,200 |
| (2) | 3,110 |
| (3) | 1,660 |
| Power transformers | 3,000 |
| Lightning transformers | 1,500 |
| Total | 47,480 |

### Summary of Total Connected Horsepower

| | Number | Horsepower |
|---|---|---|
| Motors—hot mill | 1,407 | 81,550 |
| Generators—hot mill | 24 | 23,850 |
| Total—hot mill | 1,431 | 105,401 |
| Motors—cold mill | 514 | 35,050 |
| Generators—cold mill | 18 | 13,675 |
| Total—cold mill | 532 | 48,725 |
| Total installed units | 1,963 | 154,126 |

All of the above units are controlled by 350 2-pole 60-ampere 110-volt circuit breakers with overload protection, enclosed in cast iron case. These breakers are fed from the sectionalized 110-volt lighting busses.

To give a more comprehensive picture of the power requirements of this hot- and cold-strip mill, the following curves have been plotted to graphically show the relation between the kilowatt-hours, the kilowatt demand, and tons charged.

(Figure 7) top curve shows the kilowatt-hours consumed by the total Lackawanna plant for 1936 and the first quarter of 1937, including the strip mill, while the bottom curve shows kilowatt-hour consumption of the strip mill alone for the same period. The top curve shows the gradual increase in kilowatt-hours for the total plant from 13,200,000 kilowatt-hours in February 1936 to 32,578,000 kilowatt-hours in March 1937 and corresponding to this increase in total energy consumed, the strip mill, starting in January 1936, used 1,600,000 kilowatt-hours, gradually increasing to 9,256,000 kilowatt-hours in March 1937, or approximately 28.4 per cent of the total plant power, which averages 1,050,000 kilowatt-hours per day.

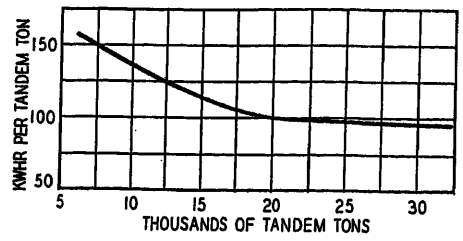



**Figure 12. Cold mill**

Figure 8 shows the maximum 15-minute monthly demand for the total plant and the maximum 15-minute monthly demand for the hot- and cold-strip mill. The total plant demand has increased from 32,000 kw in February 1936 to 61,140 kw in March 1937. The maximum demand for the strip mill has gradually increased from 15,000 kw in May 1936, the first month that the demand meter was installed, to 22,680 kw in March 1937. This demand has gradually increased with the increase in tonnage rolled.

(Figure 9) curve 1 on this graph represents the charged tons which have gradually increased from 4,000 tons, the first month of rolling, to 77,800 tons in March 1937. Curve 2, showing total kilowatt-hours per charged ton, has gradually decreased from 333 to 85 kilowatt-hours per ton. Curve 3 shows the kilowatt-hours per charged ton for the main drive, and represents that part of the total power used by the main drive motors, and the difference between curves 2 and 3 represent that part of the total power used by the auxiliary equipment. The main drive equipment uses approximately 75 per cent of the total power and the auxiliary equipment uses approximately 25 per cent.

Figure 9 shows that the total kilowatt-hours per ton remains approximately constant above 55,000 tons. However, below 55,000 tons, the curve begins to rise at an increasingly rapid rate. Figure 10 shows a curve plotted between charged tons and kilowatt-hours per charged ton and confirms the above statement.

In analyzing the tandem tons rolled in the cold mill, (figure 11), it will be noted that the total kilowatt-hours per ton, curve 2, has decreased from 143 to 92, as the tandem tons, curve 1, increased from 8,000 to 28,000 tons. Further, it will be noted that the kilowatt-hours per ton for the main drive equipment remained almost constant at 49 kilowatt-hours per ton, while the variation in total kilowatt-hours per ton to the mill occurred in the auxiliary drive equipment. The cold-mill main drive equipment uses approximately 53 per cent of the total energy and the auxiliaries, approximately 47 per cent, and the kilowatt-hours per ton for the cold mill remain almost constant above 22,000 tons, but rises sharply as the tonnage decreases. Also, the curve in figure 12, plotted between tandem tons and kilowatt-hours per tandem ton, flattens out at 22,000 tons, indicating approximately a constant value of kilowatt-hours per ton above this tonnage.

# Some High Lights in the Use of Electricity in Steel Mills

By GORDON FOX
MEMBER AIEE

## Synopsis

Approximately one tenth of the investment in the American steel industry is in electrical plant. The power consumption of steel mills is increasing. About two thirds of the power used is generated within the plants but there is a trend toward increased purchase of power.

Electricity is gaining a foothold in the field of transportation through the Diesel-electric locomotive.

D-c motors are being used more for main-roll drives. Synchronous motors are also gaining favor. Reversing drives have developed interesting ramifications.

There is a trend toward subdivision of main roll drives. The combination of reduction gears and mill pinions into a single unit is of interest. The use of new types of bearings affects power requirements.

The concentration of d-c power associated with the main-roll drives of wide strip mills has introduced problems concerning interrupting capacity of circuit breakers and strength of bus installations.

In the field of auxiliary drives, the increased application of small individual induction motors is notable.

Electrical precipitation finds greater acceptance in the field of gas cleaning.

Electric melting furnaces supply a small but growing increment of total steel production. High-frequency heating is finding some uses. New types of electric furnaces are being installed for heat treating and annealing operations.

NOT SO MANY years ago electricity played but a minor part in the steel industry. It has gained rapidly and steadily in importance. Today, in a total investment on the order of $5,000,000,000 represented by the American steel industry, more than $500,000,000 is involved in electrical plant. Considering a typical steel plant as a whole, about 10 per cent of the total investment is electrical.

The relationships between electrical plant and total investment are indicated by the approximate figures shown in table I.

The cost of materials is the major element in the cost of producing steel. The cost of electric power is a minor element. In the iron- and steel-producing departments, the cost of electric power is generally not more than 5 per cent of the total conversion cost. In the rolling mills, the cost of electric power commonly amounts to about 10 to 15 per cent of the conversion cost. Although relatively a minor item, in an absolute sense the amount of electric power consumed and the cost thereof are substantial figures.

The installed capacity in main-drive motors in American steel mills is nearly 3,000,000 horsepower. The capacity of main and auxiliary drives combined approaches 8,000,000 horsepower. The installed generating capacity driven by prime movers amounts to about 1,250,000 kw. The present annual power consumption of the industry is about 7,000,000,000 kilowatt-hours. All American public utilities combined generated in 1934 about 95,000,000,000 killowatt-hours.

The rate of power consumption of American steel mills is increasing for several reasons:

1. Mills are becoming more fully electrified.
2. New applications of electricity are being developed.
3. The character of product is changing.

In 1926, about 20 per cent of the rolled product was represented by heavy sections such as rails and structurals, which involve only a moderate amount of work per ton due to moderate elongation in rolling. The total power represented in a ton of rails is about 100 kilowatt-hours. Today less than 15 per cent of the finished product leaves the mills in these heavy shapes.

Such products as sheets, strip, tin plate, and wire rod require relatively large amounts of power for rolling. A ton of sheets or rods may represent an accumulated expenditure of more than 200 kilowatt-hours of power. In 1926, about one third of the product took these forms. Today about two thirds is so rolled.

Approximately two thirds of the power consumed in our steel plants is generated in their own power plants. About one third is purchased from utilities.

The figures for 1929 are approximately as follows:

| | |
|---|---|
| Electric power purchased from public utilities | 3,500,000,000 kilowatt-hours |
| Electric power generated by prime movers in steel plants | 6,000,000,000 kilowatt-hours |
| Total use of electric power | 9,500,000,000 kilowatt-hours |

Table I

| Unit or Department | Per Cent Investment Represented by Electrical Plant |
|---|---|
| Coke ovens, blast furnaces, and steel making (open hearths) | 5 |
| Mills, average | 15 |
| Power and blowing plant | 25 |
| Total plant average | 10 |
| Modern wide strip mill (hot) | 25 |
| (cold) | 10 |
| (total) | 20 |

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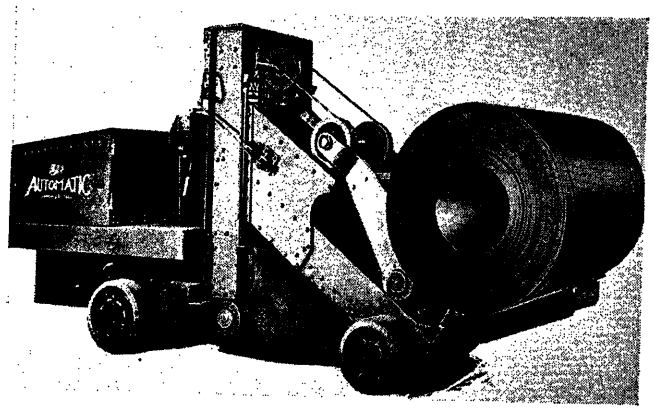



**Figure 1. Industrial truck handling 8-ton coil of strip**

The steel industry is probably the largest industrial consumer of electric power. However, because of the large amount of power generated in its own plants, it is only on an approximate par with 3 other industries as a purchaser of electric power from utilities. The big four are the steel industry, chemical industry, food products, and printing.

The trend, in the steel industry, is toward purchase of a greater amount of power, both in absolute and in relative sense. Three factors which encourage this trend may be mentioned:

1. Large increases in power demand are generally associated with installation of heavy mill equipment involving large expenditures. Additional simultaneous investment for power generating plant may be undesirable.

2. The increase in power consumption per ton of rolled product results in a decrease in the amount of available by-product fuels relative to the power load. Moreover, by-product fuels are being diverted to process uses where they are more valuable. The availability of by-product fuels for power generation is decreasing both in relative and in absolute sense. Hence, power generation must be based, in increasing degree, upon purchased fuel.

3. The utilities are encouraging power purchase through more reliable supply and through development of contracts suited to the special requirements of the steel mills.

4. The applications of electricity in steel mills are so varied in character and have so many ramifications that it is possible, in a brief discussion, to touch upon only a few features, selected somewhat at random, but with a view to developments of recent years.

## Modernization of Generating Stations

A number of steel plants have taken steps toward modernization of their existing power plants, involving the installation of new high-pressure boilers and topping turbine generators exhausting into the existing steam mains. This practice has permitted modernization of boiler plants, increase in generating capacity, and improvement in economy to be accomplished at minimum expense. The resulting plants compare favorably in performance with those of the public utilities.

## Steam Drives

Although electrification in steel plants is very general, steam drive is still retained for a few classes of equipment. Most notable are coke-oven exhausters and gas boosters and blast-furnace blowers. Exhausters are steam driven because of the nicety of speed regulation required, and because the exhaust steam is needed for process uses. Gas boosters are quite large units, well suited in speed requirement to turbine drive. Centrifugal blast-furnace blowers continue to be driven by steam turbines because of ease and perfection of speed control and also because they excel, both in over-all economy and in first cost, any method of electric drive yet proposed. Moreover, involving less steps of transformation, they are more reliable than would be motor-driven units supplied by turbine generators.

In the Buffalo district, where power is exceptionally cheap, a motor-driven centrifugal blast furnace blower has been installed. The drive is a 2-pole synchronous motor. Control of pressure and volume is by a device, termed a power wheel, which throttles the inlet pressure by means of a set of adjustable vanes somewhat akin to the vanes of a water wheel. The velocity imparted to the intake air in throttling is partially converted into power in the first stage of the compressor intead of being dissipated in eddies, as by an ordinary damper. Good regulation of volume is obtained. The equipment is quite simple. The efficiency is comparable with that which might be obtained with a wound-rotor motor drive using secondary resistance control.

## Transportation

Another field in which electricity has not made great inroads is that of transportation. There are a few individual runs in steel plants where electric locomotives or cars are employed. Both overhead and third-rail systems are represented. But there is, I believe, no steel plant in this country which has a completely electrified transport system. The principal deterrent rests in the

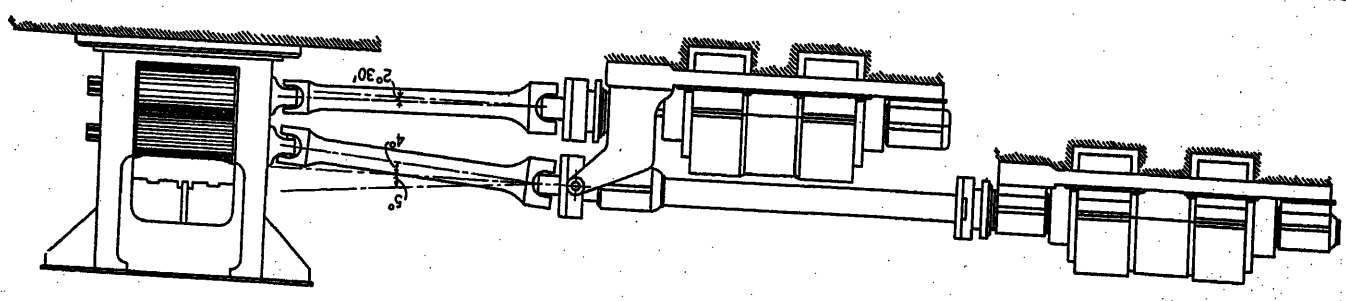



**Figure 2. Twin-motor reversing drive**

ections to either overhead or third-rail systems of ply.

The Diesel-electric locomotive has made its debut in the l plant, where it is used for switching purposes. It is tively high in first cost but it is faster in operation and operating costs and maintenance costs are substanly lower. For some classes of service its use appears to well warranted.

There has recently been put into service at one of the nts in the Chicago district a gas-electric locomotive ton, 500 horsepower) using butane as fuel. This unit broadly comparable in first cost with the gasolinetric unit and comparable in operating cost with the esel-electric type.

Another field of transportation in which electricity is ying an important part is the industrial truck. These cks are finding considerable use in the finishing departnts of strip mills and wire mills, for instance. Storagettery units and so-called "ready power" units employing gasoline-engine-driven generator as the power source are th popular. Figure 1 shows a truck handling one 8-ton il of strip.

## onnected Load and Power Consumption

In a typical steel plant the large main-drive motors at e rolling mills represent less than half of the total inalled motor capacity. They have a higher load factor an the auxiliary drive motors, however, and are therere responsible for a greater relative share of the power nsumption. Table II shows typical relationships.

D-c auxiliary drives are used mostly on cranes, roller bles, and manipulating devices which are subject to

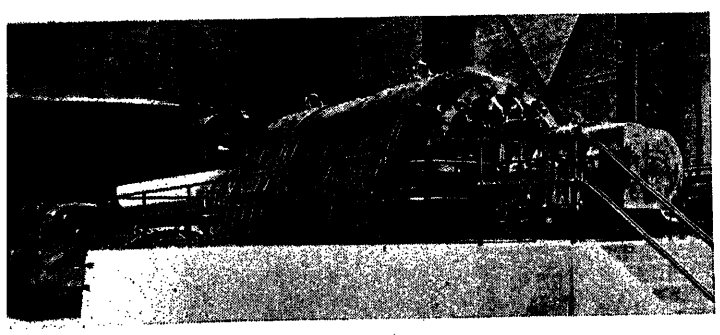


**Figure 3. Twin-motor reversing drive**

much starting and stopping, but which have substantial dle periods. Their load factor is very low. A-c auxiliries include many pumps, fans, conveyors, and similar ontinuously running drives. Their load factor is quite igh.

## The Trend in Main-Roll Drives

Over a period of years, the application of motors to main-roll drives has changed in a number of respects. The changes are more or less interrelated but may be discussed separately.

Formerly the a-c motor prevailed. Today the d-c motor holds foremost place. In 1928, about 40 per cent of the main roll drive motors sold were for alternating current, 60 per cent were for direct current. In 1936, only 13 per cent were a-c motors and 87 per cent were d-c motors.

D-c main-drive motors are being so generally adopted because of their controllability, as for reversing drives, and because of their ability to meet adjustable-speed requirements. Adjustable speed is more and more commonly

**Table II. Motor Capacity and Motor Load—Typical Steel Plant**

| Class of Motors | Per Cent of Total Installed Capacity | Per Cent of Total Motor Load |
|---|---|---|
| Main-roll drives | 37 | 55 |
| D-c auxiliaries | 50 | 20 |
| A-c auxiliaries | 13 | 25 |

demanded, partly for reasons of flexibility and greater precision of rolling, partly because of higher rolling speeds, and partly because more modern continuous and semicontinuous types of mills, with stands in tandem, introduce requirements which were not met in the earlier layouts using Belgian roll trains.

There has been a trend toward individually driven roll stands or subdivision into small groups as contrasted with the older practice in which one or two large motors drove a whole mill. Some of the reasons have been higher speeds, greater capacities, greater operating flexibility, greater flexibility of layout, mechanical simplification.

In a-c drives, there has been a trend away from the induction motor and toward the synchronous motor as will be discussed at greater length a little later.

In general, the trend has been in such direction as to increase greatly the cost of main roll drive equipment.

## Reversing Drives

Reversing motors have been used for many years to drive blooming mills, roughing mills, plate mills. Somewhat more recent is their application in tandem on slabbing mills and beam mills. In a slabbing mill, for instance, 2 sets of rolls work on the piece simultaneously. The horizontal rolls reduce its thickness; the vertical rolls restrict or reduce its width. These 2 sets of rolls are driven by separate reversing motors. These motors must accelerate, run, decelerate, and reverse in unison. The relative speeds must be different in the forward and in the reverse direction of travel. This is accomplished by feeding both motors from the same generator or generators, using variable-voltage control. The relative speed of the vertical roll motor is changed, for the 2 directions of travel, through change of the field strength of that motor.

There are installed in one plant in the Chicago district 2 very interesting reversing motor drives designated as double motor drives. Each roll in the 2-high reversing

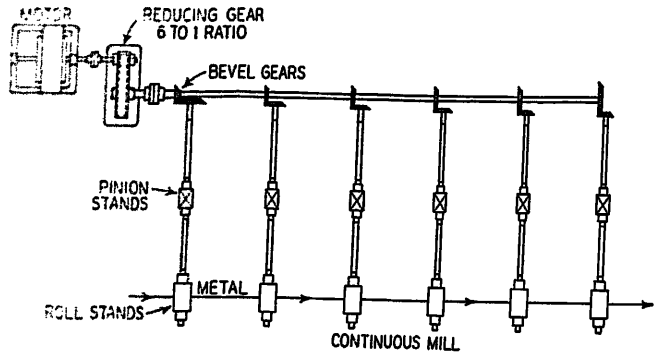



**Figure 4. Group drive through lay shaft and bevel gears**

mill is driven by a separate 5,000-horsepower motor. The driving spindle for the upper roll passes over the motor which drives the lower roll. The use of the twin motor is dictated, in a large measure, by mechanical considerations. The construction of a 10,000-horsepower motor at 40 rpm base speed within limits of size feasible for transport and erection, would be difficult. The manufacture of suitable mill pinions would also be difficult. The twin motor affords substantial advantage due to its relatively low inertia, resulting in a "lively" mill. It eliminates the necessity of matching roll diameters. Omission of the pinions reduces friction losses and eliminates a source of back-lash and noise.

It has long been customary to employ Ilgner-type motor generator sets for supplying direct current to reversing motors. Flywheels were provided. To drive these sets, wound-rotor induction motors were used, in conjunction with liquid slip regulators. This is still the accepted practice for blooming mills, slabbing mills, sheared plate mills, etc., where the load is heavy and passes are short and of brief duration and the load is consequently very peaked. In a few recent instances a synchronous motor has been substituted for the wound-rotor motor of the set and the flywheel has been omitted. This practice is only feasible for mills having relatively long passes. Even then the power fluctuations are so severe that they can be permitted only on a large power system. Where applicable, the synchronous motor drive has advantage in first cost, efficiency, power factor, and sustained speed as well as in greater simplicity.

A relatively new field for reversing drives is found in both hot and cold strip mills. These mills involve not alone the main reversing motor, but also the drives for the coiling reels upon which the strip is alternately wound and unwound as the mill reverses its direction of rolling. The reel motors must reverse and the speed must increase and decrease in unison with speed changes of the main reversing motor; in addition, they must compensate automatically for the varying diameter of the coil as it builds up or runs off the reel.

## Synchronous Motors

Ten years ago there were very few synchronous motors in use in the steel industry. They were applied only to drive motor-generator sets and for occasional pumps or blowers. Today they are widely used for main roll drives. Perhaps more commonly they are applied to groups of stands. In many instances, however, they drive single stands. In very few instances are the starting requirements of main roll drives difficult for synchronous motors to meet. More exacting, perhaps, are the severe peak loads of brief duration sometimes experienced. The synchronous motor is now the normal selection for constant-speed main roll drives except where flywheels are required. Incidentally it may be remarked that flywheels are not now used as generally as they once were.

An interesting application of synchronous motors is that in which stands or pairs of stands in tandem, in continuous relationship, are driven by separate motors. The synchronizing power of the motors causes the rolls in the several stands to retain their speed relationship as effectively as if they were driven from a common line shaft. Figure 4 shows the former prevalent practice, employing a single drive motor with line shaft and bevel gears.

Figure 5 shows the newer practice employing subdivided drive and herringbone gearing.

The number of synchronous motors connected to steel-plant systems is increasing, not alone because of their more frequent use for main roll drives and for driving accessory equipment but also because of the great increase in motor-

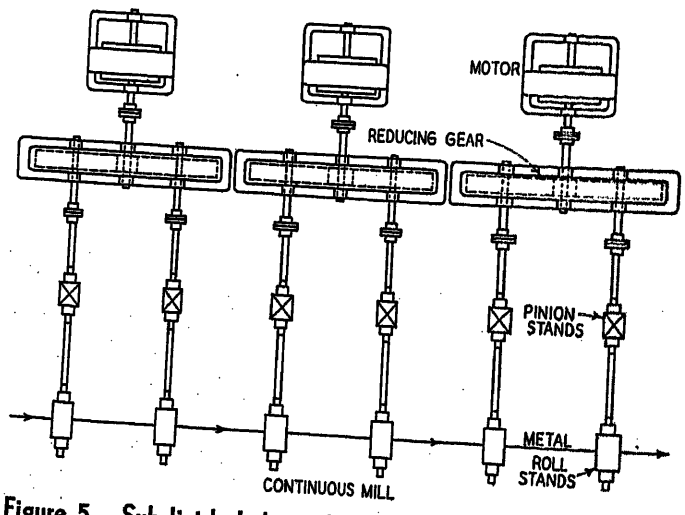



**Figure 5. Subdivided drive through helical or herringbone gears**

generator capacity occasioned by the increased adoption of adjustable-speed d-c drives.

Most of the synchronous motors initially used in steel mills were rated on 80-per-cent-power-factor basis. They were overexcited and were utilized for power-factor correction. Due to the substantial increase in synchronous equipment in use, the need for power-factor correction has diminished. It is not desirable to operate 80-per-cent-power-factor motors with much less than their full excitation lest they be deficient in pull-out torque. Hence, more motors rated on 90- to 100-per-cent-power-factor basis are being selected.

## D-C Drives

Adjustable speed is being provided to an ever-increasing extent for main roll stands. The d-c motor at 600 volts is practically standard for this service. Figure 6 shows a 4,500-horsepower 125/250-rpm motor of this type such as is applied to the finishing stands of a hot wide strip mill. This is representative of the maximum size attained by motors of this type. These motors are usually started by connecting them at standstill to the supplying generator or generators at zero voltage, then building up the voltage as the motors accelerate. Because of the large motor capacities involved, it is usually necessary to operate several generators in parallel to supply the direct current. Several schemes have been tried to obtain satisfactory parallel operation of these generators and, at the same time, to secure a closely maintained operating voltage. One of these schemes involved interconnected cumulative and differential series windings. It is now prevailing practice to use simple shunt-wound generators or to provide a slight differential winding to give a drooping voltage characteristic, thereby insuring satisfactory parallel operation. Generators of this type may be paralleled at zero voltage. The voltage of all units may then be built up in unison, thereby starting all the driven motors at once. When the motors attain full speed, all is in readiness for rolling. It is no longer necessary to start the motors by building up the voltage of one generator and then to parallel with the other generators before the load is applied.

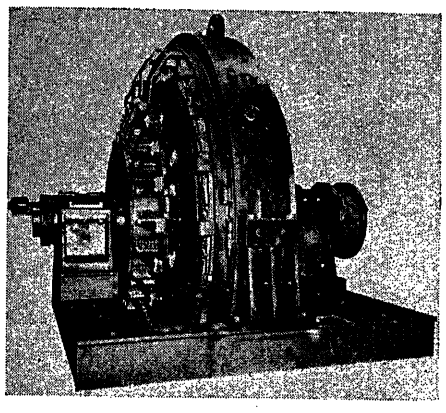


**Figure 6. Adjustable-speed d-c motor**

When generators with drooping voltage characteristics are employed, a voltage regulator is provided to maintain constant operating voltage. This functions in connection with an exciter which is common to the fields of all of the generators operating in parallel; see figure 7.

D-c reversing motor drives are an exception to this practice. When 2 or 3 generators are paralleled to supply a single reversing motor or combination of motors, interconnected differential and cumulative field windings are generally used to insure division of load among the generators, even under severe load changes; see figure 8.

## Cold-Rolling Mills

In final cold rolling of coils of annealed strip in a so-called skin pass, it is advantageous to maintain tension upon the piece while it is being compressed between the main rolls. It is also desirable that different amounts of tension be independently maintained in the process of unwinding the coil from one reel and in winding it upon another reel. In a recent design of skin pass mills, pinch rolls are installed between the unwinding reel and the mill stand being entered; a similar pair of pinch rolls is located on the delivery side of the mill ahead of the reel upon which the coil is wound. These pinch rolls are controlled to maintain the most advantageous drag and pull tensions in the strip on the entering and delivery sides of the main rolls. The unwinding and winding reels, in turn, are controlled to maintain suitable values of drag and pull tension in the strip between these respective reels and the adjacent pinch rolls.

These tensions are governed by field control responsive to current, which determines the tension. The speed of the mill as a whole can be varied, without disturbing the relationships of the individual elements, by variation of the voltage of the generator which supplies all drives in common.

The ability to control the tension as well as the rolling pressure appears to be an important contribution to the art of cold rolling steel.

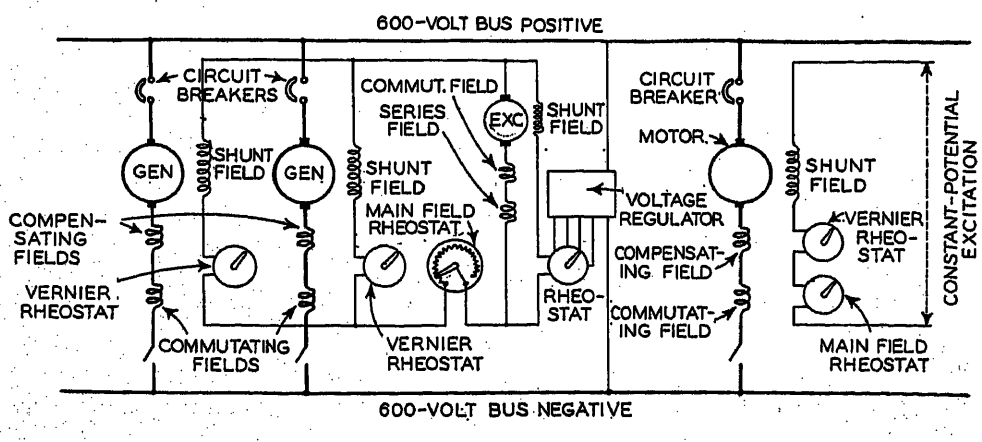



**Figure 7. Parallel operation of shunt generators supplying adjustable-speed motors**

## Combination Gear and Pinion Stands

While discussing main roll drives, mention should be made of recent practice in which the motor speed reducing gear or the train of helical or herringbone gears, through which the motor drives, is combined with the mill pinions in a single unit. Such an arrangement results in compactness and rigidity.

## Bearings

As a development affecting motor drive practice, we should mention the increasing use of roller bearings, composition bearings, and precision type oil-lubricated bearings in connection with mill rolls. These bearing types have resulted in reductions of rolling power in amounts ranging from 10 to 50 per cent, depending upon the type of mill, the product being rolled, and the particular conditions of the case.

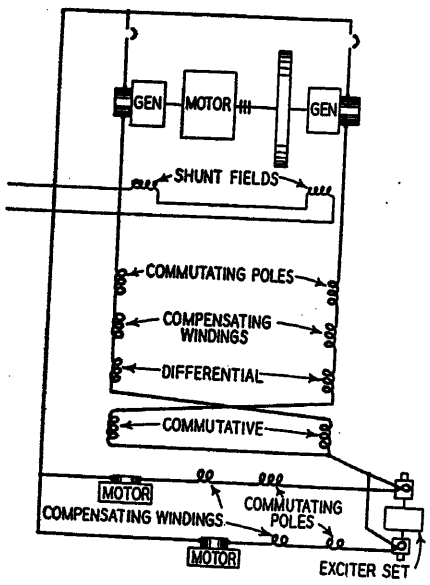



**Figure 8. Parallel operation of cumulative - differential compound-wound generators**

## Concentrations of D-C Power

Wide strip mills usually have about 6 finishing stands, each individually driven by a motor of 2,000- to 4,000-horsepower capacity. This is a substantial aggregation of motors. See figure 9. The combined full-load rated current on a common bus connecting such a group of generators and motors may be on the order of 30,000 to 40,000 amperes. Perhaps 15,000 kw of d-c generators will be connected to such a bus. The motors may total the equivalent of 20,000 kw. Due to their flat regulation characteristics, these motors can and will act as generators almost instantly. In the event of a short circuit on such a system, the amount of fault current which can flow is tremendous. It amounts to several hundred thousand amperes, and experience, in the matter of damage done, indicates that it has plenty of wrecking ability. Very substantial bus construction using structural shapes is essential. The positive and negative busses are well separated to minimize magnetic stresses. Circuit breakers must be reinforced to prevent being bent out of shape by magnetic forces. Circuit breakers have been recently developed for this work which, under test, have ruptured successfully 70,000 amperes of direct current (as much as it is possible to provide for test purposes). These circuit breakers have ruptured successfully under test as much as 400,000 amperes at 60 cycles. The time of interruption is about 3 cycles.

An interesting development in connection with these large circuit breakers is a feature which causes them to trip particularly quickly in case the rate of increase of current is rapid, as when a severe short circuit occurs. This is accomplished in the following manner: The section of bus connecting to the circuit breaker is divided into 2 parallel paths. One path is surrounded by a laminated steel yoke. The series trip coil of the circuit breaker is interlinked with the other path. Normally the current flows equally or proportionally through the 2 paths. Only a portion of the current through the breaker passes through and acts upon its trip coil. However, when a short circuit occurs and the current rises quickly, most of the current flows through the low reactance path which is not surrounded by the steel yoke. As a consequence of this action, most of the current flowing through the breaker passes through and acts on its trip coil and causes it to trip more quickly than it would in the case of gradually applied load of equal value.

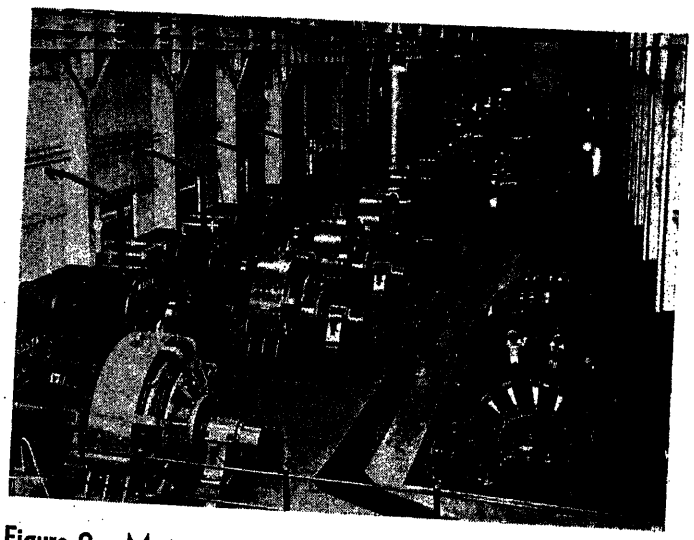


**Figure 9. Motor room, wide strip mill, Youngstown Sheet and Tube Company**

## Auxiliary Drives

It has long been the practice to equip the main tables, side guards, manipulator and screw-down mechanisms of blooming mills with mill-type motors and magnetic controllers supplied from a 230-volt d-c system. In a recent installation, individual generators are provided to supply

the respective drives and Ward-Leonard variable voltage control is employed. This arrangement results in somewhat faster action together with closer speed control over a wider range. Since approximately half of the total rolling time of such a mill is consumed in reversing and manipulating the ingot between passes, expedition of these functions may have an appreciable influence upon output. This is increasingly true in view of the higher percentage of slabs now being rolled in many such mills.

A notable recent development in auxiliary drives is the extensive application of individual small squirrel-cage induction motors to table rollers, coilers, sheet mill lifting tables. In a single mill recently constructed there are some 900 of these motors; see figure 11.

For individual table-roller drives, the adjustable-frequency system of speed control is commonly employed. The table drive motors are supplied from a-c generators which, in turn, are driven by adjustable speed d-c motors. A speed range of 3 or 4 to 1 is common.

In some cases it is necessary that these tables reverse frequently. If the table drive motors were plugged from full speed, they would draw very heavy currents from the generators supplying them and they would also overheat due to the large rotor losses incident to plugging. To avoid these difficulties, the table-drive motors are first

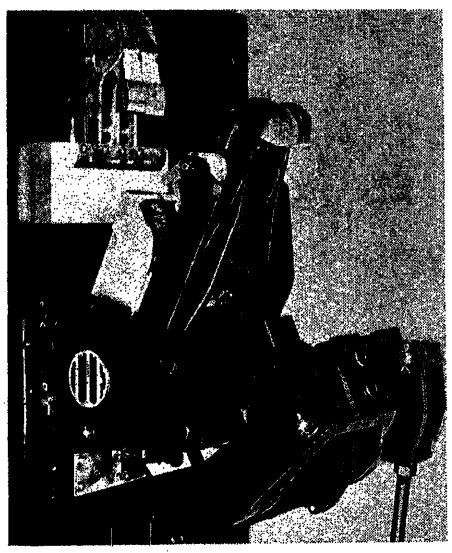


**Figure 10. D-c circuit breaker**

slowed down by reducing the frequency to a low value. They are then plugged, from low speed in one direction to low speed in the other direction. They are then accelerated by increasing the frequency. By this means most of the deceleration and acceleration of the table drive motors takes place with the motors operating with running characteristics, that is, with small values of slip. Only during a small part of the reversing cycle do the motors operate with starting characteristics, that is, with large values of slip.

In the operation of the coilers, the mechanisms which coil the flat product emanating from a wide strip mill, frequent starting and stopping is involved. The coilers are not reversed but it is desirable to stop them quickly and accurately. The simplest possible mechanism involves the use of several separate motors of small horsepower; see figure 12. The most successful control to meet these requirements employs dynamic braking. The motors are of squirrel-cage induction type. They are supplied with power at adjustable frequency in the general manner previously described. To stop them, the frequency is first reduced, then the primary windings are disconnected from the a-c supply, and direct current at low voltage is applied to these windings. This direct current is obtained from a small motor-generator set.

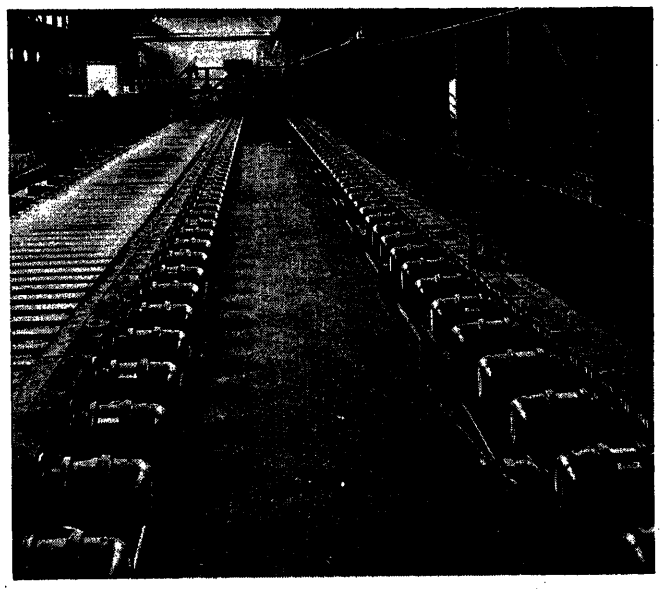


**Figure 11. Individual roller-table drives**

## Water-Cooled Motor

Small induction motors have been applied to a number of drives which involve very frequent starting, stopping, and reversing. The load is comprised largely of inertia. Squirrel-cage motors can be made with very light rotors. When 40 starts per minute, or perhaps more, are involved, it becomes quite a problem to dissipate the heat generated in the motor. To use a larger motor does not help much since the rotor inertia increases and the load increases likewise. For such cases a water-cooled motor has been developed and tried with considerable success; see figure 13.

## A-C Switching

Many steel plants have been confronted with problems in distribution and in switching, due to the rapid growth of their a-c systems. In some cases the increased use of synchronous motors has been a factor in increasing the current to be handled in case of short circuit.

In some cases the difficulties have been accentuated by the advent of purchased power from utilities. Because of

the substantial amounts of purchased power involved and the desire for economy and reliability of supply, the connection between the utility generating capacity and the steel plant consuming system is usually a fairly direct one. Consequently the flow of power in case of a fault may be great. It then becomes necessary to employ generally switching equipment of high rupturing capacity, or to devise compromises using group breakers or reactors in order that existing equipment may be safely continued in service.

In general, it may be said that the switching now being installed is of much higher rupturing capacity and substantially higher cost than in the past. The scheme of distribution and switching to be adopted is therefore deserving of increased consideration.

The advent of deionizing and oil-expulsion types of circuit breakers has been timely in permitting higher rupturing capacities to be attained within existing limitations of space and reasonable limitations of cost. In this connection, it may be mentioned that the high cost of switching has stimulated the use of fewer relatively larger

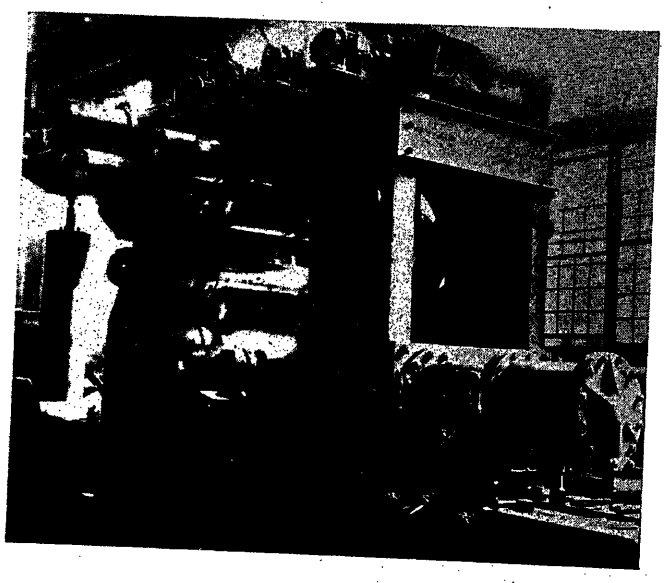


Figure 12. Individual drives for coilers

motor-generator sets and the use of 3-unit sets in which one synchronous motor drives 2 d-c generators.

## Mercury-Vapor Rectification

The first installation of a 250-volt rectifier with grid-control of voltage has recently been made in a steel mill in the Chicago district. The output is used for general d-c supply to wire drawing machinery and auxiliaries.

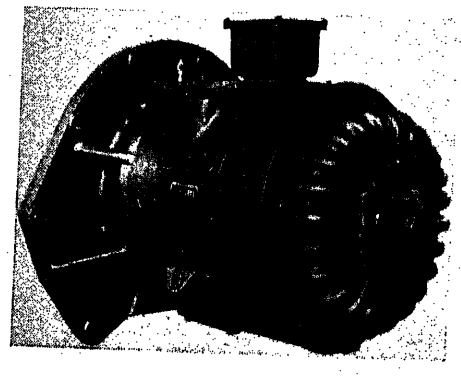
## Electrical Precipitation

Among the newer uses of electricity in the steel mill, electrical precipitation deserves mention. This method has been successfully applied to the removal of tar from coke oven gas. There are now a number of precipitators applied to cleaning blast furnace gas. Attempts to clean this gas in the hot, dry state, preserving its sensible heat, have indicated this method to be too expensive and too sensitive to be generally acceptable. Precipitation has proved to be moderately successful as a method of fine cleaning following wet scrubbing. One deterrent to its more general adoption is the rather high cost of necessary plant.

## Electric Furnaces

Electric melting furnaces and electric heating furnaces are both gaining in popularity. The amount of steel produced in electric furnaces for ingot production is a small percentage of total production. Nevertheless the percentage tends to show steady growth, as indicated by the following figures showing the relationship of the tonnage of ingots produced by electric furnaces as a per cent of total ingot tonnage:

Figure 13. Water-cooled motor



| | |
|---|---|
| 1922 | 0.55 per cent |
| 1924 | 0.61 per cent |
| 1926 | 0.70 per cent |
| 1928 | 0.90 per cent |
| 1930 | 0.78 per cent |
| 1932 | 1.05 per cent |
| 1934 | 1.35 per cent |

Sizeable installations are now being made of electric arc furnaces of the top-charged type for the melting of scrap for production of carbon steels in small ingot sizes. These furnaces involve a substantial increase over previous practice in the ratio of transformer capacity to furnace volume.

The application of high-voltage air-break (deionizing) circuit breakers for electric arc furnace service, involving frequent circuit interruption, is deserving of mention.

The coreless induction furnace is earning recognition as one of the tools of the industry. This furnace comprises essentially an insulated crucible surrounded by a cylindrical coil of copper tubing. Through this coil, current at high frequency is passed, inducing currents in the charge in the crucible. The primary or inducing coil is water-cooled.

This type of furnace is essentially a single-phase load. The frequencies used range up to 5,000 cycles per second,

but 960 cycles is a typical value. The voltage is usually about 1,000 volts. The power factor is inherently very low but is largely corrected by use of capacitors. Due to the high frequency, the cost of these capacitors is not excessive. Power of these characteristics is supplied by special motor-generator sets. The consumption ranges between 600 and 1,000 kilowatt-hours per ton of metal, being comparable with arc furnaces of similar size.

As yet the coreless induction furnace has been built only in small sizes, having capacity of one ton or less. It

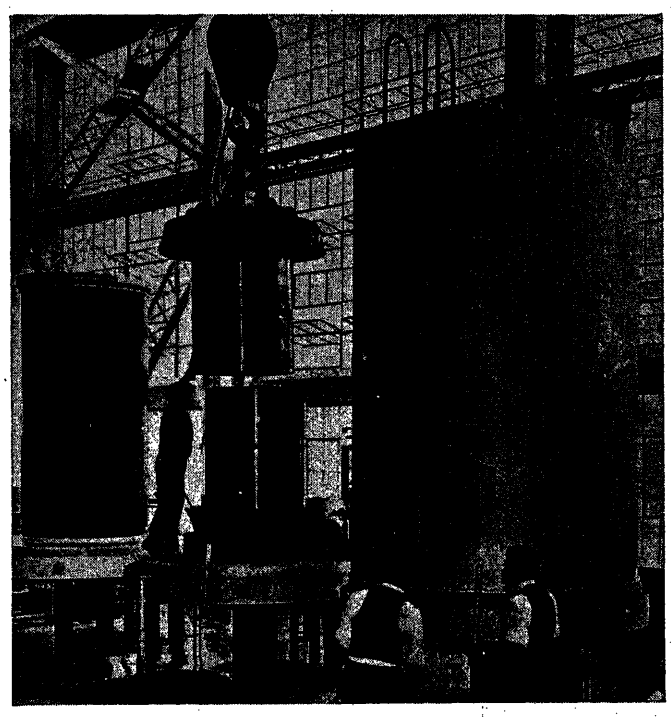


**Figure 14. Bell-type cylindrical annealing furnace**

is probable that larger units will be developed. The principal advantages of this type of furnace are:

1. Freedom of contamination of the charge (absence of electrodes).
2. Very high temperatures attainable since heat is internally generated.
3. Uniformity of analysis and rapid refining due in part to electromagnetic circulation of the charge which brings it into contact with the slag.
4. Ability to melt scraps containing alloys without oxidizing and losing these alloys in the melting process.

The coreless induction furnace is applied principally to production of steels of very low carbon content (such as some magnetic steels); highly refractory alloy melts; tool steels and heat-resisting alloys such as iron, nickel, chromium alloys.

High-frequency heating is being applied to a few lower temperature heating operations, such, for instance, as local annealing at circumferential pipe welds. Development of this field of electrical heating lies ahead of us.

Electric heating for annealing and heat treating operations gains steadily in prominence. Although bulk heat in electrical form is relatively expensive, advantages leading to better product often more than compensate. Better control, better furnace insulation, more advantageous and uniform heat application, less weight of auxiliary equipment heated—these are principal advantages.

Electric heating furnaces take a great variety of forms. Figure 14 shows a recent application of cylindrical bell-shaped furnaces for annealing coiled strip.

Electric heating is being adopted for some controlled-atmosphere furnaces. It is desirable that neither free air nor products of combustion be permitted to contact the metal being heated. The electric resistance furnace is inherently well suited since it is easily made externally gas tight. The direct, unmuffled heat tends to be most uniform and may be distributed to afford favorable temperature gradients for heat flow.

## Electronic Control

While the amount of power used in electronic devices is negligible, they are being adapted and adopted for steel-mill use, and are performing some important control functions. One of the most general applications involves the use of photoelectric tubes for the determination of temperatures of steel during the rolling process, and for such indications as the temperatures of furnace walls or roofs.

There are other interesting electrical devices which, though small in size, are important in function. Among these should be mentioned the so-called selsyn devices for remote indication or for synchronized angular movements. The "thrustor," which utilizes a centifugal oil-pump to translate the rotary motion of a small motor into linear motion with considerable force, is finding numerous applications in the steel mill. Lifting magnets have been modified to dispose the poles and the flux more advantageously for special applications, such as handling coiled strip.

Electricity is being applied in the field of measuring and regulating devices. Sensitive electromagnet gauges are being utilized for determining with extreme accuracy the thickness of strip by continuous gauging while rolling. Strain gauges are being inserted in mill housings to measure minutely their stretch, and thereby to indicate rolling pressures. Tension rolls are being installed between the stands of tandem cold-rolling mills to indicate the tension on the piece between stands and to control the drive motors of the respective stands to maintain advantageous tension. Small winches driven by torque motors are being applied to the continuous measurement of the depth of burden in blast furnaces. These are but a few examples.

I hope that this incomplete and abbreviated résumé of high lights in the use of electricity in the steel industry will give to those of you who are not familiar with the steel mills, a glimpse of the wide range of problems which confront the steel mill electrical engineer. To those of you within the industry, I trust that this review may have suggested some new and useful slant at your every-day tasks. Of one thing we may be sure, namely: there is much that is new yet ahead.

# Two-Reaction Theory of Synchronous Machines With Any Balanced Terminal Impedance

By C. CONCORDIA
MEMBER AIEE

## Introduction

R. H. PARK[1,2,3] has presented a general analysis of salient-pole synchronous machines* in terms of direct, quadrature, and zero axis quantities. This analysis is very well adapted to the case of a machine with balanced series inductance and resistance in the armature circuit, but requires modification for any other terminal impedance. S. B. Crary[4] has recently extended the method of Park to include the effects of balanced armature circuit capacitance. In the present paper the same method of analysis is further extended to include the effects of *any* balanced impedance network connected to the armature terminals. Every concept (impedance operators, per-unit quantities, $d$ and $q$ axis quantities, etc.) of the previous synchronous machine theory is preserved unchanged in this extended theory, and every problem solvable by the previous theory is now susceptible to an exactly similar solution in the extended case. Such problems are, e.g.: 3-phase short circuit, sudden application or change of load, self-excitation, asynchronous operation, hunting, pulling into step, any prescribed change of field or armature voltage, torque under any of the conditions given above.

Application of the present theory has been made to the determination of the regions of self-excitation occurring in induction and synchronous machine circuits containing series capacitors. This is described in a related paper.[6]

## Results

The results of the analysis may be stated as follows: First let

$$\begin{aligned} e_d - p\psi_d + ri_d + \psi_q(p\theta) &= D \\ e_q - p\psi_q + ri_q - \psi_d(p\theta) &= Q \\ e_0 - p\psi_0 + ri_0 &= N \end{aligned} \tag{1}$$

where $D = 0$, $Q = 0$, $N = 0$ are recognized as the 3 equations 8, 9, 10 of reference 2.

Next let the voltage of phase $a$ due to the external network be

$$z_{11}i_a + z_{12}i_b + z_{13}i_c \tag{2}$$

with similar expressions for the voltages of phases $b$ and $c$. For any balanced, 6-terminal network containing inductances, resistances, and capacitances connected in any arbitrary way there is, by ordinary circuit theory,

$$\begin{aligned} z_{ii} &= w(p)/y(p) \\ z_{ij} &= v(p)/y(p) \end{aligned} \tag{3}$$

for $i, j = 1, 2, 3$; $i \neq j$ where $w(p)$, $v(p)$, $y(p)$ are polynomials in the operator $p$. For example, let

$$\begin{aligned} w(p) &= d_0 + d_1p + d_2p^2 + \dots \\ v(p) &= c_0 + c_1p + c_2p^2 + \dots \\ y(p) &= b_0 + b_1p + b_2p^2 + \dots \end{aligned} \tag{4}$$

Further, let

$$\begin{aligned} u(p) &= w(p) - v(p) = a_0 + a_1p + a_2p^2 + \dots \\ n(p) &= w(p) + 2v(p) = e_0 + e_1p + e_2p^2 + \dots \end{aligned}$$

Then it may be shown that the general equations of a machine, to the terminals of which the balanced impedance has been connected, are

$$\begin{aligned} &b_0D + a_0i_d + p(b_1D + a_1i_d) - (p\theta)(b_1Q + a_1i_q) + \\ &\quad [p^2 - (p\theta)^2](b_2D + a_2i_d) - [2(p\theta)p + (p^2\theta)](b_2Q + a_2i_q) + \\ &\quad [p^3 - 3(p\theta)^2p - 3(p\theta)(p^2\theta)](b_3D + a_3i_d) - \\ &\quad [3(p\theta)p^2 + 3(p^2\theta)p - (p\theta)^3 + (p^3\theta)](b_3Q + a_3i_q) + \\ &\quad [p^4 - 6(p\theta)^2p^2 - 12(p\theta)(p^2\theta)p + (p\theta)^4 - 3(p^2\theta)^2 - 4(p\theta)(p^3\theta)] \times \\ &\quad (b_4D + a_4i_d) - \\ &\quad [4(p\theta)p^3 + 6(p^2\theta)p^2 - 4(p\theta)^3p + 4(p^3\theta)p - 6(p\theta)^2(p^2\theta) + (p^4\theta)] \times \\ &\quad (b_4Q + a_4i_q) + \dots = 0 \end{aligned} \tag{5a}$$

$$\begin{aligned} &b_0Q + a_0i_q + p(b_1Q + a_1i_q) + (p\theta)(b_1D + a_1i_d) + \\ &\quad [p^2 - (p\theta)^2](b_2Q + a_2i_q) + [2(p\theta)p + (p^2\theta)](b_2D + a_2i_d) + \\ &\quad [p^3 - 3(p\theta)^2p - 3(p\theta)(p^2\theta)](b_3Q + a_3iq) + \\ &\quad [3(p\theta)p^2 + 3(p^2\theta)p - (p\theta)^3 + (p^3\theta)](b_3D + a_3i_d) + \\ &\quad [p^4 - 6(p\theta)^2p^2 - 12(p\theta)(p^2\theta)p + (p\theta)^4 - 3(p^2\theta)^2 - 4(p\theta)(p^3\theta)] \times \\ &\quad (b_4Q + a_4i_q) + \\ &\quad [4(p\theta)p^3 + 6(p^2\theta)p^2 - 4(p\theta)^3p + 4(p^3\theta)p - 6(p\theta)^2(p^2\theta) + (p^4\theta)] \times \\ &\quad (b_4D + a_4i_d) + \dots = 0 \end{aligned} \tag{5b}$$

$$b_0N + e_0i_0 + p(b_1N + e_1i_0) + p^2(b_2N + e_2i_0) + \dots = 0 \tag{5c}$$

or the zero-sequence equation may be written as

$$y(p)N + n(p)i_0 = 0 \tag{5d}$$

The derivation of these general equations is given in the appendix. Equations 5 may be used directly in place of equations 8, 9, 10 of reference 2 to determine the transient performance of a synchronous or induction machine with any connected balanced network.

## Discussion

It may be shown that equations 5 yield all the previous results as special cases. For example, if there is no external impedance, all the constants $a$, $c$, $d$, $e$ are zero, while

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* It is assumed that the reader is completely familiar with the first 4 of the references given at the end of the paper.

1. For all numbered references, see list at end of paper.

$b_0$ may be any constant number. Then equations 5 reduce to

$$\begin{aligned} D &= 0 \\ Q &= 0 \\ N &= 0 \end{aligned} \tag{6}$$

which are exactly Park's equations.[2] Similarly, if there is series capacitance in the armature circuit,

$$\frac{w(p)}{y(p)} = \frac{x_c}{p}, \frac{v(p)}{y(p)} = 0$$

so $d_0 = a_0 = e_0 = x_c$, $b_1 = 1$, while all other constants vanish. Then equations 5 reduce to

$$\begin{aligned} x_c i_d + pD - (p\theta)Q &= 0 \\ x_c i_q + pQ + (p\theta)D &= 0 \\ x_c i_0 + pN &= 0 \end{aligned} \tag{7}$$

which are exactly Crary's[4] equations.

The present analysis has been restricted to the case of balanced circuits. This is because the balanced case is the only one for which the use of $d$, $q$, 0 axis quantities offers any simplification in the actual solution of problems. In all cases of operation with unbalanced impedances in the armature circuit, e.g., unbalanced faults, the phase quantities should be used directly. The phase voltage equations are given in the appendix and the expressions for phase flux linkages in terms of phase currents are given in equations 10, 11, 12 of reference 1 or equations 2 of reference 2. From the point of view of the practical engineer one reason for the use of $d$, $q$, 0 axis quantities is that such use results in the formulation of his problem as a set of linear differential equations with constant coefficients. These equations may be simply solved by the ordinary operational methods with which he is familiar. However, when the armature impedances are not balanced the machine voltage equations have variable coefficients regardless of the co-ordinate system used. Thus, it is usually simpler in such cases to use phase quantities for voltage, flux, and current; on the other hand the machine impedances should *always* be expressed along the $d$ and $q$ axes.

For a large class of problems the armature and its connected circuits may be treated as operating in the steady state and only the rotor circuit transients need be considered. This form of treatment is the basis of the practical utility of the definitions of transient and subtransient reactances and is analytically equivalent to the neglect of the $p\psi$ terms of the voltage equations. It is obvious that when the armature circuits are in steady state operation the presence of any connected impedance does not complicate the fundamental equations, and equations 6, with $p\psi = 0$, will apply to any case of balanced armature impedance. From this point of view the exact equations derived here are seen as a refinement and need be used only for exceptional cases. However, in these exceptional cases the refinement is all-important, as entirely misleading and useless results may be obtained without it. Such, e.g., was the case in the calculation of the regions of self-excitation in references 4 and 6.

## Examples

1. Suppose the external impedance is simply a balanced series self- and mutual inductance and resistance, the phase $a$ voltage being

$$(r_s + pl_s)i_a - pm_s(i_b + i_c) \tag{8}$$

then

$$\begin{aligned} w(p) &= r_s + l_s p \\ v(p) &= -m_s p \\ y(p) &= 1 \end{aligned}$$

Therefore,

$$\begin{aligned} a_0 &= r_s, & a_1 &= (l - m), & a_2 &= 0, & \ldots \\ e_0 &= r_s, & e_1 &= (l + 2m), & e_2 &= 0, & \ldots \\ b_0 &= 1, & b_1 &= 0, & \ldots & & \end{aligned}$$

and by equations 5,

$$\begin{aligned} D + r_s i_d + p(l - m)i_d - (p\theta)(l - m)i_q &= 0 \\ Q + r_s i_q + p(l - m)i_q + (p\theta)(l - m)i_d &= 0 \\ N + r_s i_0 + p(l + 2m)i_0 &= 0 \end{aligned} \tag{9}$$

It is evident that these equations may be reduced at once to the elementary form

$$\begin{aligned} D' &= e_d - p\psi_d' + r' i_d + \psi_q'(p\theta) = 0 \\ Q' &= e_q - p\psi_q' + r' i_q - \psi_d'(p\theta) = 0 \\ N' &= e_0 - p\psi_0' + r' i_0 = 0 \end{aligned} \tag{10}$$

where the primed quantities are of the same nature as the unprimed quantities, and

$$\begin{aligned} r' &= r + r_s \\ \psi_d' &= \psi_d - (l - m)i_d \\ \psi_q' &= \psi_q - (l - m)i_q \\ \psi_0' &= \psi_0 - (l + 2m)i_0 \end{aligned} \tag{11}$$

2. Suppose the external circuit consists of an inductance coil (having also resistance) in parallel with a capacitor in each phase. Then

$$\frac{w(p)}{y(p)} = \frac{1}{\frac{1}{r_l + x_l p} + \frac{p}{x_c}} = \frac{x_c r_l + x_c x_l p}{x_c + r_l p + x_l p^2} \tag{12}$$

and

$$\frac{v(p)}{y(p)} = 0$$

Therefore

$$\begin{aligned} a_0 &= x_c r_l, & a_1 &= x_c x_l, & a_2 &= 0, & \ldots \\ e_0 &= x_c r_l, & e_1 &= x_c x_l, & e_2 &= 0, & \ldots \\ b_0 &= x_c, & b_1 &= r_l, & b_2 &= x_l, & b_3 = 0, \quad \ldots \end{aligned}$$

and by equations 5

$$\begin{aligned} &x_c D + x_c r_l i_d + p(r_l D + x_c x_l i_d) - (p\theta)(r_l Q + x_c x_l i_q) + \\ &\quad [p^2 - (p\theta)^2]x_l D - [2(p\theta)p + (p^2\theta)]x_l Q = 0 \\ &x_c Q + x_c r_l i_q + p(r_l Q + x_c x_l i_q) + (p\theta)(r_l D + x_c x_l i_d) + \\ &\quad [p^2 - (p\theta)^2]x_l Q + [2(p\theta)p + (p^2\theta)]x_l D = 0 \\ &(x_c + r_l p + x_l p^2)N + (x_c r_l + x_c x_l p)i_0 = 0 \end{aligned} \tag{13}$$

These equations may be used to determine the transient performance of, e.g., a synchronous machine supplying an open-circuited transformer and shunt capacitor. In many

cases it will be possible to neglect the transformer resistance, thus effecting a considerable simplification.

3. Let the external *inductance* be zero in the previous case. Then

$$\begin{aligned} x_c D + x_c r i_d + p r_l D - (p\theta) r_l Q &= 0 \\ x_c Q + x_c r i_q + p r_l Q + (p\theta) r_l D &= 0 \\ (x_c + r_l p) N + x_c r i_0 &= 0 \end{aligned} \tag{14}$$

These equations, when put in the form

$$\begin{aligned} \left(p + \frac{x_c}{r_l}\right) D + x_c i_d - (p\theta) Q &= 0 \\ \left(p + \frac{x_c}{r_l}\right) Q + x_c i_q + (p\theta) D &= 0 \\ \left(p + \frac{x_c}{r_l}\right) N + x_c i_0 &= 0 \end{aligned} \tag{15}$$

are seen to be of exactly the same form as Crary's[4] equations but with $p$ replaced by $(p+x_c/r_l)$ wherever it operates on the elementary functions $D$, $Q$, $N$. Putting the resistor in shunt with the capacitor thus does not complicate the problem but only introduces the ratio $x_c/r_l$ where $r_l/x_c$ may be interpreted as the time constant of the resistor-capacitor circuit considered by itself.

## Appendix I

1. We first derive Park's equations in their original form from the phase equations.

We have

$$e_a - p\psi_a + r i_a = 0 \tag{16}$$

with 2 similar equations for phases $b$ and $c$. There are also the 9 transformation equations (equations 14, 15, 16 of reference 2).

$$a = i_d \cos\theta - i_q \sin\theta + i_0, \text{ etc.} \tag{17}$$

Substitute 17 in 16 and obtain

$$\begin{aligned} &e_d \cos\theta - e_q \sin\theta + e_0 - \\ &\quad p(\psi_d \cos\theta - \psi_q \sin\theta + \psi_0) + r(i_d \cos\theta - i_q \sin\theta + i_0) = 0 \end{aligned}$$

Perform the indicated differentiations and segregate the coefficients of the trigonometric functions.

$$\begin{aligned} &[e_d - p\psi_d + r i_d + \psi_q(p\theta)] \cos\theta - \\ &\quad [e_q - p\psi_q + r i_q - \psi_d(p\theta)] \sin\theta + \\ &\quad [e_0 - p\psi_0 + r i_0] = 0 \end{aligned} \tag{18}$$

By combining equation 18 with the 2 similar equations for phases $b$ and $c$ it may be shown that the coefficients of 18 must be separately equal to zero. Then,

$$\begin{aligned} e_d - p\psi_d + r i_d + \psi_q(p\theta) &= 0 \\ e_q - p\psi_q + r i_q - \psi_d(p\theta) &= 0 \\ e_0 - p\psi_0 + r i_0 &= 0 \end{aligned} \tag{19}$$

which are the familiar stationary axis equations.

2. Now suppose there is connected to the terminals of the machine a balanced impedance network containing inductances, resistances, and capacitances connected in any manner. The network may be represented by the operational expression $w(p)/y(p)$ where $w(p)$, $y(p)$ are polynomials in $p$ as shown in equations 4. Equations 16 are now replaced by

$$e_a - p\psi_a + r i_a + \frac{w(p)}{y(p)} i_a = 0 \tag{20}$$

If the impedance network has, in addition, mutual effects which cannot be eliminated by the use of an equivalent circuit there is also a mutual impedance $v(p)/y(p)$ where $v(p)$ is a polynomial as shown in equation 4. Since the circuit is balanced all the mutual coefficients are the same. The phase $a$ voltage equation now becomes

$$e_a - p\psi_a + r i_a + \frac{w(p)}{y(p)} i_a + \frac{v(p)}{y(p)} (i_b + i_c) = 0 \tag{21}$$

By the substitution

$$i_b + i_c = 3i_0 - i_a \tag{22}$$

we obtain after clearing of fractions,

$$y(p)(e_a - p\psi_a + r i_a) + [w(p) - v(p)] i_a + 3v(p) i_0 = 0 \tag{23}$$

The result of the previous section for the special case of no external impedance can still be used now, i.e., expression 18 can be substituted directly for $(e_a - p\psi_a + r i_a)$ in 23. Then

$$\begin{aligned} &y(p)\{[e_d - p\psi_d + r i_d + \psi_q(p\theta)] \cos\theta - [e_q - p\psi_q + r i_q - \psi_d(p\theta)] \times \\ &\quad \sin\theta + [e_0 - p\psi_0 + r i_0]\} + [w(p) - v(p)](i_d \cos\theta - i_q \sin\theta + \\ &\quad i_0) + 3v(p) i_0 = 0 \end{aligned} \tag{24}$$

By equations 1

$$\begin{aligned} &y(p)(D \cos\theta - Q \sin\theta + N) + [w(p) - v(p)] \times \\ &\quad (i_d \cos\theta - i_q \sin\theta + i_0) + 3v(p) i_0 = 0 \end{aligned} \tag{25}$$

and by (4)

$$\begin{aligned} &(b_0 + b_1 p + b_2 p^2 + \ldots)(D \cos\theta - Q \sin\theta + N) + \\ &\quad (a_0 + a_1 p + a_2 p^2 + \ldots)(i_d \cos\theta - i_q \sin\theta + i_0) + \\ &\quad 3v(p) i_0 = 0 \end{aligned} \tag{26}$$

As before, perform the differentiations required to segregate the trigonometric coefficients.

$$\begin{aligned} &b_0(D \cos\theta - Q \sin\theta + N) + b_1[(pD) \cos\theta - D \sin\theta(p\theta) - (pQ) \sin\theta - \\ &\quad Q \cos\theta(p\theta) + pN] + \ldots + a_0(i_d \cos\theta - i_q \sin\theta + i_0) + \\ &\quad a_1[(pi_d) \cos\theta - i_d \sin\theta(p\theta) - (pi_q) \sin\theta - i_q \cos\theta(p\theta) + pi_0] + \\ &\quad \ldots + 3v(p) i_0 = 0 \end{aligned} \tag{27}$$

Again utilizing the result of the previous section, the coefficients of $\cos\theta$, $\sin\theta$, and the constant term are equated separately to zero. The result is the set of equations 5. These equations have been given explicitly for polynomials of up to the fourth degree in $p$, but further terms may be formed as indicated in equation 27. It is probable, however, that the mathematical complexity encountered will preclude the solution of the equations for polynomials of any higher degree and perhaps even for the fourth degree. It is therefore believed that the equations given are as complete as will be necessary for any practical case.

## Appendix II

### Nomenclature

The notation is in general the same as that of Park[1,2,3] and Crary.[4]

| | |
|---|---|
| $e$ | = armature voltage |
| $i$ | = armature current |
| $\psi$ | = armature flux linkage |
| $d, q, 0$ | = subscripts denoting direct-axis, quadrature-axis, and zero-sequence quantities, respectively |
| $p$ | = $d/dt$ |
| $r$ | = armature phase resistance |
| $\theta$ | = rotor angular displacement |
| $a, b, c$ | = subscripts denoting the 3 armature phases |
| $x_c$ | = capacitive reactance |

## Appendix III

In the last few years considerable interest has been shown in the application of tensor analysis to electrical engineering problems.[5] A derivation of the general equations of this paper in tensor symbolism is therefore appended below. It is believed that this form of derivation has the great virtue that, to one familiar with the notation, the principal and necessary steps of the derivation stand out clearly. That is, the main line of reasoning is not obscured by lengthy algebraic manipulations.

The voltage equations 21 in terms of phase quantities may be written as:

$$e + R \cdot i - p\psi + Z \cdot i = 0 \tag{28}$$

where $Z$ is the impedance tensor of the outside network having components specified by equation 3.

Now if voltage and current are expressed along the $d$, $q$, 0 axes by transforming $e$, $i$, $\psi$ by Park's transformation $C$, where $C$ is the tensor whose components are the coefficients of equations 14, 15, or 16 of reference 2, equation 28 becomes:

$$C \cdot e' + R \cdot C \cdot i' - pC \cdot \psi' + Z \cdot C \cdot i' = 0 \tag{29}$$

where the primed quantities are measured along the $d$, $q$, 0 axes.

By multiplying the first 3 terms of 29 by $C \cdot C^{-1}$, where $C^{-1}$ is the inverse of $C$, equation 29 becomes:

$$C \cdot P + Z \cdot C \cdot i' = 0 \tag{30}$$

where

$$P = e' + R \cdot i' - p\psi' - J \cdot \psi' p\theta \tag{30a}$$

$P$ is seen to be the expression which in Park's analysis is equal to zero. The tensor $J$ is

$$J = C^{-1} \cdot \frac{dC}{d\theta} = \begin{array}{|c|c|c|}\hline 0 & -1 & 0 \\ \hline 1 & 0 & 0 \\ \hline 0 & 0 & 0 \\ \hline \end{array} \tag{31}$$

The external impedance $Z$ may be expressed as

$$Z = \frac{1}{y(p)} A \tag{32}$$

where $A$ is the tensor whose elements are $a_{ii} = w(p)$, $a_{ij} = v(p)$ $i \neq j$. Then 30 becomes

$$y(p) C \cdot P + A \cdot C \cdot i' = 0 \tag{33}$$

But this may be expressed as

$$(b_0 + b_1 p + \ldots) C \cdot P + (A_0 + A_1 p + \ldots) \cdot C \cdot i' = 0 \tag{34}$$

where

$$A_0 = \begin{array}{|c|c|c|}\hline d_0 & c_0 & c_0 \\ \hline c_0 & d_0 & c_0 \\ \hline c_0 & c_0 & d_0 \\ \hline \end{array} \qquad A_1 = \begin{array}{|c|c|c|}\hline d_1 & c_1 & c_1 \\ \hline c_1 & d_1 & c_1 \\ \hline c_1 & c_1 & d_1 \\ \hline \end{array} \quad \text{etc.} \tag{35}$$

If in equation 34 the indicated differentiations are performed, the result is

$$b_0 C \cdot P + b_1 \left[ \frac{dC}{d\theta} \cdot P p\theta + C \cdot pP \right] + \ldots + A_0 \cdot C \cdot i' + A \cdot \frac{dC}{d\theta} \cdot i' p\theta + \ldots = 0 \tag{36}$$

It remains only to multiply the whole equation 36 by the inverse transformation tensor $C^{-1}$ to obtain the set of equations 5. The elements of $C^{-1}$ are the coefficients of the set of equations 3, 6, or 7 of reference 2. That this multiplication eliminates the $C$'s is evident since:

$$C^{-1} \cdot C = \begin{array}{|c|c|c|}\hline 1 & 0 & 0 \\ \hline 0 & 1 & 0 \\ \hline 0 & 0 & 1 \\ \hline \end{array} \tag{37}$$

$$C^{-1} \cdot \frac{dC}{d\theta} = -C^{-1} \cdot \frac{d^3C}{d\theta^3} = C^{-1} \cdot \frac{d^5C}{d\theta^5} = \text{etc.}, =$$

$$= \begin{array}{|c|c|c|}\hline 0 & -1 & 0 \\ \hline 1 & 0 & 0 \\ \hline 0 & 0 & 0 \\ \hline \end{array} = J \tag{38}$$

$$-C^{-1} \cdot \frac{d^2C}{d\theta^2} = C^{-1} \cdot \frac{d^4C}{d\theta^4} = -C^{-1} \cdot \frac{d^6C}{d\theta^6} = \text{etc.}, =$$

$$= \begin{array}{|c|c|c|}\hline 1 & 0 & 0 \\ \hline 0 & 1 & 0 \\ \hline 0 & 0 & 0 \\ \hline \end{array} \tag{39}$$

The final equation is thus:

$$b_0 P + b_1 [J \cdot P p\theta + pP] + \ldots + A_0' \cdot i' + A_1'' \cdot i' p\theta + A_1' \cdot pi' + \ldots = 0 \tag{40}$$

where

$$A_0' = C^{-1} \cdot A_0 \cdot C = \begin{array}{|c|c|c|}\hline a_0 & 0 & 0 \\ \hline 0 & a_0 & 0 \\ \hline 0 & 0 & e_0 \\ \hline \end{array}$$

$$A_1'' = C^{-1} \cdot A_1 \cdot \frac{dC}{d\theta} = \begin{array}{|c|c|c|}\hline 0 & -a_1 & 0 \\ \hline a_1 & 0 & 0 \\ \hline 0 & 0 & 0 \\ \hline \end{array}$$

$$A_1' = C^{-1} \cdot A_1 \cdot C = \begin{array}{|c|c|c|}\hline a_1 & 0 & 0 \\ \hline 0 & a_1 & 0 \\ \hline 0 & 0 & e_1 \\ \hline \end{array}$$

It will be noted that here the same transformation $C$ has been applied to both $e$ and $i$, rather than applying the transformation $C_i^{-1}$ to $e$. The latter transformation has the property of maintaining the power $e \cdot i$ as an invariant, while in the former the only requirement has been that the trigonometric functions be eliminated from the differential equation $e = Z \cdot i$, without regard to the formula for power. A transformation tensor can, of course, easily be found which will resemble as nearly as possible Park's transformation yet which has the further property of invariance of power. This transformation tensor is:

$$C = \sqrt{\frac{2}{3}} \begin{array}{|c|c|c|}\hline \cos\theta_1 & -\sin\theta_1 & \sqrt{1/2} \\ \hline \cos\theta_2 & -\sin\theta_2 & \sqrt{1/2} \\ \hline \cos\theta_3 & -\sin\theta_3 & \sqrt{1/2} \\ \hline \end{array} \tag{41}$$

where $\theta_2 = \theta_1 - 120°$, $\theta_3 = \theta_1 + 120°$. It will be found that now $C_i^{-1} = C$, so that it is immaterial which is used in the derivation of the equations.

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# Resistance Characteristics of Tellurium and Silver-Tellurium Alloys

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## Synopsis

The problem of correcting temperature errors in electrical instruments with copper windings is explained and the high electrical efficiency obtainable by correcting these errors with series resistors having negative temperature coefficients of resistance is noted. A method is described for making such resistors of tellurium and of silver-tellurium alloy. Tests at various loads are described as a result of which the suitability of these resistors for various applications is determined.

## General

THE WINDINGS of electrical instruments and meters must usually be made of copper or aluminum wire to obtain high conductivity. Where, as in a millivoltmeter, the resistance of the winding has an effect on the accuracy of the instrument, the high temperature coefficient of resistance of the winding causes the instrument to have a correspondingly high temperature error.

A simple method commonly used for correcting this error is to connect a resistor of some material of low temperature coefficient, such as manganin, in series with the winding. The chief disadvantage of this method is that it increases the full-scale millivolts of the instrument in nearly an inverse ratio to the decrease in the temperature error, a total increase of 19 times[1] in the full-scale millivolts being required for complete compensation.

Another method which is more efficient and also more complicated makes use of a network of manganin and copper, iron, or nickel resistors. Brooks[1] has shown that by this method it is possible to compensate accurately the temperature error of a millivoltmeter by increasing the full-scale millivolts to nearly 5 times the millivolts of the uncompensated instrument.

Compensation by means of a series resistor having a negative temperature coefficient of resistance is an efficient method which has been used in instruments for many years. To the writer's knowledge, the only materials of negative temperature coefficient which have previously been known to have the required linear temperature-resistance curves are carbon and certain carbides. These materials as used in commercial instruments have negative temperature coefficients of resistance nearly equal numerically to the positive temperature coefficient of resistance of copper. Complete compensation of the temperature error is obtained at the expense of a 100 per cent increase in the full-scale millivolts of the uncompensated instrument. (Temperature errors due to the magnet and springs are disregarded because they are much smaller than the error due to the resistance change and may be compensated by the same method.) While instruments compensated with these materials are more sensitive than are instruments compensated by the other methods, a further gain in sensitivity may be obtained by the use of materials of higher negative temperature coefficients of resistance. The materials which are to be described have temperature coefficients which are numerically about 3 times as great as the temperature coefficient of copper. This makes it possible to obtain complete compensation at the expense of only a 33 per cent increase in the full-scale millivolts of the instrument.

In a search which the writer made for information on materials of negative temperature coefficient of resistance, he noted the values given in the International Critical Tables[2] for silver-tellurium alloys slowly cooled from their melting temperatures. These data were quoted from a thesis written by Riviere at the University of Paris in 1912.

All available data on tellurium indicated that it was inconstant in resistance and that small traces of impurities affected its resistivity so greatly as to preclude the use of commercial tellurium as a resistor material.[3]

## Method of Fabricating and Testing Resistors

As the result of tests it was found that the silver-tellurium alloys could be readily formed into rods by melting the constituents in a porcelain crucible, stirring the melt thoroughly, and drawing the molten alloy into a long glass tube of which one end was plunged under the surface of the melt and the other was attached to a rubber bulb used to create a partial vacuum in the tube. The rods could sometimes be pushed out of the tubes without breaking, but it was often necessary to dissolve the tubes in hydrofluoric acid in order to obtain the rods.

The method of attaching the leads was to electroplate the ends of the resistors with nickel, cobalt, platinum, or rhodium and solder them on with ordinary lead-tin solder. No failures of any of the resistors were observed to be traceable to plated joints in which any of these four metals were used. Most of the tests were made on resistors with platinum- or rhodium-plated joints.

The temperature-resistance tests were made by connecting the resistor to a Wheatstone bridge and immersing it in a bath of water for temperatures above 0 degrees

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1. For all numbered references, see list at end of paper.

centigrade and of alcohol cooled with solid carbon dioxide for temperatures below zero degrees centigrade. Check tests with several different voltages applied to the bridge were frequently taken in order to detect any variation in resistance with current density. No changes in resistance were detected in this way except those attributable to self heating.

## Improvement in Alloy to Obtain Linear Temperature-Resistance Curve

Tests on resistors made from an alloy of 15 per cent Ag with 85 per cent Te melted under illuminating gas to prevent oxidation gave temperature-resistance curves similar to that shown in figure 1. The method by which the resistors were heat treated will be explained later. It will be noted that, like those of Riviere's alloys which were all melted in a nonoxidizing atmosphere, the curve shows a sudden departure from a linear form near −15 degrees centigrade and below this temperature the slope changes rapidly. When resistors so made were suddenly cooled to any temperature between −15 and −60 degrees centigrade it was noted that their resistances did not at once assume definite values but that they slowly increased for an hour or more. The resistance corresponding to the temperature on any linear portion of the curve was attained quickly, and no subsequent variation was observed to occur while the temperature was held constant.

A melt which had not been protected from oxidation was found to have a linear temperature-resistance curve from −70 to +70 degrees centigrade and no resistance variation occurred while the temperature was held at any value in this range. As a result of tests on several melts of each type, the nonlinear and erratic resistance variation was found to be characteristic of the alloy melted in illuminating gas, and the linear temperature-resistance curve with a definite resistance for each temperature was found in every melt that had been melted in air.

All melts subsequently made were stirred in the presence of air until the formation of a scum of undissolved oxide indicated that no more would dissolve.

## Development of Heat-Treating Process

In view of recent developments in the age hardening of alloys it appeared that the results that Riviere obtained by slowly cooling the Ag-Te alloys might be due to precipitation and that they could be more effectively accomplished by annealing at a constant temperature than by slow cooling. The results of subsequent tests tend to confirm this assumption.

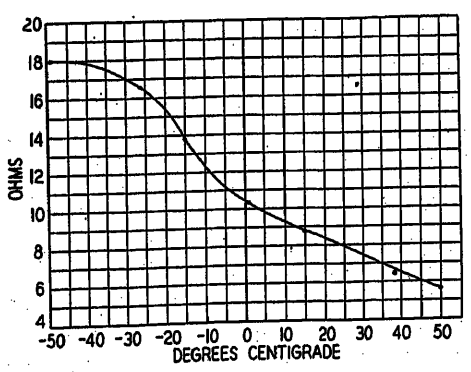



**Figure 1. Temperature - resistance curve of a 15 per cent silver-tellurium alloy resistor melted in an atmosphere of illuminating gas and annealed 15 hours at 115 degrees centigrade**

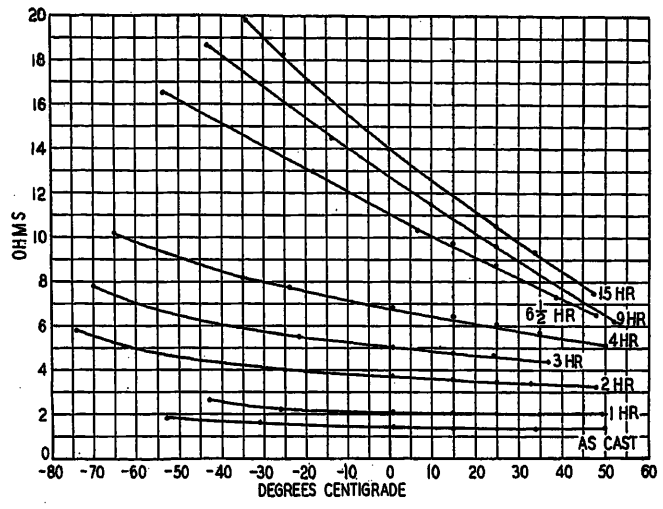



**Figure 2. Effect of annealing time at 115 degrees centigrade on the temperature-resistance curve of a resistor of 15 per cent silver with 85 per cent tellurium. Effective length of resistor, $^{9}/_{32}$ inch; diameter of resistor, 0.102 inch**

Figure 2 shows the effect of annealing at a constant temperature of 115 degrees centigrade on the temperature-resistance curve of a 15 per cent Ag, 85 per cent Te alloy. In order to get the data in this form, it was necessary to perform the annealing in a series of steps, taking a temperature-resistance curve between each of the steps. No difference has been observed between resistors annealed in in this way and resistors which were given the same total hours annealing time in a single treatment.

Groups of curves similar to those shown in figure 2 were taken for annealing temperatures from 105 degrees centigrade to 145 degrees centigrade and the results are summarized in figures 3 and 4. Some data were taken at 95 degrees centigrade, but at this temperature the rate of change was so slow that it would apparently have required a period of weeks to effect the entire change.

The increase in resistivity during the heat treatment, with a few exceptions which may be due to cracks, almost exactly parallels the increase in the negative temperature coefficient of resistance of both in 15 per cent Ag-Te alloy and of the purest grade of tellurium which we could readily obtain (Eimer and Amend *CP*). This tends to show that the same physical change is responsible for both effects.

## Effect of Direct Current on Polycrystalline Resistors of 15 Per Cent Silver-Tellurium Alloy

In the course of tests made under various conditions on resistors prepared and annealed as previously described, it was found that when a direct current of 25 milliamperes was continuously passed through a resistor of approximately 0.10 inch in diameter its resistance decreased for a period of from 2 to 4 weeks when it had decreased about

10 per cent after which time its resistance began to increase. This increase in resistance was evidently due to cracks which occurred spontaneously and gradually extended until they caused a fracture of the resistor. It was also found that the same effect could be produced by immersing the resistor in either oil or water for cooling and passing a direct current of 0.9 ampere through it for one to 2 hours.

In studying this effect it was noted that these resistors had a structure as shown in figure 5. The first visible change in the resistor previous to failure was usually a widening of the longitudinal crack, followed by the development of cracks which branched from the longitudinal crack, usually at right angles to it. These cracks appeared to develop at crystal boundaries, so it was thought that if the resistor were so made that the current did not pass through the boundaries between crystals, this effect might be eliminated.

## Effect of Direct Current on Single-Crystal Resistors of 15 Per Cent Silver-Tellurium Alloy

In order to determine whether the type of failure just described was related to the crystal structure, tests were conducted as follows: Sealed glass tubes containing the 15 per cent alloy were passed through a 480 degree-centigrade furnace at a rate of $^3/_8$ inch per minute. The alloy was molten at this temperature, and the time that it remained in the furnace after melting was not important. Where the tube emerged from the lower end of the furnace it passed into an oil bath. Rods made in this manner were found to have a single-crystal structure. Resistors made from these rods showed practically the same temperature-resistance characteristics and responded in the same manner to heat treatment as did those made by the simple casting process.

A number of these resistors were placed on a life test

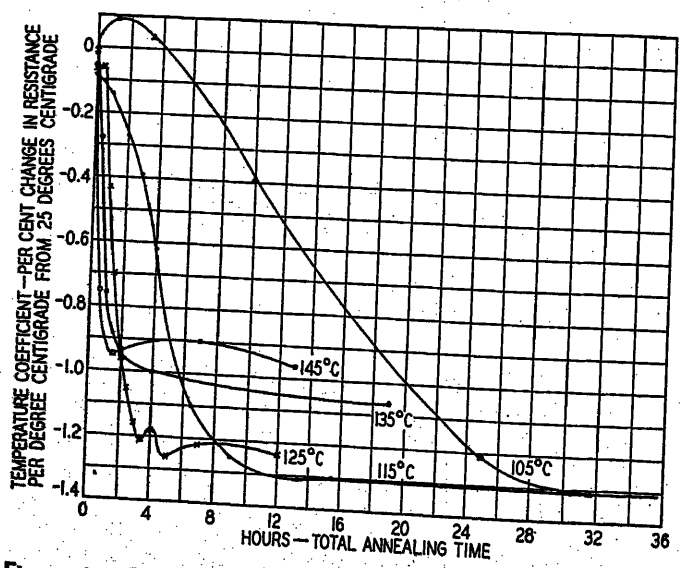



**Figure 3. Effects of time and temperature of annealing on the temperature-resistance coefficient of an alloy of 15 per cent silver with 85 per cent tellurium**

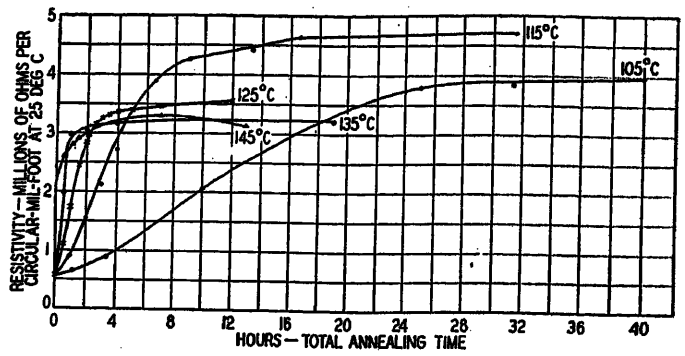



**Figure 4. Effects of time and temperature of annealing on the resistivity at 25 degrees centigrade of an alloy of 15 per cent silver with 85 per cent tellurium**

with a direct current of 25 milliamperes flowing continuously through them. Their resistances continued to decrease for a period of several weeks, the total decrease ranging from 8 per cent to 20 per cent and the length of time required to attain minimum resistance ranging from 3 weeks to 7 months, most of the change in every case taking place in the first month. After attaining the minimum resistance some of the resistors tended to remain constant in resistance for several months and others increased slowly in resistance. After a period of 257 days all of a group of 4 resistors which were tested under these conditions showed a bulge at a distance of $^1/_8$ inch from the cathode end of the resistor. Cracks appeared in these bulged sections and the resistors broke spontaneously. Figure 6 shows photographs of a resistor in which this bulge has developed, together with a similar resistor which has not been subjected to direct current long enough for this type of failure to develop.

## Effect of Alternating Current on Single-Crystal Resistors of 15 Per Cent Silver-Tellurium Alloy

Since the failures of the resistors were evidently due to an effect resembling electrolysis, tests were made similar to those just described except that 60-cycle alternating current was used instead of direct current. In the test at 0.9 ampere with the resistor immersed in a cooling liquid, the resistance increased slowly, the total increase in resistance being 12 per cent for a period of 14 days during which time the current was passed continuously through the resistor except for the brief periods during which it was removed from the circuit to have its resistance measured. At the end of this period it was put through a temperature cycle from −62 degrees centigrade to +74 degrees centigrade after which its resistance was only 7 per cent above the original value.

Since the chemical as well as the heating effect of the current is involved in the effect of direct current on the resistors, comparisons should be made on the basis of average as well as on effective values of current. However, in this case the difference in the effects of alternating and of direct current is so great that the comparison is little affected by a change in the alternating current equal

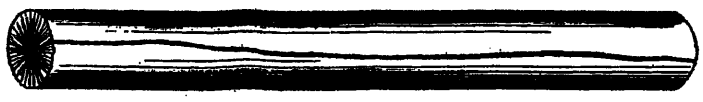


**Figure 5. Arrangement of crystals and longitudinal crack in a cast resistor of 15 per cent silver-tellurium alloy**

to the difference between the effective and the average values. Comparatively stated: a direct current of 0.9 ampere applied to a 15 per cent Ag-Te resistor which has been annealed 15 hours or more at 115 degrees centigrade caused it to decrease 40 per cent in resistance in 3 hours and to fracture spontaneously in $4^1/_2$ hours. An equivalent (root-mean-square) value of alternating current applied to a similar resistor under similar conditions for over 300 hours caused a semipermanent increase of 12 per cent in its resistance and no mechanical damage. It is reasonable to suppose that this increase in resistance may have been due to heat rather than to any other effect of the current.

## Effect of Direct Current on Resistors With Various Percentages of Silver

Annealed resistors of single-crystal tellurium of both the *CP* and the technical grades withstood direct current for a much longer period than did the alloy resistors. The tests at 0.9 ampere direct current were not continued longer than 10 hours, and at the end of this time the resistances had decreased only 2 per cent and there was no evidence of physical change in the resistors.

Tests at 0.9 ampere direct current on resistors with 5 per cent and 10 per cent of silver showed that the 5 per cent alloy resistors withstood the current longer than did the resistors with 10 per cent of silver. Failure of resistors containing 10 per cent of 15 per cent silver occurred by fracture, while with resistors containing 5 per cent silver a separation of the electroplated joints occurred at the cathode ends of the resistors. This separation was accompanied by the formation of a black coating on the separated surfaces.

For reasons to be explained later the 10 per cent alloy was the only one which appeared to have substantially as good temperature-resistance characteristics as those of the 15 per cent alloy. Hence it was the only one to be tested with a small current over a long period of time. Under these conditions it failed in a shorter time than did the 15 per cent alloy.

## Effect of Composition on the Temperature-Resistance Characteristics of Silver-Tellurium Alloys

Preliminary tests on alloys with different percentages of silver and tellurium had indicated that compositions low in silver content gave temperature-resistance curves which were concave downward below −10 degrees centigrade while compositions which were high in silver content gave curves which were concave upward over the same temperature range. Since the composition which gave the most nearly linear curve over the range from −70 degrees centigrade to +70 degrees centigrade was that containing 15 per cent silver, most of the previously described work was done with an alloy of this composition.

The temperature-resistance characteristics of compositions ranging from zero (*CP* tellurium) to 50 per cent were determined by making a series of resistors of the required compositions in the manner which had been found to give the best results with the 15 per cent alloy. This procedure comprised melting in air, casting in glass tubes, progressive solidification, and annealing for 15 hours at 115 degrees centigrade.

The temperature-resistance curves for this range of compositions are shown in figures 7 and 8. In figure 8 it will be noted that portions of the curves are indicated by dotted lines. Over the temperature ranges so indicated the resistance is not constant at any given temperature. When the temperature of the resistor is lowered to a value on the dotted curve the resistance assumes the value so indicated, but when the temperature is held constant in this region, the resistance continues to increase at a diminishing rate for a period of several hours or more. In one case a resistance increase of 70 per cent in 45 minutes was observed. In all observed instances, this increase in resistance was not permanent; that is, the original resistance at any point on the solid portion of the curve could be again obtained by bringing the temperature to the corresponding value.

This behavior resembles that of the 15 per cent alloy melted in a reducing atmosphere, although the alloys with the higher percentages of silver were melted in an oxidizing atmosphere, using the same procedure as that used in producing the 15 per cent alloy which had a linear temperature-resistance curve.

It will be noted that the resistivity of the 15 per cent alloy resistor in figure 7 is lower than that of the resistor of the same composition in figure 4. This difference may be accounted for by the fact that the former is a single crystal, while the latter is polycrystalline in structure.

When the single-crystal resistors were found to be superior to the polycrystalline resistors, sufficient tests were made to determine the fact that they responded to heat treatment in a manner similar to that of the polycrystalline

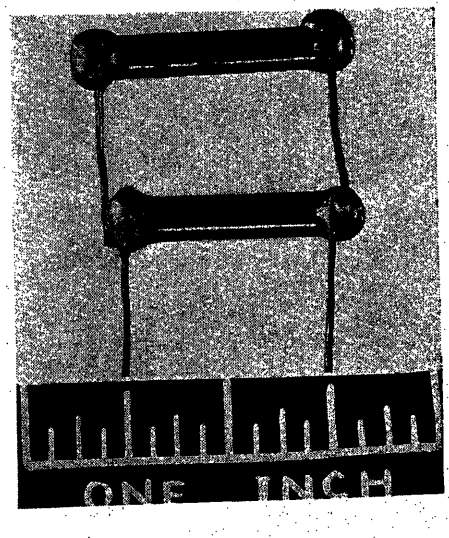



**Figure 6. At top, a silver-tellurium resistor in which bulge has formed due to passage of direct current over a long period of time; at bottom, a similar resistor which has not been subjected to current**

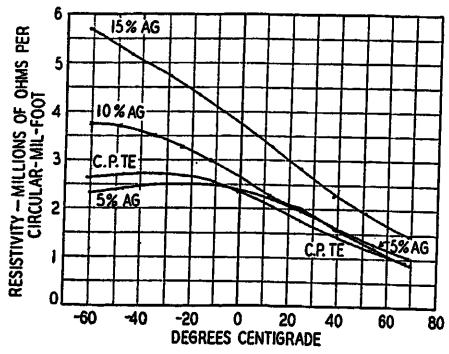



**Figure 7. Temperature - resistivity curves of Ag-Te alloys with zero to 15 per cent Ag annealed 16 hours at 115 degrees centigrade**

resistors, although the resistivities of the single-crystal resistors were the lower. The series of tests summarized in figures 1 to 4 inclusive were made with polycrystalline resistors and were not repeated with single-crystal resistors. Figures 7 and 8 were made with single-crystal resistors or at least with resistors which had been solidified progressively in a manner which had been found to produce single crystals.

Referring to figure 7, the temperature-resistivity curve of annealed chemically pure tellurium is linear between −10 degrees centigrade and +70 degrees centigrade. Tests on commercial tellurium from 4 different sources showed that unannealed single-crystal resistors of these materials had temperature coefficients within the range +0.1 to −0.1 per cent per degree at 25 degrees centigrade. Unannealed single-crystal resistors of chemically pure tellurium had temperature coefficients of approximately −0.7 per cent per degree at 25 degrees centigrade. After the annealing treatment, the temperature-resistivity curves of the commercial and of the chemically pure tellurium resistors were practically the same. Both had temperature coefficients of −1.2 per cent per degree at 25 degrees centigrade.

## Thermal Electromotive Force

The thermal electromotive force as measured on an unannealed sample of 15 per cent Ag-Te alloy was found to be 0.46 millivolts per degree with the hot junction at 50 degrees centigrade and the cold junction at 25 degrees centigrade. This is close to the value usually given for tellurium.[4]

The annealing treatment which had such a great effect on the resistivity and temperature coefficient of resistance of the alloy lowered the thermal electromotive force as measured over the above temperature range to 0.25 millivolt per degree.

## Aging Tests

The accelerated life tests which have been described were made sufficiently severe to destroy the resistors. While these tests did not represent service conditions, they were valuable guides in selecting the compositions and treatments of the resistors on which aging tests were made.

The following test results indicate the constancy that may be expected under the specified conditions of use:

1. In a group of 9 single-crystal tellurium resistors of 0.1 inch diameter, tested at 0.025 ampere direct current for 81 weeks, the maximum change was +1.2 per cent in one resistor, and the average change for the group was +0.15 per cent.

2. In a group of 3 single-crystal Ag-Te resistors of 0.1 inch diameter, tested at 0.10 ampere alternating current for 78 weeks, the maximum change was +2.1 per cent in one resistor, and the average change for the group was +1.4 per cent.

3. In a group of 4 single-crystal Ag-Te resistors of 0.1 inch diameter, tested at 0.001 ampere direct current for 80 weeks, the maximum change was +2.2 per cent in one resistor, and the average change for the group was +1.4 per cent.

In all of these groups most of the change took place during the first part of the period, indicating a tendency to stabilize at a higher value of resistance. It should be noted that in the previously described tests in which the Ag-Te resistors were broken by electrolytic action, a considerable decrease in resistance always preceded failure. The tests at one milliampere direct current indicate that this effect is not occurring at this low current density, since the resistance is increasing.

Aging tests on polycrystalline Ag-Te resistors of the type shown in figure 5 showed resistance changes several times as great as those in the single-crystal resistors.

## Applications

The heat-treated tellurium resistors of single-crystal structure are more constant than are the similarly treated Ag-Te alloy resistors, their temperature coefficient is practically the same from −10 degrees centigrade to +70 degrees centigrade, and they are not subject to electrolytic effects. Therefore, they are to be preferred to the Ag-Te alloy resistors for all applications in which compensation is not required at temperatures below −10 degrees centigrade. Since the resistance of these resistors should not be more than 25 per cent of the resistances of the instrument circuits in which they are used, the maximum change of 1.2 per cent which was noted in one resistor during the aging test would have caused a maximum instrument error of 0.3 per cent. From these data it appears that this material may be used in instruments with rated accuracies of one per cent to 2 per cent, provided that other sources of error are kept sufficiently low.

The 15 per cent Ag-Te alloy is suitable for long-range

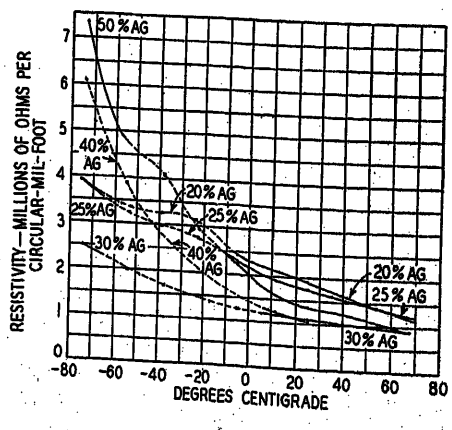



**Figure 8. Temperature - resistivity curves of Ag-Te alloys with 20 per cent to 50 per cent Ag annealed 16 hours at 115 degrees centigrade**

temperature compensation, but when used with direct current the current density should not exceed one milliampere in a 0.1 inch diameter resistor. A suitable application of this kind is for compensating the resistance change in a thermocouple temperature indicator with cold-junction compensation for measuring temperatures in aircraft engines or for portable use in measuring temperatures of molds, bearings, and molten metals.

An application in which the 15 per cent Ag-Te alloy has been tried with good results is in the compensation of "class 2" temperature error in watt-hour meters. This error is principally due to the change in phase angle of the flux of the potential coil due to the change in resistance of the potential winding with changing temperature. It has been entirely corrected by substituting for the usual solid copper lag plate a wound copper lag coil with a resistor of Ag-Te alloy connected across its terminals. The maximum aging change of 2.1 per cent for this alloy as tested under similar conditions with alternating current would cause an error not greater than 0.1 per cent in the meter accuracy. Another method, as described by Kinnard and Trekell,[5] which has recently been developed for correcting this error has the advantage of a better mechanical design.

In compensating millivoltmeters with these materials, it is necessary on account of the high thermal electromotive force of Te and of Ag-Te to shield them from rapid temperature fluctuations and to mount them so as to equalize the temperatures at the ends of the resistor.

Figure 9 illustrates 2 resistors which have been made for use in instruments.

## Theory

Because the results just described were obtained with tellurium which was not investigated spectroscopically to determine its purity and which was known to contain dissolved oxide, they are not directly comparable with those of Cartwright and Haberfeld-Schwarz[3] who used tellurium of high purity melted in vacuum. They considered the increase in resistivity which occurred during annealing to be due to the formation of cracks. This theory does not explain the increase in temperature coefficient which accompanied the increase in resistivity in our tests. Neither pressure up to the crushing strength of the material, nor a current which would have fused the resistor had it not been cooled in liquid, decreased the resistance of our annealed tellurium resistors.

**Table I. Summary of Electrical Characteristics of Resistor Materials**

Single Crystals Annealed 15 Hours at 115 Degrees Centigrade

| Composition Per Cent Ag | Composition Per Cent Te | Resistivity at 25 Degrees Centigrade in Megohms Per Circular-Mil-Foot | Temperature Coefficient of Resistance at 25 Degrees Centigrade | Effect of Direct Current | Effect of 60-Cycle Alternating Current |
|---|---|---|---|---|---|
| 0 | 100 | 1.7 | —1.2 | Thermal | Thermal |
| 5 | 95 | 1.9* | —1.1* | Thermal and electrolytic | Thermal |
| 10 | 90 | 2.0 | —1.3 | Thermal and electrolytic | Thermal |
| 15 | 85 | 2.8 | —1.3 | Thermal and electrolytic | Thermal |

* These data based on tests on only one sample.

The behavior of all the resistors tested by the writer may be explained as follows: In rapid cooling from the melting temperature, silver telluride and other impurities are held in solid solution in the tellurium, which solid solution has the property of metallic conduction with a very small temperature coefficient of resistance. Assuming that the impurities are precipitated during the heat treatment, the conductivity decreases due to the reduction in the number of free electrons. This theory is supported not only by the fact that the temperature-resistivity curves of the impure and the pure tellurium are made to coincide by heat treatment, but also by the fact that the thermal electromotive force of the Ag-Te alloy is lowered by the heat treatment. Cartwright and Haberfeld-Schwarz[3] have shown that the thermal electromotive force of pure tellurium is much lower than the value usually given and that is increased by the additions of small amounts of silver and of other metals.

The breakdown of the Ag-Te resistors produced by direct current may be due to electrolysis of silver telluride accompanied by migration of the silver ions toward the cathode. Evidence has been shown to indicate that this effect does not take place when the voltage across the resistor is very low.

The observations here recorded were obtained in determining the utility of tellurium and of its alloys with silver as special resistor materials. It is hoped that the data thus obtained may be of some value in the further determination of the nature of the conductivity of semiconductors.

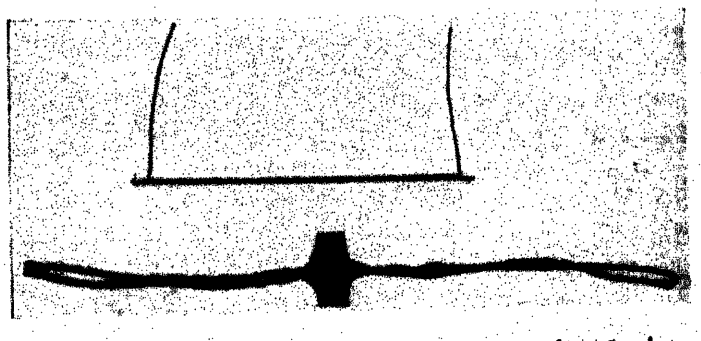


**Figure 9. At top, a silver-tellurium resistor of 200 ohms resistance (length 3 inches, diameter 0.059 inch); at bottom, a tellurium resistor of 0.06 ohm resistance**

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# Regulation of Grid-Controlled Rectifier

By L. A. KILGORE ASSOCIATE AIEE J. H. COX ASSOCIATE AIEE

## Synopsis

This paper discusses several factors which have not been included in the previously published regulation formulas and which should be considered in the practical application of rectifiers. Approximate solutions are given to take system reactance, and the load inductance into account. The effect of grid pickup characteristics on regulation, and means of modifying the inherent regulation characteristics by regulators or compensators are discussed.

## Introduction

SEVERAL PAPERS[3,4] have been written on the general characteristics of grid-control rectifiers, and formulas have been derived for the regulation. The conventional formula, equation 1, is based on the assumptions that a sinusoidal voltage exists at the point where the rectifier is connected to the system, and that the inductance in the load circuit is sufficiently large to prevent the current from going to zero when the voltage drops below the counter electromotive force of the load circuit. These assumptions are sufficiently accurate for some cases, but in many practical cases other factors, such as the effect of system reactance and the effect of a limited amount of inductance in the load circuit must be considered.

The conventional formulas and regulation curves involve the angle of delay ($\alpha$). In the practical application of these formulas it may not be correct to assume that the actual angle of delay is constant for a certain setting of the grid-control apparatus. The angle of delay may vary with the load due to a variation in the grid pickup voltage, and in some cases it may vary due to a shift of phase of the grid voltage due to system reactive drop.

It is the purpose of this paper to consider these other factors and to present approximate methods of including them in the determination of regulation. A more exact solution is outlined in the appendix. The use of regulators and compensators for the purpose of modifying the inherent regulation of grid-controlled rectifiers and ignitrons is also discussed, and results obtained with certain types are given.

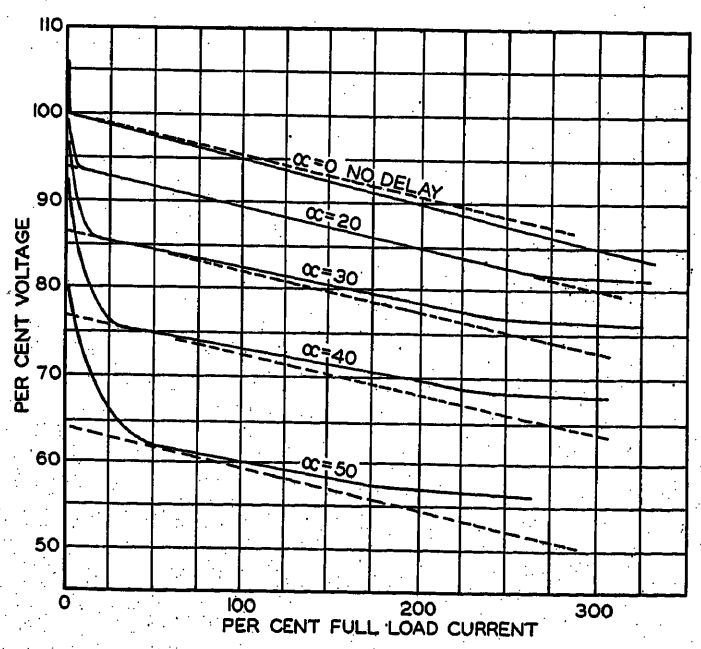



**Figure 1. Test and calculated regulation curves of experimental grid-controlled rectifier**

Double 3-phase connection. Dotted lines show calculated values for fixed delay

## Conventional Regulation Formula

What might be termed the conventional regulation formula for grid-controlled rectifiers (equation 1) has been derived several times;[2,3] and the derivation will not be repeated.

$$E_d = \left[\frac{\sqrt{2}EP \sin\frac{\pi}{P}}{\pi}\right]\cos\alpha - \frac{IX_TP}{g2\pi} - \frac{W_T}{I} - A \qquad (1)$$

This formula is exact within the limits of the assumptions made in deriving it. These assumptions are: (1) a sinusoidal voltage at the terminals of the rectifier transformer, (2) a load inductance sufficiently high to prevent the current from going to zero, (3) the effect of all the transformer and lead resistance to be equivalent to a series resistance in the d-c circuit giving the same loss, and (4) only 2 anodes in one group firing at one time. This formula gives straight-line regulation curves as shown by the dotted lines of figure 1, providing the curve of arc drop against current is straight. It should be noted that the curves are parallel; that is, a given angle of grid delay ($\alpha$) drops the output voltage the same number of volts whether at no load or at full load.

If a rectifier is supplied through a line of appreciable reactance directly from a large system whose voltage is

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3. For all numbered references, see list at end of paper.

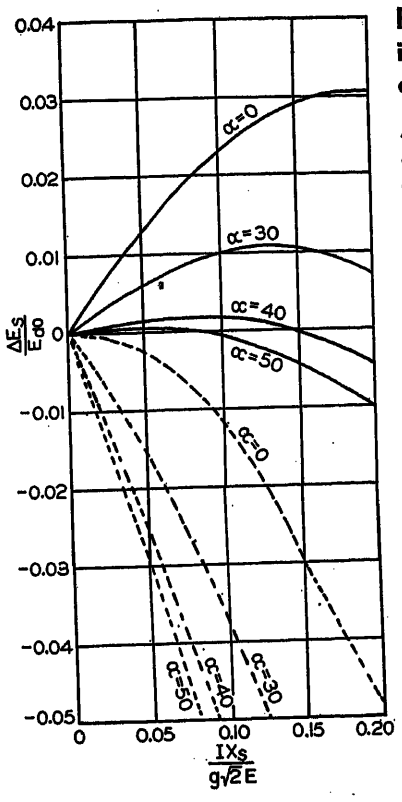



**Figure 2. Apparent increase in regulation due to system reactance**

A normal transformer with about 3 per cent reactive drop is assumed. Full lines are for double 3-phase and dotted lines are for 12-phase quadruple zigzag

not affected by the rectifier load, the line reactance can obviously be included in the total commutating reactance. In this case $E$ in equation 1, is the system voltage. The additional commutating reactance due to the line is calculated by multiplying the ohms per phase (line to neutral) by the square of the ratio of primary to secondary line to neutral voltages.

For the more common case where the system voltage is affected appreciably by the rectifier load, equation 1 can still be used as an approximation if the primary voltage is known. However, a further analysis as presented below is necessary to obtain an accurate method of dealing with this case.

## Effect of System Reactance

In the general case of a rectifier connected to an a-c system there is no one source of constant sinusoidal voltage. It greatly simplifies the problem if an equivalent sinusoidal source voltage can be found which may be considered as unaffected by rectifier currents. The principle of superposition, which has proved such a useful tool in other system problems, may be applied to determine a voltage which can be considered as acting through the combined impedance of the system and the rectifier transformer.

Since the back current of a power rectifier is negligible, the effect is equivalent to opening each anode circuit whenever the current tends to reverse. A method of applying superposition to obtain as complete a solution as desired is outlined in the appendix. For practical purposes, the capacity and resistance of the a-c circuit and any effect of harmonics produced by other rectifiers, will be neglected.

As shown in the appendix, the voltages acting in the secondary to produce the anode currents are the voltages which would exist with no rectifier currents flowing. This voltage acts through the reactance of the transformer and the reactance of the system measured from the point of connection. This voltage may be treated as an equivalent sinusoidal source voltage and the system reactance may be added to the commutating reactance of the transformer as described for the line reactance in the simpler case mentioned previously.

In general the voltage $E$ at the primary of the rectifier transformer is known or can be calculated. The system reactance $X_s$ can be measured or estimated. As shown in appendix $B$, the system reactance to be used is the same as that used for calculating single-phase short-circuit current; that is, the average of the negative-sequence and positive-sequence subtransient reactances: $X_s = (X_2 + X_d'')/2$.

The fundamental frequency voltage $E$, at the primary terminals may be taken equal to the root-mean-square value for practical purposes. If the fundamental-frequency system reactive drop be added vectorially to the terminal voltage the equivalent sine-wave source voltage $E''$ is obtained. Using $E''$ instead of $E$ and $(X_T + X_s)$ in place of $X_T$ in equation 1, gives the general equation;

$$E_d = \left[\frac{\sqrt{2}\,E''P\sin\frac{\pi}{P}}{\pi}\right]\cos\alpha - \frac{I(X_T + X_s)}{g2\pi} - \frac{W_T}{I} - A \qquad (2)$$

where

$$E'' = \sqrt{(E + I_1X_s\sin\theta_1)^2 + I_1^2X_s^2\cos^2\theta_1} \qquad (3)$$

With good approximation,

$$I_1 = \frac{I\sqrt{2}}{\pi g}\sin\frac{\pi}{P} \qquad (4)$$

The fundamental-frequency power factor is approximately:

$$\cos\theta_1 = \cos\alpha - \frac{\text{transformer reactive drop}}{\text{voltage at no load no delay}} \qquad (5)$$

This may be demonstrated as follows. All the power is supplied by the fundamental since the source voltage is

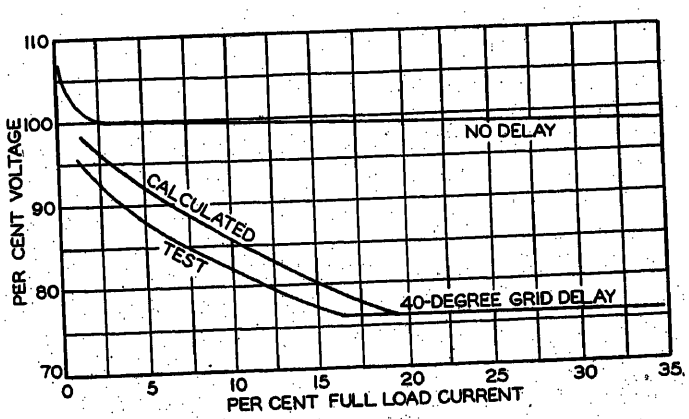



**Figure 3. Light-load voltage regulation curves**

Experimental grid-controlled rectifier, double 3-phase connection

assumed sinusoidal. This power factor can then be written as power divided by fundamental-frequency volt-amperes:

$$\cos \theta_1 = \frac{E_d I}{E I_1 p g}$$

and neglecting arc drop and resistance losses, this reduces to equation 5.

The fundamental reactive drop adds to $E$ the amount nearly equal to $I_1 X_s \sin \theta_1$. If the average of the power factor angles at the source and at the terminals be used the accuracy of this approximation is improved. The effect of the system reactance is to add to the source voltage and to the reactive drop. The net correction expressed as an addition to the regulation (to be subtracted from the right-hand side of equation 1) is:

$$\Delta E_s = \frac{I X_s P}{2\pi g}\left[1 - \frac{4g}{\pi}\sin^2\frac{\pi}{p} \times \cos\alpha \sin\cos^{-1}\left\{\cos\alpha - \frac{I\left(X_T + \frac{X_s}{2}\right)}{2\sqrt{2}gE\sin\frac{\pi}{p}}\right\}\right] \qquad (6)$$

Curves of $\Delta E_s/E_{d0}$ for different values of $IX_s/g\sqrt{2}E$ are given in figure 2, for a rectifier with about 3 per cent regulation in the transformer. It will be seen that the correction can be either positive or not depending on the type of connection and the angle of delay. It should be noted that the angle of delay ($\alpha$) is measured relative to the source voltage, and that the angle of overlap ($u$) as measured on an oscillogram will be determined by the total reactance ($X_T + X_s$) thus:

$$\cos(u + \alpha) = \cos\alpha - \frac{I(X_T + X_s)}{g\sqrt{2}\,E' \sin\frac{\pi}{P}} \qquad (7)$$

To illustrate the importance of the correction for system reactance, consider a rectifier where the primary voltage is held constant as it might be in a regulation test. If the system reactance is 10 per cent based on the rectifier kilovolt-amperes and the transformer reactive drop is 3 per cent, the ratio of $X_s$ to $X_T$ is 1.74 for a double 3-phase connection and the measured regulation may be 2.3 per cent less with zero delay than the value which would be obtained if a sine-wave voltage were impressed. That is, the regulation might measure 2.7 instead of 5 per cent. As another example take a 12-phase quadruple zigzag connection with the same per cent line reactance and transformer reactive drop. In this case the ratio of $X_s$ to $X_T$ is 0.87 and the regulation will be increased only 0.3 per cent at no delay; but at 20 per cent reduction in voltage by grid delay the measured regulation will be decreased 4 per cent, that is; it may measure one per cent instead of 5 per cent.

## Light Load Voltage Rise

The rise in voltage at very light loads on a double 3-phase rectifier is a well-known phenomenon. This has been explained by saying that below some transition value of load, at which the load current just equals the interphase transformer excitation current, the rectifier is operating 6 phase; and that the commutating current flows between anodes of alternate groups through the windings of the interphase transformer. This is an accurate explanation for the case of straight resistance load or for the theoretical case of infinite inductance in the load circuit.

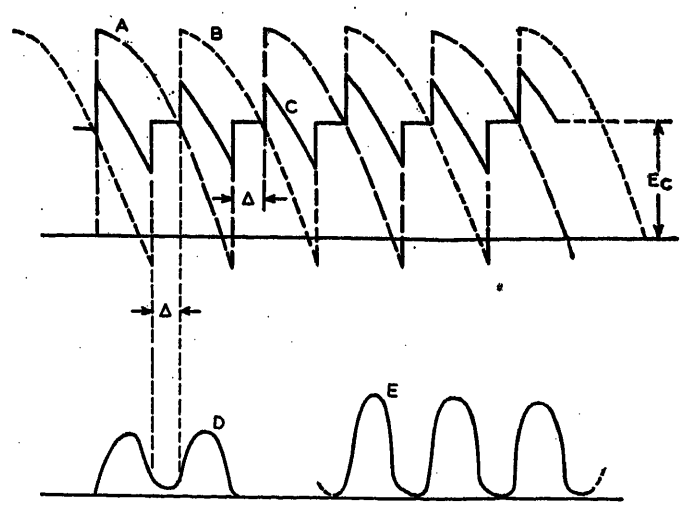



**Figure 4. Current and voltage waves when operating at light load with counter electromotive force**

Curve *A*—Voltage of one group of double 3-phase winding
Curve *B*—Voltage of other group
Curve *C*—Net voltage output
Curve *D*—Current in first group
Curve *E*—Total current output

However, for the case of load with a counter electromotive force and with normal inductance a different phenomenon appears which radically alters the light-load regulation characteristics, especially when operating with appreciable grid delay. Whenever the output voltage of the rectifier dips below the counter electromotive force the total load current tends to go to zero but is restricted in this action by the inductance of the circuit. Above a certain critical load the current is prevented from reaching zero. This phenomenon occurs for all type of rectifiers both with and without interphase transformers.

When interphase transformers are used the action is more complicated. Interphase transformers are designed to have a high inductance ($L_i$) between the 2 transformer neutrals so as to prevent one group from dropping the current ahead of the other except at light loads. However, it is the leakage inductance ($\mathfrak{L}_i$) between the 2 halves of the winding which opposes the rise and fall of total current so long as both groups are conducting. This leakage inductance, measured with the windings in parallel, the magnetomotive forces being opposed, is very much smaller than $L_i$. This is true because the windings are normally made with close coupling.

As long as both groups are firing, it is the total inductance ($\mathfrak{L}$) of the load circuit, including $L_i$ and the paralleled inductance of the phase circuits of the anodes which are conducting at the same time, which damps out the pulsations of load current.

As discussed in the appendix, a complete solution would require consideration of the effective resistance and reactance of fundamental frequency as well as the impedance to suddenly applied voltages. The resistance in the load circuit causes a voltage drop both on the rising and dropping parts of current cycle and thus has relatively little effect on the total swing of the current unless the total line drop is 10 per cent or more at the load considered.

For most practical purposes the following equation determines the amplitude of total current pulsation:

$$i_\Delta = \frac{1}{L}\int e_x - E_c\,dt \qquad (8)$$

At a critical value of load this pulsation of current ($i_\Delta$) reaches a value equal to the average current, and the total current tends to go out between each pulse.

Consider the voltage waves for a double 3-phase circuit at light load and some delay, as shown in figure 4, for the interval of 1/6 of a cycle. The total current will rise and fall during this period, but since there is a slight difference in the currents of the 2 groups due to difference in voltage acting through the high inductance, $L_0$, only the current in one group goes out, and the current in the group having the last anode to pickup is maintained but at some very low value. One group at a time will be out for a period $\Delta$ and the current wave of each group will be as shown by curve $D$ of figure 4. The total current shown by curve $E$ will not go completely out but will be very low for the period $\Delta$. The output voltage at the neutral point of the interphase rises to the counter electromotive force value ($E_c$), assuming the inductance of half the interphase to be large compared with that of the load circuit. Equations could be written for the critical load value in terms of inductance and the angle of delay, but for practical purposes a graphical solution is satisfactory. Plotting the output voltage for an assumed value of $\alpha$ and $\Delta$ as shown in figure 4, the current can be solved by taking the area of one half cycle of the voltage ripple in volt seconds divided by the inductance $L$ as indicated by equation 8. Also from this curve the average voltage may be determined graphically.

The results of this method are given in figure 5 plotted as the rise in voltage ($\Delta E_c$) versus ($I\omega L/\sqrt{2}E$). Curves obtained in a laboratory test with counter electromotive force are shown in figure 3. This rise in voltage at light loads with appreciable angles of delay is much more pronounced than the usual light-load voltage rise at no delay. However, in practice this is not generally a serious matter since danger due to overvoltage exists in the great majority of cases only when the normal voltage at no delay is exceeded.

If exactly straight-line regulation curves are desired at very light loads and appreciable angles of delay it may be necessary to use more than normal load inductance. An iron-core reactor may be used in series with the d-c bus to provide a high inductance at low values of current.

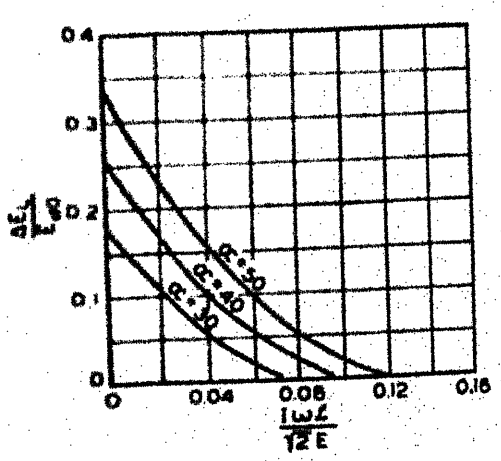



**Figure 5. Rise in voltage at light load as a function of d-c circuit inductance and load current**

## Effect of Grid Characteristics

The regulation formula and conventional regulation curves are based on the actual angle of delay. However, the angle of delay for a given phase shifter or bias setting may vary appreciably with load. This may be due to variation of the pickup voltage or an actual shift of the grid voltage with respect to the source voltage.

The pickup voltage will vary with the degree of ionization and the vapor pressure in the tank. At light loads a slight positive voltage relative to the cathode may be required to make the grids pickup, and at higher loads an appreciable negative voltage may be required to prevent them from picking up.

A simplified explanation of the action of the grids is as follows: A positive ion space charge sheath is formed around the grids when they are negative with respect to the ionized gas preventing the ionization from reaching the anode. The thickness of this layer[6] varies roughly as the $^3/_4$ power of voltage and inversely as the $^1/_2$ power of the ionization. When the thickness of the space charge sheath just fails to close the holes in the control-grid structure, positive voltage on the anode accelerates the electrons sufficiently to increase the ionization and further reduce the space charge thickness and cause complete pickup.

It is difficult to test for the pickup voltage of the grid under actual operation but a method of testing the grid characteristics statically was developed. An arrangement was made whereby the load could suddenly be removed from one anode and definite continuous voltages applied to that anode and control grid. Curves of grid voltage at which the anode picked up for different values of total load were plotted as shown in figure 6. These characteristics were found to vary some with anode voltage and the temperature of the cooling water. Obviously conditions were not identical with those under actual operating conditions. However, it was found that these static curves could be used to predict approximately the deviation of the test regulation curves from a straight line under overload conditions as shown in figure 1.

In order to explore a range of grid characteristics an experimental rectifier was built with grids having large holes so that the variation in pickup voltage caused a noticeable effect on the regulation curves even at rated load when using a sine-wave grid voltage. Without appreciably increasing the arc drop, it was possible to build a grid structure with sufficiently limited variation in pickup voltage so that it had no appreciable effect on regulation out to at least 200 per cent load. The test curves of

figure 1 show a flattening out of the regulation curves at about 250 per cent load at large angles of delay. However, grids sufficiently tight to give straight line regulation curves at very high overloads result in excessive arc drop.

When paralleled with other apparatus having a straight or drooping characteristic on high overloads, this effect will add to the tendency for the rectifier to take more than its share of the overload. However, so long as the departure from straight line regulation occurs at well over 150 per cent load, the rectifier will return to normal after the load is decreased, and no damage is done since the rectifier is suited to short time overloads.

By the use of steep-wave-front impulses on the grids it is possible to obtain straight-line regulation even with comparatively loose grid structures, since in this case a variation in the pickup voltage has little influence on the time of pickup.

The voltage control characteristics of an ignitron rectifier are similar to those of a multianode rectifier except that the pickup of the auxiliary tubes is not affected by the load current. Tests on a 6-phase ignitron rectifier, both as grid-controlled rectifier and as an inverter, show straight line regulation curves at all angles of delay and advance out to very high overloads.

Where the system reactance is comparable with the transformer reactance an increase in delay with load, due to a shift of the fundamental voltage at the point where the grid transformers are attached to the system, might be expected. For the sine wave grid transformer with only resistance in the grid circuits, tests show the effect on regulation to be negligible, even though the fundamental voltage shifts several degrees. This may be explained by the fact that the voltage applied to each grid through a resistance has almost identically the wave shape of the primary voltage. That is, it will have a wave proportional to the source voltage with nicks cut into it due to commutating currents, rather than a sine wave shifted in phase. Since the nicks in the voltage wave occur only during commutation they do not affect the voltage just before pickup provided only 2 anodes are commutating at one time, as is normally true.

## Regulators and Compensators

It is possible to regulate the output voltage of a grid-controlled rectifier, or ignitron, with the same types of current or voltage regulators that are used for rotating machines. The regulator may act to change the angle of delay, either by shifting the phase of the grid voltage or by varying the bias voltage applied to the neutral of a sine-wave grid transformer, which causes pickup to take place at a different point on the wave. The regulator may be made to give any desired regulation curve by using current compensation, and by cross current compensation units may be made to divide load under varying conditions. In some installations regulators have been applied so as to come into play only at high load for the purpose of limiting the overload. In electrochemical service current regulators have been used to control the output at any voltage.

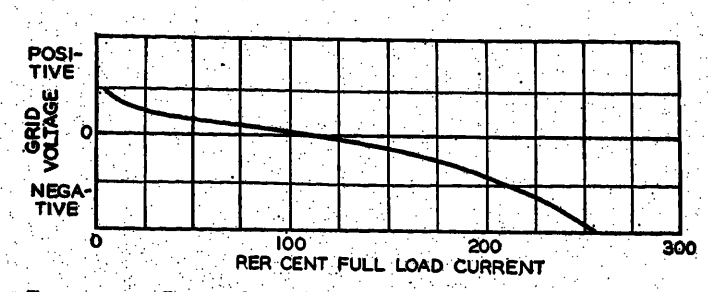



**Figure 6. Curve showing variation of grid pickup voltage with load current. Experimental rectifier**

In considering voltage regulation by grid control, either automatic or otherwise, it is essential to keep in mind its chief limitations. The transformer must provide the maximum voltage desired and any reduction in voltage is accomplished, first, at the expense of an almost proportional reduction in power factor and, second, an increase in d-c harmonics. For these reasons it may in some cases be more desirable to regulate the output voltage over the normal range by an induction regulator in the primary or by tap changing under load. A combination of tap changing and grid control can be made to give continuous control and good power factor.

Inherent compensation or compounding can be used on a grid controlled rectifier or ignitron with results similar to compounding in a d-c generator. The action of such a compensator can be made practically instantaneous, thus eliminating the tendency to hunt or overshoot.

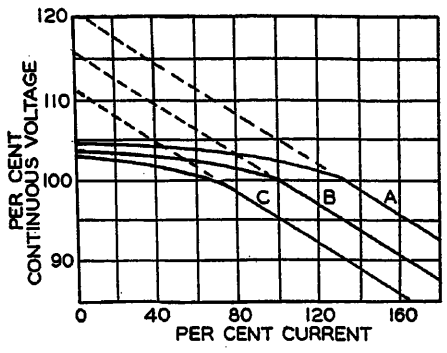
There are several methods of obtaining this compounding effect. One method is to use small series transformers, in the primary of the supply transformer, with a rectifier connected to the neutral of a sine-wave grid transformer. When adjusted for some grid delay at no load, the load current will cause an increase in positive bias which advances the phase and tends to raise the output voltage. This may be adjusted to compensate for the regulation of the transformer and line reactance or it may be made to more than compensate for the natural regulation, thus giving an overcompound regulation characteristic.

Another method of obtaining some compounding effect, and at the same time reducing the variation in continuous voltage due to variations in the a-c supply, is to connect the neutral of the grid transformer to the negative bus through a source of fixed positive bias. This gives a net bias on the grids which is proportional to the difference between the output voltage and the constant positive bias. An increase in output voltage will cause an increase in net negative bias and so increases the angle of delay and reduces the voltage. The sensitivity of this scheme will be limited by the lowest grid impulse voltage which may be used and still obtain accurate pickup of the anodes so as to insure balanced currents.

A combination of the 2 schemes of inherent regulation mentioned above may be used to give almost any regulation characteristic desired. Results similar to those discussed here were described in a recent paper by Goodhue and Power.[1] The method used by them differed in that they employed no grid transformer, but relied on the tube characteristics and the ripple of the output voltage to time the pickup of the anodes.

The regulation curves for an ignitron rectifier with current and voltage compensation are shown in figure 7. In this case as shown by the curves, the regulation is reduced from 17 per cent to 3.5 per cent and the variations in output voltage with the high line are reduced except at higher loads. The desirability of such characteristics for certain applications is obvious.

**Figure 7. Rectifier regulation curves, showing the effect of compounding to correct for a high reactive drop and variations in high line voltage**




Curves *A*, *B*, and *C* are for 104, 100, and 96 per cent high line voltage

## Conclusions

The following conclusions may be drawn from the work presented in this paper:

1. Accurate determination of the regulation of a rectifier connected to system, whose voltage is affected by the rectifier current, requires a modification of the conventional regulation formula as given in equation 2. The effect of the system reactance may also be taken into account by adding a correction term given by equation 6 and by the curves of figure 2.

2. With a normal amount of load inductance the conventional formula (equation 1) is not accurate at light loads where there is a counter electromotive force. This effect is much more pronounced with appreciable grid delay than at no delay. A graphical method of evaluating this effect is given and the results plotted in figure 5 as a correction term which is a function of delay and load circuit inductance. A comparison with test is given in figure 3. This is generally not important but may be corrected by adding inductance.

3. There is a tendency for the regulation curves of a rectifier, operating with a fixed phase-shifter or grid-bias setting, to curve up at overloads. This effect is due to the fact that with high ionization in the tank the grids pick up at a more negative voltage. The results of this effect on the regulation curves of the rectifier are shown in figure 1. This effect may be minimized by applying steep-wave-front impulses to the grids, or making a grid structure whose pickup voltage is only slightly affected by the amount of ionization in the tank.

4. Current and voltage regulators of the same general type as used for controlling the fields of rotating machines may be used to control the output voltage of grid-controlled rectifiers and ignitrons. It is also possible to use current and voltage compensation inherently to modify the regulation characteristics giving results similar to compounding on a d-c machine.

## List of Symbols

$A$ = arc drop
$e_d$ = instantaneous output voltage
$E$ = root-mean-square voltage anode to neutral, at no load
$E''$ = fundamental-frequency voltage back of system reactance
$E_c$ = counter electromotive force
$E_d$ = average output voltage
$E_{d0}$ = theoretical no-load output voltage
$f$ = fundamental frequency
$g$ = number of groups
$I$ = average total current output
$I_1$ = fundamental of secondary current
$L_t$ = total interphase inductance, from one transformer group to the other
$\mathfrak{L}$ = total output circuit inductance
$\mathfrak{L}_t$ = interphase leakage inductance, measured with windings in parallel, magnetomotive forces opposed
$P$ = number of phases per group
$P'$ = total number of phases for the rectifier
$u$ = angle of overlap
$W_T$ = copper loss of main and interphase transformers
$X_e$ = effective value of generator reactance to be used in rectifier calculations
$X_d''$ = direct-axis subtransient reactance
$X_q''$ = quadrature-axis subtransient reactance
$X_s$ = system commutating reactance converted to secondary ohms per phase
$X_T$ = transformer commutating reactance in ohms per phase in secondary
$X_2$ = negative-phase-sequence reactance
$\alpha$ = angle of retard or delay
$\Delta E_L$ = increase in voltage due to lack of inductance in load circuit
$\Delta E_s$ = increase in voltage regulation due to system reactance
$\theta_1$ = power factor angle of fundamental-frequency power

## Appendix A. Outline of a General Method of Analysis

The discussion of the paper has been confined to practical solutions which involved numerous assumptions and approximations. It is interesting therefore, to consider what might be done in the way of a more general solution taking into account many more factors. Although the mathematical formulas are not given, such a general method of analysis is outlined here in order to give a physical picture of what is involved and to aid in judging the simplifying assumptions made in the practical formulas.

The principle of superposition has been previously used[8] in the calculation of commutating currents. This principle can be extended to the solution of the currents and voltages in the complete rectifier system including both a-c and d-c circuits by solving a series of transient states. The a-c system impedance including capacity and resistance as well as reactance, may be accurately dealt with. Also the counter electromotive force, the inductance of the d-c system, and the shunt capacity of any filter circuits may be included in the analysis.

The only limitations of this method of analysis, other than the general limitation that the circuit constants must remain fixed are: (1) that the currents drawn by the rectifier being analyzed must have negligible effect on any other sources of harmonics such as those from another rectifier and, (2) that the arc drop is constant for a given value of average current. Where several similar rectifiers are connected to the same source and are similarly loaded they may be analyzed as if they were a single rectifier.

For this exact analysis the voltage on each anode at no load, and the actual angle of delay must be known. The picking up and the extinction of the arcs in the rectifier may be thought of as switching operations. In the analysis for any given condition the arc drop may be considered as a voltage source in series with each anode.

The ripple on the output voltage wave has a period equal to $1/P_1$ times the period of the fundamental frequency. This period may be further broken down into several time intervals, one for each different combination of anodes firing. The principle of superposition can be used in solving the transient within each interval. In general a transient resulting from a change in the circuit may be

solved by assuming an imaginary voltage equal and opposite to the applied no-load voltage so that the circuit may be left closed with no current flowing. A second imaginary voltage is then applied to cancel the first and to give the transient current.

When 2 anodes are firing they are in effect connected together. Using the above method the average of their no-load voltages opposed by the counter electromotive force for the load may be thought of as acting through the paralleled impedances of the transformer windings and their associated primary and system impedances, and through the load impedance.

An accurate analysis would require that equivalent circuits be constructed for the system as viewed from the rectifier terminals. It may also be necessary to set up an equivalent circuit for the load if there are several branches. If there are several sources of counter electromotive force an equivalent value may be obtained.

If the no-load voltages consist of several appreciable harmonics, as well as a suddenly applied fundamental, the equivalent circuit must be solved for each. If the harmonics are negligible the solution can be greatly simplified.

In order to determine the length of time an anode fires it is necessary to determine when the resultant current goes to zero. When the current reaches zero there is no reverse current (except in case of an arcback), hence the circuit is in effect switched open. The total current in an anode circuit is the resultant of the load component calculated as described above and a commutation current which is circulating due to the difference in voltages of any anodes that are firing at the same time. This commutating current can be solved by the same general methods outlined above, in which case the load circuit is not involved. The interphase transformer may be involved if the commutating current between 2 groups is considered, as in calculating the light-load voltage rise.

From this outline it is apparent that we can resolve the calculation of all voltages and currents involved into the solving of a series of transient states. Because it is necessary to determine the time intervals from the solutions for the total current in an anode, the mathematical determination of the boundary conditions may be difficult.

## Appendix B. Generator Reactance to Be Used in Rectifier Calculations

If a rectifier is fed from a single generator the generator adds to the commutating reactance increasing the angle of overlap and affecting the output voltage. The generator reactance drop to fundamental-frequency current may be added to the fundamental of the terminal voltage to get the internal sine-wave voltage. Using this internal voltage and the total commutating reactance the regulation can be calculated by the conventional formulas as indicated in the first part of the paper.

A question arises as to what generator reactance should be used. Since commutation is equivalent to a momentary short circuit the same reactance is effective as for the first fraction of a cycle of a single-phase short circuit. This reactance may vary between the direct-axis subtransient reactance ($X_d''$) and the quadrature-axis subtransient reactance ($X_q''$) depending on the load and the instant of short circuit. For zero delay and no load on the generator, $X_d''$ would be the value at the first instant of short circuit. For a delay angle $\alpha$, and load angle $\gamma$ between internal voltage and the terminal voltage, the effective reactance would be:

$$X_e = \frac{X_d'' + X_q''}{2} - \frac{X_q'' - X_d''}{2} \cos(2\alpha + 2\gamma) \qquad (1B)$$

If we use the method of symmetrical components to calculate the fundamental component of single-phase short circuit for a fundamental voltage applied, the effective reactance

$$X_e = \frac{X_d'' + X_2}{2} = \frac{3X_d'' + X_q''}{4} \qquad (2B)$$

This corresponds in the first equation to $\alpha + \gamma = 30$ degrees which is probably an average for conditions in which $\alpha$ does not exceed 30 degrees.

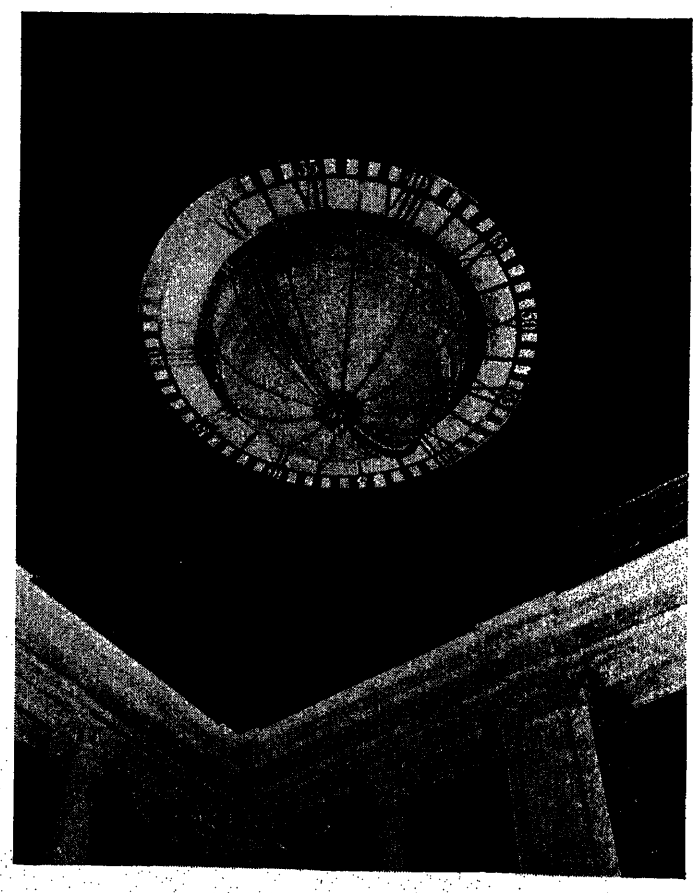
For the great majority of cases $X_d''$ and $X_q''$ will be so nearly equal that the approximate equation 2$B$, consistent with the method of symmetrical components, is sufficiently accurate and should be used.

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## Unusual Electric Clock

BEAUTY and individuality are combined with utility in this unique terrestrial-globe electric clock hanging in the foyer of the Christian Science Monitor Building in Boston, Mass. Lights in the dial around the globe indicate the hours by large Roman numerals and minutes by the smaller Arabic numerals around the edge. A twin celestial globe at the other end of the foyer gives the day of the month. Both are driven by Telechron motors.



# Tension Measurement and Control in Cold-Strip Mills

By C. M. HATHAWAY ASSOCIATE AIEE M. MOHLER Member Assn. Iron and Steel Engrs.

## Introduction

THE COLD rolling of steel strip on tandem mills requires the measurement and control of tension in the strip, and to meet this requirement the tensiometer herein described has been developed. The tensiometer produces a continuous indication of the tension in the strip during the rolling operation, and functions in connection with auxiliary control equipment to automatically maintain the tension at any desired value. An additional function of the tensiometer is the instantaneous indication of any difference in tension between the 2 edges of the strip.

## Value of the Tensiometer

A brief outline of the process of cold-strip rolling and of the problem involved is as follows:

A tandem mill consists of 2 or more mill stands placed in line so that the strip passes from one mill directly into the other. It is highly desirable to maintain tension in the strip between these stands. Greater reductions can be obtained, a greater number of elongations can be made without intermediate annealing to soften the strip, and a flatter and smoother strip can be rolled if the proper tension in the strip is maintained. Furthermore, much can be done to compensate for defects in roll shape, strip lubrication, mill-housing stretch, etc., by properly manipulating the tension.

However, in order to control tension it must be measured, and the control cannot be more accurate than the measurement. So far only 2 methods have been discovered for measuring this tension. One method is by electrically measuring the input to the motor producing the tension, and the other is by means of the tensiometer to be described. A brief comparison of these methods of control follows.

### Input Control

The input to a motor can be measured by measuring the armature voltage and current, and if the voltage is constant, it is only necessary to measure the current. The current in the armature of the motor driving the mill stand is therefore a function of the tension in the strip, provided all the input to the motor goes into tension.

This is not the case in a tandem mill, however. In this case the rolling load may represent about 90 per cent, and the tension 10 per cent, of the motor input. It is hardly conceivable that the rolling load does not vary at least plus and minus 10 per cent. This is equivalent to a variation in tension of 200 per cent if the total input to the motor is maintained at 100 per cent by a current regulator. The difficulties involved in attempting to control the strip tension by means of motor input control are apparent.

### Mechanical Control

Because of the difficulties involved in controlling the strip tension by controlling motor input, various mechanical schemes of measuring tension have been tried, but the major difficulty with such devices has centered around the inertia of the moving parts. These devices usually involve a roller over which the strip passes in such a way that the strip tension produces a force on the roller. If the roller is resiliently mounted and connected to some device for measuring its displacement when the tension is applied, a measure of the tension can be obtained. If this roller has to move an appreciable distance troubles are experienced in high-speed rolling due to inertia forces of the roller itself, so that the strip tension could change considerably before the roller could be accelerated and moved to its new position. The tensiometer makes use of this general scheme but uses a sensitive electric gauge for measuring the roller deflections, so that very small deflections are required. The natural frequency of the roller can then be made high enough to eliminate troubles resulting from inertia of the moving parts.

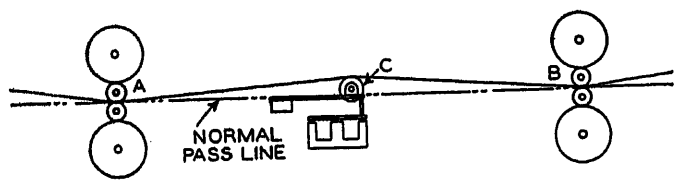



**Figure 1. Diagram showing location of pass roller C between 2 stands A and B**

### Level Indication

In addition to the tension problem, there has been a great need for some method of indicating whether the strip was the same thickness throughout its width. One edge can be measured with a flying micrometer but not the entire width. If one edge is the proper thickness and the tension is the same in both edges of the strip, it is reasonable to assume that the thickness of the other side is the same as that measured. If the other side is thicker, the tension will be greater on that side, and vice versa.

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This differential tension or "level" indication can also be obtained with the tensiometer.

## The Tensiometer

The need for a device for the measurement of total strip tension and of differences in tension between the 2 edges of the strip has been pointed out. The tensiometer produces a continuous indication of the total tension, provides a sensitive indication of any out-of-level condition, and operates in conjunction with standard control equipment to automatically maintain the total tension at any desired value by controlling the input to the mill motors. The tensiometer measures the total tension by measuring the force necessary to deflect the strip a given distance from the normal pass line. The strip as it passes from one mill to the next is caused to pass over a roller located so as to deflect the strip a small distance from the normal pass line. A force is thus produced on the roller at right angles to the normal pass line, and this force is proportional to the total strip tension. The arrangement is shown sche-

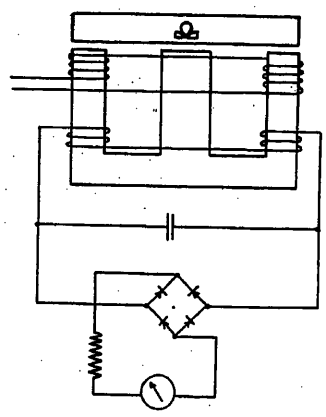
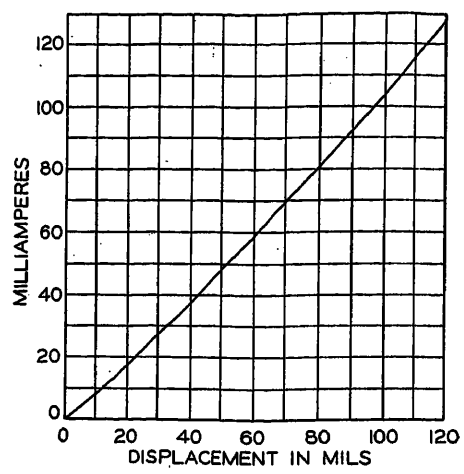


**Figure 2. Electric gauge for measurement of pass-roller deflection**

matically in figure 1 in which the strip is shown passing from *A* to *B* over the pass roller *C* of the tensiometer.

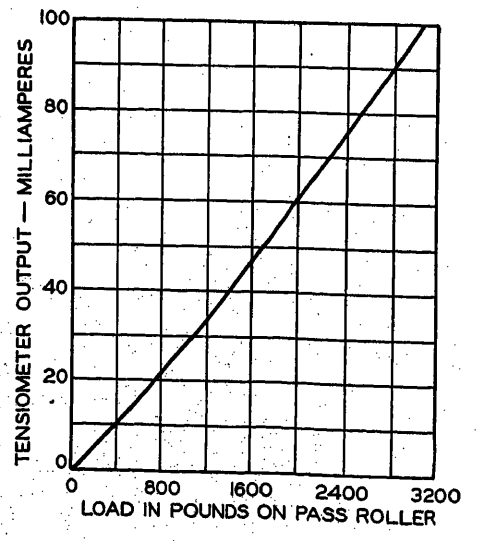
Each end of the pass roller *C* is mounted by means of antifriction self-aligning bearings on a stiff cantilever beam, and the deflection of each beam when load is applied to the pass roller is measured by means of an electric gauge. The electric gauge is a device capable of modulating or controlling an electric current in proportion to a small linear displacement. Each electric gauge has an output directly proportional to the deflection of the beam to which it is attached, and therefore, to the vertical load supported by the beam. The sum of the outputs of the 2 electric gauges is proportional to the total vertical load applied to the pass roller, and this is in turn proportional to the total strip tension if the deflections of the cantilever beams are small enough to be negligible in comparison to the elevation of the pass roller *C* above the normal pass line. The outputs of the 2 gauges are added by an instrument calibrated directly in thousands of pounds total strip tension. A second instrument is used to indicate any difference in output between the 2 gauges so that an indication can be obtained of any out-of-level condition that may exist in the mill.

**Figure 3. Electric gauge output current versus armature displacement**




The electric gauges used for the measurement of the deflection of the pass-roller supports consist of a stack of E-shaped laminations mounted adjacent to a laminated armature as shown in figure 2, so that a small air gap exists between the 2. The armature is supported at its center on knife-edge bearings, so that a movement of the armature on its bearings will increase the air gap at one end and decrease it at the other. On each of the outer legs is a primary and a secondary winding. The primary windings are connected in series across the a-c power source, and in such a direction that the resultant primary flux passes through the center leg. The secondaries are also connected in series, but in such a direction that the resultant flux due to a secondary current will flow around the outside of the laminated structure rather than through the center leg. With the primary and secondary windings connected in this manner, the induced voltage across the secondary terminals will be zero when the armature is in its mid-position and the air gaps at its ends are equal. For this condition, the voltages induced in the 2 secondary coils are equal and opposite. A displacement of the armature from this position will decrease one air gap and increase the other causing an unequal distribution of primary flux between the 2 secondary coils, and a voltage will appear across the secondary terminals that is a function of the armature displacement.

**Figure 4. Tensiometer output current versus pressure on pass roller**



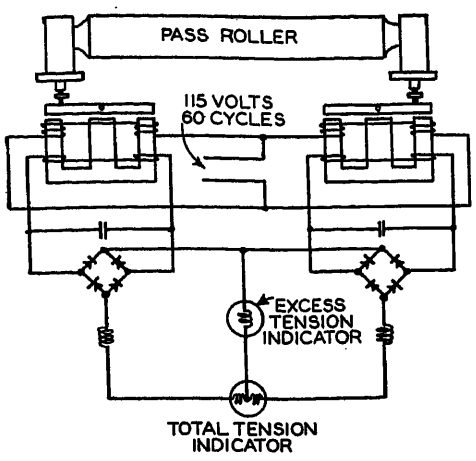



**Figure 5. Connection diagram of tensiometer indicating instruments**

The electric gauge unit can, therefore, be used to measure the deflection of the springs supporting the pass roller. The secondary output is rectified by a copper-oxide rectifier as shown in figure 2, and the rectified output is used to operate the indicating instrument and the control equipment. A capacitor across the secondary terminals greatly increases the sensitivity of the gauge because of the voltage rise produced by the passage of the leading current of the capacitor through the leakage reactance of the secondary.

The relationship between armature deflection from the neutral position and the rectified current in the secondary circuit is shown in figure 3. In figure 4 is shown the rectified current as a function of pressure on the pass roller as obtained by actual measurement on a typical tensiometer equipment.

If it is desired to indicate unequal tension between the 2 edges of the strip as well as the total tension, each end of the pass roller must be mounted on a separate spring and the deflection of each spring measured separately so that 2 electric-gauge units are required. The outputs of the 2 gauges can be added to obtain the total tension, and any difference between the outputs will be an indication of an out-of-level condition. These indications are obtained as shown in figure 5, in which *A* is the instrument for indicating total strip tension. This instrument carries 2 separate windings on its moving element. Each winding is connected in one of the detector unit circuits so that the instrument torque is proportional to the sum of the 2 electric-gauge outputs or to the total strip tension. Any difference in current between the 2 circuits will flow through the instrument *B* and will produce a sensitive indication of an out-of-level condition.

In some cases it may be desired to roll strip of a wide range of width and thickness in the same mill, and in such cases the total tension may vary over such wide limits that it is necessary to provide a means for changing the scale of the tensiometer. This could, of course, be done by changing the springs on which the pass roller is mounted when it is desired to change scales, but it can be done more easily by changing the mechanical ratio of the

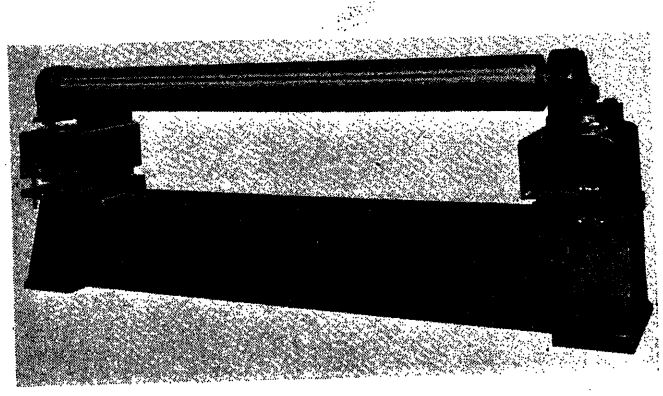


**Figure 7. Tensiometer stand with 93-inch pass roller**

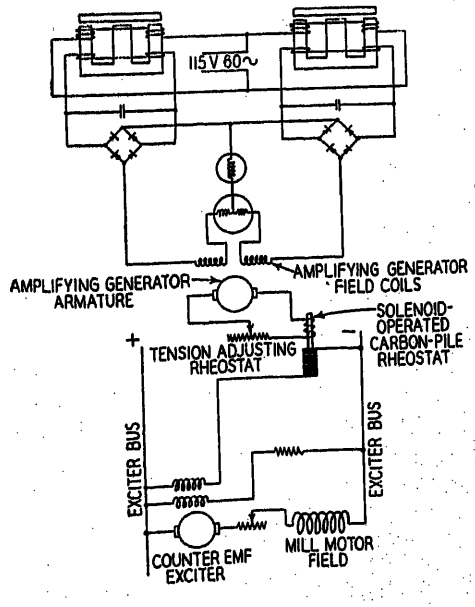



**Figure 6. Tension control system**

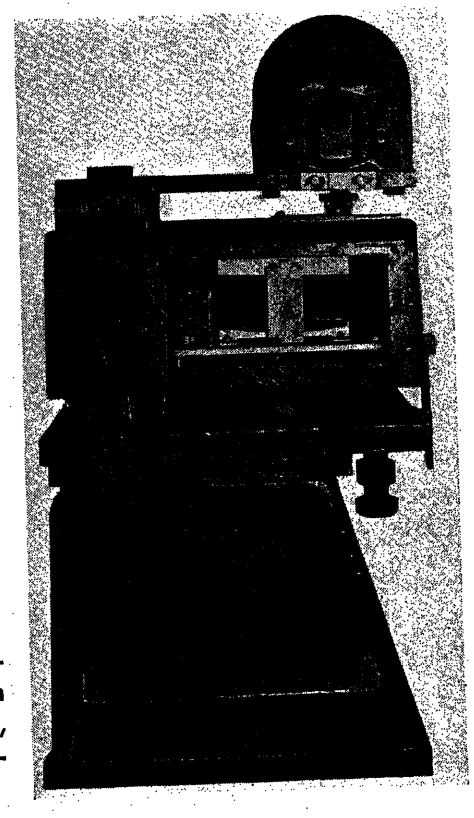


**Figure 8. Tensiometer stand with cover removed, showing electric-gauge unit**

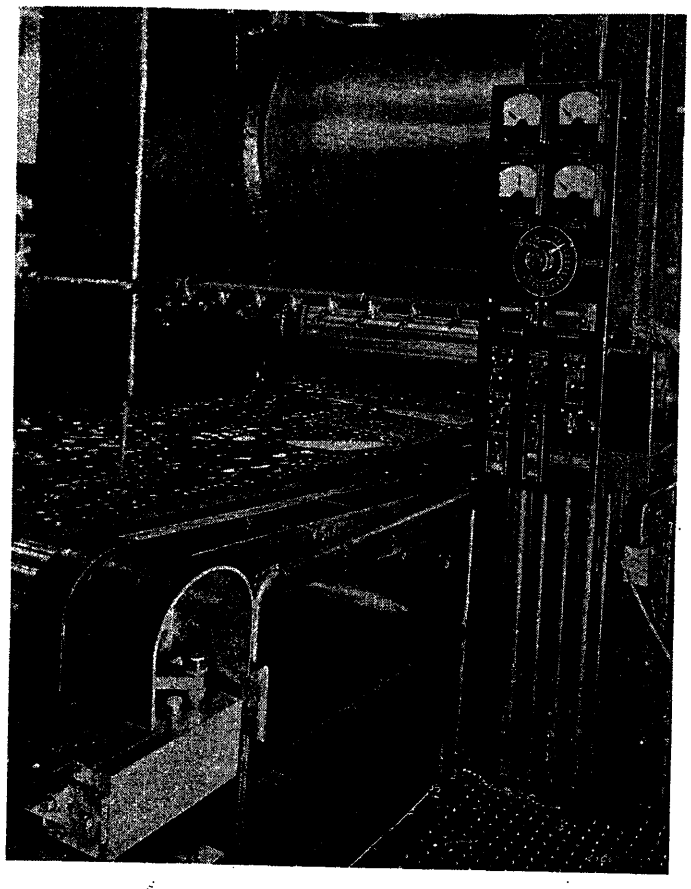


Figure 9. Tensiometer installation

linkage between the pass roller bearings and the electric-gauge armatures.

The upper element of the pass roller is located 2 or 3 inches above the normal pass line and the distance between stands is usually of the order of 10 or 20 feet. The diameters of the working rolls on the mills on each side of the tensiometer roller are not fixed but decrease with time due to wearing and resurfacing, so that the normal pass line is variable by as much as several inches. Provision must be made, therefore, for conveniently adjusting the elevation of the pass roller above the normal pass line, so that this value can be maintained at standard. To aid in making this adjustment, vernier height gauges are attached to each of the pass roller bearings. These gauges are calibrated directly in working-roll diameter, and must at all times be set to coincide with the average measured diameter of the 2 lower working rolls.

## Tension-Control System

A satisfactory control system for use in association with the tensiometer equipment for automatically maintaining the total strip tension at any desired value is shown schematically in figure 6. Referring to this figure the electric gauge outputs are amplified by means of a small 150-watt amplifying generator so that sufficient output is available for operation of a constant-current regulator. The regulator is used to control the field current in one winding of the counter-electromotive-force generator in the field circuit of the mill motor of the stand preceding the tensiometer.

## Typical Installations

In figure 7 is shown a tensiometer stand equipped with a pass roller 93 inches long. The electric-gauge units are enclosed in the steel boxes at each end of the roller, and the cantilever springs on which the pass roller is mounted are clearly shown. The cover is removed in figure 8, showing one of the electric-gauge units. Figure 9 shows a tensiometer and its associated control cabinet installed in a mill. One end of the tensiometer roller can be seen under the strip at the extreme left side of the photograph.

## Conclusions

A device termed a tensiometer has been described for the measurement of the tension in the strip during rolling in a cold-steel mill, and for the indication of any difference in tension between the 2 edges of the strip. The tensiometer can function in connection with auxiliary control equipment for the automatic maintenance of the total tension to any desired value. The value of tension measurement and "level" indication has been outlined, and the use of the tensiometer will aid to a more scientific study and operation of the cold-strip mill.

# "Science More or Less"

EVERY technical change brings about maladjustments, more or less serious depending on the number of people involved. Much more is involved than mere unemployment or the lowering of price to consumers. New processes may destroy the capital investments of sleeping corporations; they render men and equipment obsolete; they uproot whole industries and ways of life. To date, invention and scientific discovery have kept to the black side of the ledger; they have been credits to civilization. We should like to keep them there.

No one has yet solved the problems of human obsolescence, mass motivation, or technological unemployment. Unless our sociological inventiveness can show great improvement in the next 25 years we will not have made much progress no matter how pleasant and comfortable the air-conditioned lives of a few of us may be. I do not mean to imply that to get out of the woods we must have rigidly planned economy. The problem is much too complicated for that. The best plan in the world would be useless without the proper personnel, and with the proper personnel the plan, with its attending unpleasantness, is unnecessary. Education is far more important than coercion.

From an article by C. C. Furnas of the Yale University school of engineering, New Haven, Conn., published in volume 1, number 1, of *Amateur Scientist*.

# Mechanical High-Speed Resistance-Welder Control

By F. H. ROBY
ASSOCIATE AIEE

*Operating speeds of 350 or more welds per minute are made practical with a new type of control equipment for pneumatically operated portable welding tools.*

A DEMAND for higher production rates in the automobile and related industries has resulted in the adoption of pneumatically operated portable type resistance welding machines.[1] Fully automatic repeat control devices are needed to obtain maximum operating speeds without sacrificing the quality of the welds. To be practical this control must be simple and inexpensive.

This paper is concerned with a control device developed for use in connection with a high-speed portable air-operated machine now commonly used in the automobile industry. The principles outlined apply as well to other types of equipment.

A "stitch" welder consists of a pneumatically operated welding tool, a solenoid-operated valve and a separate welding transformer connected to the tool by means of water-cooled cables, 6 feet or more in length. When the operator squeezes a momentary contact push button in the pistol-grip handle of the tool, the automatic control device closes the electrodes, applies power, disconnects it, opens the electrodes and keeps them open for a definite period of time before repeating the cycle. Repeat operation continues for as long as the push button is closed. The term "stitch" welder has been applied because of similarity to an electric sewing machine.

Those connected with the application of resistance welding to the fabrication of sheet metal are familiar with the principle upon which the art depends—that the heat generated in the weld is proportional to the product of the welding current squared, the resistance between pieces of work and the time during which the current flows.[2] Few realize the difficulties encountered in satisfactorily controlling these 3 variables.

The current is determined by selecting the turn ratio of the welding transformer by means of a tap switch on the primary side. The resistance of the weld decreases or increases as the pressure applied to the work increases or decreases, respectively, and is controlled by regulating that pressure. Timing has previously involved the use of expensive and complicated control equipment. A recent trend is toward simplified but more comprehensive control.

## Control Equipment Now Used

Electronic control devices (power interrupted by electronic tubes instead of magnetic contactors) are made to accurately control the period of time during which the welding current is allowed to flow.[3] These devices select the point on the current wave at which the circuit is made and broken. Such equipment is necessary for some special applications but the first cost is high and complicated circuits make highly trained maintenance men necessary.

Other less-expensive systems of control consist of a magnetic contactor and some form of timing device. The timer may be mechanical, electromagnetic, or electronic.[4,5,6] Most designs determine only the period of time during which the welding current flows. A few control the interval of time between welds as well as the welding period.

## Four Independent Timing Periods Required

Recent experience has made clear that the factor of time in the weld has 4 component parts. For purpose of identification these have been named "delay," "weld," "hold," and "off."

The "delay" period is the interval required between the operation of the solenoid valve and the application of power. Two conditions may result from insufficient time delay. If the electrodes are energized before they touch the work a "flash" will result, leaving the surface of the work mutilated and the electrodes damaged. If the electrodes are closed but are under insufficient pressure when power is applied, the weld will appear to be satisfactory but it will not hold. Reference to the thermal gradient chart (figure 1) will make clear that heat is generated at 3 points in the secondary circuit. If the pressure on the work is low when the transformer is energized, the heat generated at points *A* and *C* will be large compared to that generated at *B*. The surfaces of the work will be burned before the temperature at point *B* is raised to the fusion point.

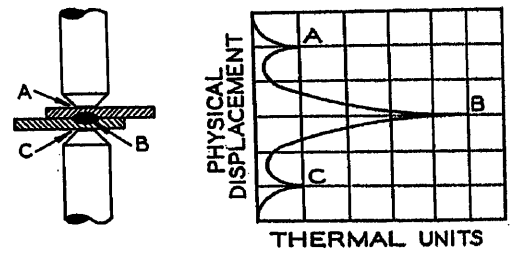



**Figure 1. Thermal gradient chart showing distribution of heat in weld**

Some manufacturers of welding equipment have recognized the need for obtaining a sufficient amount of pressure

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1. For all numbered references, see list at end of paper.

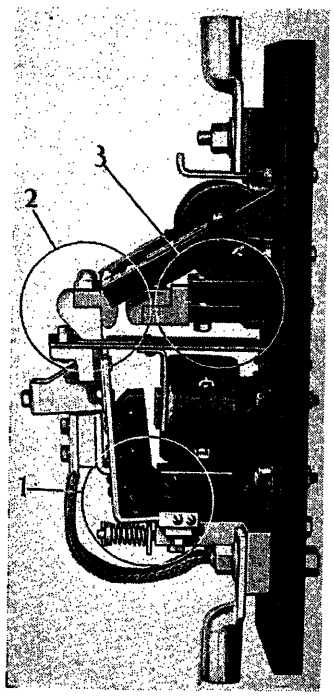



**Figure 2. Profile view of high-speed magnetic contactor**

on the electrodes within the shortest possible time and to this end have designed tools with favorable operating characteristics. Short strokes, large ports, and operating valves mounted as close to the tool as possible are essential. At least one automobile body manufacturer speeded up production by designing a solenoid valve in the handle of the tool itself, thereby eliminating the delay involved in building up pressure in the line between the valve and the tool.

A pressure switch is ordinarily connected in the air line in such a manner that the contacts of the switch close when the pressure on the operating piston has reached the desired value. The closing of the switch initiates the remainder of the welding cycle. Although satisfactory for most applications, the pressure switch has been eliminated from stitch-welder control. It represents an additional delay in the time required for the pressure to build up and exhaust in the line between the tool and the switch. Also, experience has determined that pressure switches will close prematurely because of turbulent air conditions, "slugs" of water in the line or because the electrodes are called upon to force together 2 or more pieces of work which have been formed improperly and do not fit perfectly. The solution of the problem lies in including in the control means for providing a definite time delay between the operation of the valve controlling the electrodes and the application of power. This period must be adjustable to compensate for the difference in the design of tools and the idiosyncrasies of the installation.

Much has been said about the "weld" time in other published information.[3,4,5,6] It is sufficient to point out that in the interest of high-speed production and improved welds, this period has been continually shortened until 5-cycle welds (60-cycle frequency) are considered average in industries using sheet metal ranging in thickness from 12 to 22 gauge. Shortened timing periods give less time for the heat generated in the weld to be conducted to the surface of the metal, thereby defacing or deforming the work.

In general, "fixed" timing is used. There is little need for "current responsive" timing which, in one manner or another, compensates for variations in the welding current.[5] The value of this current is essentially predetermined by the secondary voltage and the short-circuited impedance of the secondary circuit. The resistance of the weld itself has little effect on the impedance of the circuit formed by a pair of electrodes at the end of 2 cables at least 6 feet in length. Then, too, high-grade body stock is not usually subject to scale, rust, or other imperfections which materially influence the resistance of the weld. Changes in resistance of the weld affect results because of the presence of the resistance factor in the heat equation. Even accurate compensation for minor current changes would not alter this condition.

The shortest timing period practical when magnetic contactors are used to interrupt the primary of the welder transformer is between 2 and 3 cycles. There are 3 limitations. The so-called high-speed welder contactor requires slightly less than a cycle to close after the operating coil has been energized, and a little more than a cycle to open after it has been de-energized. If a contactor, when once closed, remains so for over a cycle, it cannot be used to energize a transformer for a period of time less than this amount. In fact, a longer period of time should be allowed to insure that the pole pieces of the magnet seal each operation. Otherwise, extremely erratic performance will result.

Secondly, magnetizing current transients[3,7] which result when the transformer is energized at the zero point of the voltage wave, cause wide variations in results if shortened timing periods are used. One welder application studied had peak primary currents of 217 and 1,030 amperes, respectively, on 2 consecutive spot welds. Without a doubt, this case is extreme but it serves to illustrate a limiting factor in shortened weld periods. The transient currents contribute to a lowered secondary voltage and a "cold" spot is the result. Fortunately, such transients die out along an exponential curve with a very steep characteristic, and they are effective for only one or 2 cycles.

Finally, a magnetic contactor will not respond accurately to a given electrical impulse unless that impulse begins each operation at the same point on the reference voltage wave. Otherwise, the transient in the operating coil may cause the contactor to fail to respond.

One solution to the transient problem is the use of a control device having electronic tubes as interrupters instead of magnetic contactors. The point at which the circuit

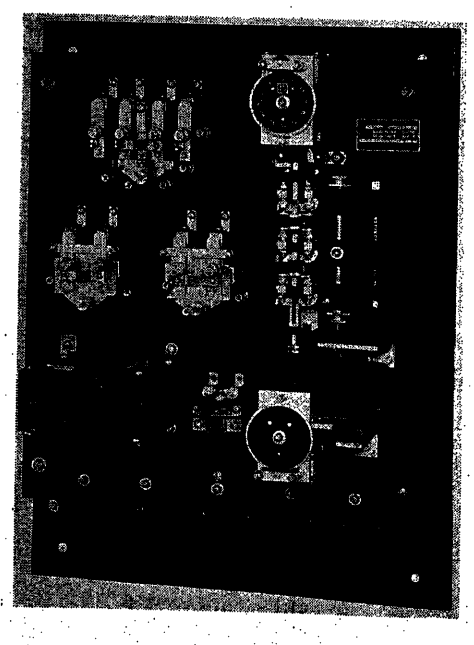


**Figure 3. Mechanical high-speed resistance-welder control unit**

is made and broken can then be controlled. The use of such complicated and expensive control equipment is not necessary when ordinary ferrous metals are being welded because the plastic range of the metal is wide enough to absorb reasonable variations in control. The timing period can be lengthened to 3 or more cycles to make the variations small when compared to the total.

The design of a magnetic contactor which will consistently perform at the rate of 350 or more operations per minute and will have the operating characteristics needed for short timing is a problem in itself. Long mechanical life, immediate interruption of the arc, rapid operation, and accessibility are imperative. The high-speed heavy-duty welder contactor illustrated (figure 2) has knife edge bearings (1); short gap (2); strong blowout coil and large copper contacts with gap adjustment (3).

The "hold" time is the interval least discussed in the timing cycle and yet is one of the most importance. Until recently, it was general practice to de-energize the operating coils of the welding contactor and the solenoid valve at the same instant. It was assumed that the welding contactor would open before the electrodes parted. Such practice was effective for as long as tools were sluggish and exhaust lines restricted. Modern tools, with valve in the handle, open as fast or faster than the welding contactor, making a predetermined "hold" time necessary.

When the electrodes are allowed to remain on the work a period of time after the power is off, the appearance of the weld is improved. The water-cooled electrodes conduct away the heat as it comes to the surface, thereby preventing abnormal discoloration. A weld allowed to cool under pressure also has finer grain structure and greater strength.

Two additional advantages of "hold" time have made themselves apparent in the automobile industry. Welds made on pieces of work not properly fitted together are prevented from breaking open before the weld is cooled below the plastic stage and heat is prevented from traveling ahead of the spot being welded. The electrodes of the tool are apt to stick to the surfaces of work made plastic by heat from a weld immediately adjacent.

The "off" period needs little discussion. When repeat operation is desired, the operator continues to hold down the momentary contact push button in the handle of the tool and the timing device regulates the period during which the electrodes remain open before the cycle is repeated. The minimum "off" time is determined by the interval required to open the gun and the delay involved in moving the tool to a point at which the next weld is to be made.

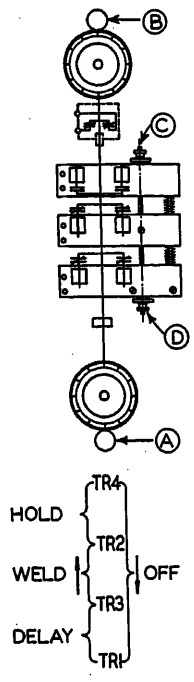



**Figure 5. Graphical representation of control adjustments**

## Description of Control Unit

The need for separately adjustable timing periods is clear. To obtain them without seriously complicating the control device has presented a problem. One solution is illustrated in figure 3. The nucleus of the device is formed by 2 diaphragm-type pneumatic time-delay assemblies joined by means of a rod upon which a series of contacts is mounted. With the rod in its normal position, the top diaphragm *A* of the lower assembly (figure 4) is cupped downward, forcing the air in the upper chamber down through the spring-held release valve *B*. Lower diaphragm *C* responds to the movement of the top diaphragm confining the air to the lower chamber and making it unnecessary to expose the mechanism to the danger of faulty operation because of dust or other foreign matter in the air surrounding the installation. When force is applied to the contact rod, tending to move it upward, air must be drawn into the upper chamber from the lower one. Because valve *B* has seated itself the only possible passage is regulated by needle valve *D*. A similar mechanism coupled to the upper end of the rod regulates its downward travel.

The interval off time required for the rod to complete its upward stroke must be long enough to include the "delay," "weld," and "hold" periods (figure 5). The "off" period is determined by the interval required for the rod's return to its initial position.

Once the rod speed has been established, adjustment *C* can be regulated to provide spacing between contacts *TR*2 and *TR*3 and obtain the "weld" time needed. Adjustment *D* proportions the "delay" and "hold" periods to meet the requirements of the application. The "weld" time is not changed by this adjustment inasmuch as contacts *TR*2 and *TR*3 are moved the same amount.

## Schematic Diagram of Circuit

Figure 6 is a schematic diagram of the electrical connections used. Closing the push button energizes control relay *CR*1 which in turn applies power to the check valve and the operating coil of control relay *CR*2. This relay energizes the solenoid operated 4-way valve which applies air to the tool and also connects the operating coil of timing relay *TR*1 to the line. The armature of the timing relay magnet closes instantly, compressing a spring which applies force to the contact rod. Timing is, therefore, independent of voltage.

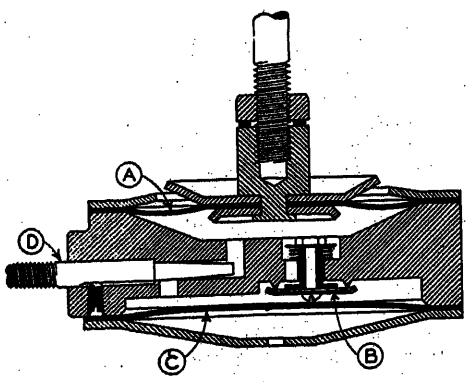



**Figure 4. Cross-sectional view of time-delay unit**

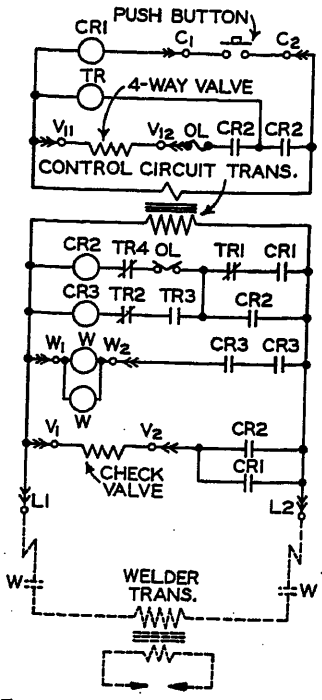



**Figure 6. Schematic diagram of electrical connections**

During the upward travel of the rod, contact *TR*1 is opened first, disconnecting the pole of relay *CR*1 which functions from the push button. Operation continues because relay *CR*2 has formed its own maintaining circuit. Later in the rod travel contact *TR*3 closes, energizing relay *CR*3 which in closing energizes the magnetic contactor that applies power to the machine. Still later contact *TR*2 opens, dropping out relay *CR*3 and de-energizing the welding contactor. The pressure on the electrodes is not removed until the rod reaches the end of its upward travel, opening contact *TR*4 and de-energizing control relay *CR*2. The cycle is not repeated again until the rod is returned to its initial position, reclosing contact *TR*1.

Features not ordinarily required can be included in the control device. The installation of a check valve to close the air-supply line during the period in which the tool is not in use is not difficult. Double action air cylinders are ordinarily used to speed up operation and considerable leakage occurs in the head end of such cylinders.

A low-voltage transformer large enough to supply the solenoid operating valve can be mounted on the panel. It is considered good practice to energize the valve solenoid from a low-voltage supply source if it is located in the handle of the tool where a ground would endanger the operator. To prevent the burning out of the valve solenoid if it should lodge in the open position, a thermal protective device can be included in the circuit.

Maintenance is simplified by the use of a separable connector on the panel to make it unnecessary to disconnect any wiring if the panel is removed. Panels can be interchanged with minimum delay and repairs or adjustments on the defective unit can be made later in the electrician's shop.

## Test Procedure

The information contained in this paper has been verified in a series of field tests conducted by one of the large automobile-body manufacturers. A cathode-ray oscillograph was used to analyze the various components of the timing period previously described. The circuit of the oscillograph was arranged to show simultaneously on the viewing screen 4 elements of the weld cycle. To accomplish this the a-c voltage applied to the solenoid-operated air valve was fed through a rectifier to the vertical plates of the cathode-ray tube. A second a-c signal having as its source the voltage drop across the work itself was applied directly to the same set of plates. Horizontal plates of the cathode-ray tube were energized from a sweep circuit which forms a part of the oscillograph. A pattern similar to that illustrated in figure 7 resulted. Synchronizing contacts on the control device being studied caused the image to appear at the same place on the screen each operation.

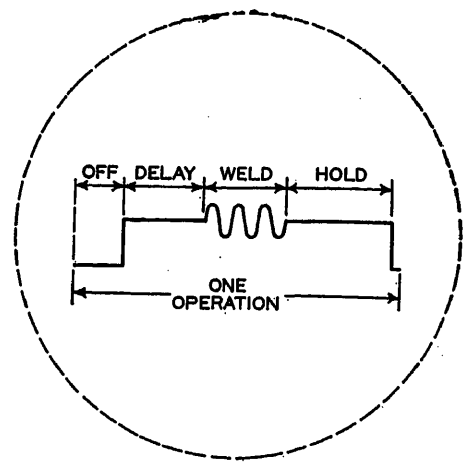



**Figure 7. Representation of oscillograph screen showing method of measuring weld cycle.**

Practical problems in welding were considered and a theoretical solution to each problem was advanced. Adjustment of the timing device to meet the specifications outlined in the theoretical solution was accomplished with the aid of the oscillograph. Samples of materials were welded and results checked. In each instance it was determined that satisfactory welds could be made if the 4 component parts of the welding cycle were properly proportioned. At least 25 installations of the type described have been in operation for several months on an automobile-body assembly line. Reports indicate that the conclusions reached during laboratory tests were justified.

## Conclusions

Under laboratory controlled conditions good welds have been made at the rate of 600 per minute. Commercial results will depend upon the design of the equipment being used and the application involved. It is certain, however, that good welds will be made at the maximum rate only if each portion of the welding cycle is accurately and independently controlled.

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# Double-Line-to-Neutral Short Circuit of an Alternator

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*Starting with R. H. Park's formulas for the flux linkages of an ideal synchronous machine, the case of a fault from 2 line terminals of a generator to neutral is treated in a manner similar to that used by Doherty and Nickle for other unsymmetrical faults. Expressions are given for the armature currents in the faulted phases and for the main field current, at any time after the short circuit. An expression for the voltage across the open phase a short time after the fault is also developed.*

## Introduction

THE PROBLEM of short circuits at the terminals of synchronous machines is one that has been studied extensively for a number of years. R. H. Park[1] has given a rigorous solution of the 3-phase symmetrical fault, and Doherty and Nickle[2] have developed expressions for the currents flowing during single-phase short circuits both between lines and from line to neutral which give excellent checks with experimental results. The present paper derives similar expressions for currents flowing in a machine when 2 lines are faulted to neutral. Park's formulas for the armature and field flux linkages of an ideal synchronous machine are used as a starting point. They are simplified by the additional assumption that all resistances are negligible. Decrement factors are applied to the resulting expressions for current and voltage in a manner analogous to that used by Doherty and Nickle. The final formulas are found to give results which are in good agreement with experiment.

The basic assumptions made in the treatment of this problem are:

1. The assumptions made by R. H. Park in his definition of an ideal synchronous machine.[5]
2. That the resistances of all field and armature circuits are negligible except where they appear in decrement factors.
3. That the speed of the rotor is constant at all times.

The second assumption is equivalent to saying that the flux linkages in both the direct and quadrature axes remain constant, that is, the effects of the terms $p\psi_d$ and $p\psi_q$ of reference 1 are neglected. If this assumption were strictly adhered to, the initial values of the currents as given by equations 11 would persist indefinitely. We know, however, that if assumption 2 were not made the fluxes and consequently the currents would decrease according to certain decrement factors obtained from the roots of a determinantal equation arising in the solution of equations 11, 12, and 13 of reference 1. Since in the case of a double-line-to-neutral fault this equation cannot be solved algebraically these decrement factors are obtained approximately and applied to the appropriate terms of equations 11. This treatment should not produce much error unless either the decrement factor of some circuit or the armature circuit resistance is large.

The third assumption should not introduce much error except in the case of a machine with a small moment of inertia which might slow down appreciably at the instant of short circuit.

The machine is considered to have 2 field circuits in the direct axis, referred to as the main and the additional field. In the quadrature axis there is no main field, so only the additional (amortisseur) field is present. Direct current excitation is applied only in the main field.

The short circuit is assumed to occur directly at the terminals of the machine at a time when it is carrying no load. If the short circuit occurred through external reactance this reactance could be added to the direct- and quadrature-axis reactances and the sums used in equations 35. If there is much external resistance the equations of this paper cannot be used because of assumption 2.

## System of Units

All quantities said to be in armature terms are in a per-unit system based on the following normal values:

$e_n$ = rated phase voltage of the machine in volts
$i_n$ = rated phase current in amperes
$X_n = r_n = \frac{e_n}{i_n}$ = normal reactance or resistance in ohms
$\omega_n = 2\pi f_n$ = normal angular velocity in radians corresponding to a normal frequency of $f_n$ cycles
$L_n = \frac{X_n}{\omega_n}$ = normal inductance in henrys
$\psi_n = L_n I_n$ = normal flux linkages in volt seconds

The term "per unit" means that the quantity in question is expressed as a fraction of the appropriate normal value. Note that at normal frequency per-unit reactance equals per-unit inductance. The symbol $x$ as used in the paper can therefore be thought of as either an inductance or a reactance, whichever is most convenient.

For reasons that will be brought out later it is sometimes convenient to express quantities in field terms. Quantities said to be in main field terms have the following normal values:

$E_{fn} = \frac{e_n R_{fd}}{x_{afd}}$ = voltage in volts which if connected to main field terminals will cause normal field current to flow

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1. For all numbered references, see list at end of paper.

where

$R_{fd}$ = per-unit resistance of the main field in armature terms
$x_{afd}$ = per-unit mutual inductance of the armature with the main field in armature terms
$I_{fn} = \frac{i_n}{x_{afd}}$ = normal main-field current, that is main-field current which will produce rated terminal voltage on open circuit

$R_{fn} = \frac{e_n}{i_n} R_{fd}$ = normal main-field resistance

Quantities said to be on additional field terms are based on similarly defined normal values except that the subscript $f$ is replaced by one.

To change a per-unit quantity from one system to another simply multiply the per-unit quantity in the old system by the ratio of its normal value in the old system to its normal value in the new system. Thus for example:

$$I = I_{fd} \times \frac{i_n}{I_{fn}} = x_{afd} I_{fd}$$

where:

$I$ = main-field current in main-field terms, direct axis
$I_{fd}$ = main-field current in armature terms, direct axis

## Development of General Equations

Let the following symbols represent per-unit quantities in armature terms:

$\psi_a, \psi_b, \psi_c$ = armature phase flux linkages in phases $a$, $b$, and $c$
$i_a, i_b, i_c$ = armature phase currents in phases $a$, $b$, and $c$
$x_d'', x_d', x_d$ = subtransient, transient, and synchronous reactances in the direct axis
$x_q'', x_q', x_q$ = subtransient, transient, and synchronous reactances in the quadrature axis
$x_0$ = zero-sequence reactance
$\theta$ = angular position of the rotor in degrees measured from the axis of phase $a$
$e$ = open-circuit terminal voltage for one phase
$r$ = resistance of one armature phase

Let the following symbols represent per-unit quantities in main field terms:

$I$ = current in main field, direct axis
$E$ = excitation voltage in main field, direct axis. It is also numerically equal to the sustained steady state d-c current in main field, direct axis

Let the following symbols represent per-unit quantities in additional field terms:

$I_{d1}$ = current in additional field, direct axis
$I_{q1}$ = current in additional field, quadrature axis

It is also convenient to talk about the total excitation due to all fields in an axis. In terms of the above defined quantities there is:

$I_d = I + I_{d1}$ = excitation in direct axis
$I_q = I_{q1}$ = excitation in quadrature axis

Park gives the following formulas for armature flux linkages:

$$\psi_a = I_d \cos\theta - I_q \sin\theta - \frac{x_0}{3}(i_a + i_b + i_c) - \frac{x_d + x_q}{3}\left(i_a - \frac{i_b + i_c}{2}\right) - \frac{x_d - x_q}{3}[i_a \cos 2\theta + i_b \cos(2\theta - 120) + i_c \cos(2\theta + 120)] \quad (1a)$$

$$\psi_b = I_d \cos(\theta - 120) - I_q \sin(\theta - 120) - \frac{x_0}{3}(i_a + i_b + i_c) - \frac{x_d + x_q}{3}\left(i_b - \frac{i_c + i_a}{2}\right) - \frac{x_d - x_q}{3} \times [i_a \cos(2\theta - 120) + i_b \cos(2\theta + 120) + i_c \cos 2\theta] \quad (1b)$$

$$\psi_c = I_d \cos(\theta + 120) - I_q \sin(\theta + 120) - \frac{x_0}{3}(i_a + i_b + i_c) - \frac{x_d + x_q}{3}\left(i_c - \frac{i_a + i_b}{2}\right) - \frac{x_d - x_q}{3}[i_a \cos(2\theta + 120) + i_b \cos 2\theta + i_c \cos(2\theta - 120)] \quad (1c)$$

When the assumption is made that $r = 0$, equations 4$a$ and 5 of reference 1 become:

$$I_d = E + (x_d - x_d'')i_d \quad (2)$$

$$I_q = (x_q - x_q'')i_q \quad (3)$$

where

$$i_d = \frac{2}{3}[i_a \cos\theta + i_b \cos(\theta - 120) + i_c \cos(\theta + 120)] \quad (4)$$

$$i_q = -\frac{2}{3}[i_a \sin\theta + i_b \sin(\theta - 120) + i_c \sin(\theta + 120)] \quad (5)$$

also in the per-unit systems used

$$E = e \quad (6)$$

After substituting equations 2 to 6 into equations 1 there results:

$$\psi_a = e\cos\theta - \frac{x_0}{3}(i_a + i_b + i_c) - \frac{x_d'' + x_q''}{3}\left(i_a - \frac{i_b + i_c}{2}\right) - \frac{x_d'' - x_q''}{3}[i_a \cos 2\theta + i_b \cos(2\theta - 120) + i_c \cos(2\theta + 120)] \quad (7a)$$

$$\psi_b = e\cos(\theta - 120) - \frac{x_0}{3}(i_a + i_b + i_c) - \frac{x_d'' + x_q''}{3}\left(i_b - \frac{i_c + i_a}{2}\right) - \frac{x_d'' - x_q''}{3}[i_a \cos(2\theta - 120) + i_b \cos(2\theta + 120) + i_c \cos 2\theta)] \quad (7b)$$

$$\psi_c = e\cos(\theta + 120) - \frac{x_0}{3}(i_a + i_b + i_c) - \frac{x_d'' + x_q''}{3}\left(i_c - \frac{i_a + i_b}{2}\right) - \frac{x_d'' - x_q''}{3}[i_a \cos(2\theta + 120) + i_b \cos 2\theta + i_c \cos(2\theta - 120)] \quad (7c)$$

If $\theta_0$ is the angular position of the rotor at the last instant before short circuit, then at that instant

$$\psi_a = e\cos\theta_0$$
$$\psi_b = e\cos(\theta_0 - 120)$$
$$\psi_c = e\cos(\theta_0 + 120) \quad (8)$$

since because of our assumption that the armature resistance is negligible the flux linkages before the short circuit must equal the flux linkages after the short circuit. When equations 7$a$, 7$b$, 7$c$, and 8 are combined and solved for

$i_a$ and $i_b$ under the special condition for a double-line-to-neutral fault, $i_c = 0$, there results:

$$i_a = \frac{1}{2}\sqrt{3}e\left\{\frac{(x_d'' + x_q'')[\cos(\theta - 30) - \cos(\theta_0 - 30)]}{D} + \frac{(x_d'' - x_q'')[\cos(2\theta - \theta_0 - 30) - \cos(\theta - 30)]}{D} + \frac{2x_0[\cos(\theta + 30) - \cos(\theta_0 + 30)]}{D}\right\} \quad (9a)$$

$$i_b = \frac{1}{2}\sqrt{3}\,e\left\{\frac{(x_d'' - x_q'')\,[\cos(\theta - 90) - \cos(\theta_0 - 90)]}{D} + \frac{(x_d'' - x_q'')\,[\cos(2\theta - \theta_0 - 90) - \cos(\theta - 90)]}{D} - \frac{2x_0\,[\cos(\theta + 30) - \cos(\theta_0 + 30)]}{D}\right\} \quad (9b)$$

where

$$D = x_d''\left(x_0 + \frac{1}{2}x_q''\right) + x_q''\left(x_0 + \frac{1}{2}x_d''\right) + \left[x_d''\left(x_0 + \frac{1}{2}x_q''\right) - x_q''\left(x_0 + \frac{1}{2}x_d''\right)\right]\cos(2\theta + 60) \quad (10)$$

It can be seen that each of the phase currents is made up of 3 components. Each of these components may be expanded into a harmonic series by assuming a Fourier series and finding the appropriate coefficients. When this work is carried out there results:

$$i_a = \frac{1}{2}\sqrt{3}e\,[M(x_d'' + x_q'')(A_{ep} + A_{0p}) + M(x_d'' - x_q'') \times (A_{en} + A_{on}) + Mx_0(A_{e0} + A_{00})] \quad (11a)$$

There is a similar expression for $i_b$:

$$i_b = \frac{1}{2}\sqrt{3}e\,[M(x_d'' + x_q'')(B_{ep} + B_{0p}) + M(x_d'' - x_q'') \times (B_{en} + B_{on}) - Mx_0(A_{e0} + A_{00})] \quad (11b)$$

where

$$M = \frac{1}{2\sqrt{x_d''\left(x_0 + \frac{1}{2}x_q''\right)x_q''\left(x_0 + \frac{1}{2}x_d''\right)}}$$

$$A_{ep} = -2\cos(\theta_0 - 30)\left(\sum_{n=2}^{\infty} b^{\frac{n}{2}}\cos n(\theta + 30) + \frac{1}{2}\right)$$

The subscripts indicate that this is the series of even harmonics which is multiplied by $x_d''$ plus $x_q''$.

$$A_{0p} = +\frac{1}{2}(1 + b)\sum_{n=1}^{\infty} b^{\frac{n-1}{2}}\cos n(\theta + 30) + \frac{1}{2}\sqrt{3}(1 - b)\sum_{n=1}^{\infty} b^{\frac{n-1}{2}}\sin n(\theta + 30)$$

$$A_{en} = +\cos\theta_0(1 - b^2)\sum_{n=2}^{\infty} b^{\frac{n-2}{2}}\sin n(\theta + 30) - b\sin\theta_0 - \sin\theta_0(1 + b^2)\sum_{n=2}^{\infty} b^{\frac{n-2}{2}}\cos n(\theta + 30)$$

$$A_{0n} = -A_{0p}$$

$$A_{e0} = -4\cos(\theta_0 + 30)\left[\sum_{n=2}^{\infty} b^{\frac{n}{2}}\cos n(\theta + 30) + \frac{1}{2}\right]$$

$$A_{00} = 2(1 + b)\sum_{n=1}^{\infty} b^{\frac{n-1}{2}}\cos n(\theta + 30)$$

$$B_{ep} = -2\cos(\theta_0 - 90)\left[\sum_{n=2}^{\infty} b^{\frac{n}{2}}\cos n(\theta + 30) + \frac{1}{2}\right]$$

$$B_{0p} = -\frac{1}{2}(1 + b)\sum_{n=1}^{\infty} b^{\frac{n-1}{2}}\cos n(\theta + 30) + \frac{1}{2}\sqrt{3}(1 - b)\sum_{n=1}^{\infty} b^{\frac{n-1}{2}}\sin n(\theta + 30)$$

$$B_{en} = +\cos(\theta_0 + 60)(1 - b^2)\sum_{n=2}^{\infty} b^{\frac{n-2}{2}}\sin n(\theta + 30) - b\sin(\theta_0 + 60) - b\sin(\theta_0 + 60) - \sin(\theta_0 + 60)(1 + b^2) \times \sum_{n=2}^{\infty} b^{\frac{n-2}{2}}\cos n(\theta + 30)$$

$$B_{0n} = -B_{0p}$$

$$b = \frac{\sqrt{x_q''\left(x_0 + \frac{1}{2}x_d''\right)} - \sqrt{x_d''\left(x_0 + \frac{1}{2}x_q''\right)}}{\sqrt{x_q''\left(x_0 + \frac{1}{2}x_d''\right)} + \sqrt{x_d''\left(x_0 + \frac{1}{2}x_q''\right)}}$$

Only odd values of $n$ are to be used in the summations from $n$ = one to $n = \infty$. Only even values of $n$ are to be used in the summations from $n = 2$ to $n = \infty$. Doherty and Nickle have shown in the case of single-phase short circuits that all d-c and even harmonic terms in the armature current die to zero according to a time constant depending on constants of the armature. Odd harmonic terms die to a steady state value according to time constants depending on constants of the field circuits. In the double-line-to-neutral short there are 3 armature time constants, one to be used with the even harmonic terms of each of the components of the armature current. Before proceeding with the derivation of these time constants it will first be necessary to find an expression for the field current.

## Field Current

Let the following symbols represent per-unit quantities in armature terms:

$\psi_{fd}$ = flux linkages with the main field
$\psi_{1d}$ = flux linkages with the additional field
$I_{fd}$ = main-field current
$I_{1d}$ = additional field current
$i_d$ = current flowing in the direct-axis armature circuit
$X_{ffd}$ = self-inductance of main field
$X_{f1d}$ = mutual inductance of main field with additional field
$X_{11d}$ = self-inductance of additional field, direct axis
$x_{afd}$ = mutual reactance of armature with main field
$x_{a1d}$ = mutual reactance of armature with additional field
$E_{fd}$ = voltage across main-field terminals
$R_{fd}$ = resistance of main field
$R_{11d}$ = resistance of additional field

Waring and Crary[3] have given expressions for the field flux linkages in armature terms. In the main field, direct axis:

$$\psi_{fd} = X_{ffd}I_{fd} + X_{f1d}I_{1d} - x_{afd}i_d \tag{12}$$

and in the additional field, direct axis:

$$\psi_{1d} = X_{f1d}I_{fd} + X_{11d}I_{1d} - x_{a1d}i_d \tag{13}$$

before the fault

$$\psi_{fd} = E_{fd}/R_{fd}X_{ffd} \tag{14}$$

$$\psi_{1d} = E_{fd}/R_{fd}\,X_{1fd} \tag{15}$$

Assuming constant flux linkages these four equations may be solved simultaneously and there results:

$$I_{fd} = \frac{E_{fd}}{R_{fd}} - \frac{X_{a1d}X_{f1d} - x_{afd}X_{11d}}{X_{11d}X_{ffd} - X_{f1d}^2}\,i_d \tag{16}$$

$$I_{1d} = -\frac{x_{afd}X_{f1d} - x_{a1d}X_{ffd}}{X_{11d}X_{ffd} - X_{f1d}^2}\,i_d \tag{17}$$

Equations 16 and 17 can be rewritten in individual field terms and there results:

$$I = E - \frac{X_{a1d}X_{f1d} - x_{afd}X_{11d}}{X_{11d}X_{ffd} - X_{f1d}^2}\,(x_{afd})i_d = E + A_{fd}x_d i_d \tag{18}$$

$$I_{d1} = -\frac{X_{afd}X_{f1d} - x_{a1d}X_{ffd}}{X_{11d}X_{ffd} - X_{f1d}^2}\,(x_{a1d})i_d = A_{1d}x_d i_d \tag{19}$$

If 16 is multiplied by $x_{afd}$ and 17 by $x_{a1d}$ and the resulting equations are added it is found that:[3]

$$x_{afd}I_{fd} + x_{a1d}I_{1d} = \frac{E_{fd}}{R_{fd}}\,x_{afd} + (x_d - x_d'')i_d \tag{20}$$

If the field quantities in this equation are now expressed in terms of their individual fields 20 becomes:

$$I + I_{d1} = E + (x_d - x_d'')i_d \tag{21}$$

where

$$x_d'' = x_d - \frac{X_{11d}x_{afd}^2 - 2X_{f1d}x_{a1d}x_{afd} + X_{ffd}x_{a1d}^2}{X_{11d}X_{ffd} - X_{f1d}^2}$$

Note that equation 21 is the same as equation 2.

The factors $A_{fd}$ and $A_{1d}$ serve to divide the rotor current into the portions which flow in the main and amortisseur fields. For the transient d-c components of the rotor currents these factors can be put in a simpler form. In most practical machines the transient d-c component of $I_{1d}$ dies out very rapidly so that it is zero for most of the time that the transient part of $I_{fd}$ is flowing. Therefore we may consider that for d-c transients $X_{f1d}$ in equations 18 and 19 is equal zero. Under these conditions

$$x_d A_{fd} = x_d - x_d' \tag{22}$$

$$x_d A_{1d} = x_d' - x_d'' \tag{23}$$

Substituting in equation 18 for $i_d$ and $E$ their values from equations 4, 9, and 6 there results:

$$I = e + ex_dA_{fd}\left\{\frac{x_d'' + x_q''}{2}\left[\frac{1 - \cos(\theta - \theta_0)}{D}\right] - \frac{x_d'' - x_q''}{2}\left[\frac{1 - \cos(\theta - \theta_0)}{D}\right] + \frac{x_0[1 - \cos(\theta - \theta_0) - \cos(\theta + \theta_0 + 60) + \cos(2\theta + 60)]}{D}\right\} \tag{24}$$

The current in the additional field is the same except that the constant term is missing and $A_{fd}$ is replaced by $A_{1d}$.

Equation 24 may be expanded into a set of harmonic series in a manner similar to that used for equation 9. It then becomes:

$$I = e + ex_dA_{fd}[M(x_d'' + x_q'')(C_{ep} + C_{op}) + M(x_d'' - x_q'')\times(C_{en} + C_{on}) + Mx_0(C_{eo} + C_{oo})] + eM(x_d - x_d')\times(x_q'' + x_0 + bx_0) \tag{25}$$

Note that the d-c component is multiplied by its special value of $A_{fd}$.

In equation 25:

$$C_{ep} = \sum_{n=2}^{\infty} b^{\frac{n}{2}} \cos n\,(\theta + 30)$$

$$C_{op} = -\frac{1}{2}\cos(\theta_0 + 30)\,(1 + b)\sum_{n=1}^{\infty} b^{\frac{n-1}{2}} \cos n(\theta + 30) - \frac{1}{2}\sin(\theta_0 + 30)\,(1 - b)\sum_{n=1}^{\infty} b^{\frac{n-1}{2}} \sin n\,(\theta + 30)$$

$$C_{en} = -C_{ep}$$

$$C_{on} = -C_{op}$$

$$C_{eo} = 2\sum_{n=2}^{\infty} b^{\frac{n}{2}} \cos n\,(\theta + 30) + (1 + b^2)\sum_{n=2}^{\infty} b^{\frac{n-2}{2}} \cos n\,(\theta + 30)$$

$$C_{oo} = -2(1 + b)\cos(\theta_0 + 30)\sum_{n=1}^{\infty} b^{\frac{n-1}{2}} \cos n\,(\theta + 30)$$

Similarly the current in an additional field in the direct axis is

$$I_{d1} = ex_dA_{1d}[M(x_d'' + x_q'')(C_{ep} + C_{0p}) + M(x_d'' - x_q'')\times(C_{en} + C_{0n}) + Mx_0(C_{e0} + C_{00})] + eM(x_d' - x_d'')\times(x_q'' + x_0 + bx_0) \tag{26}$$

Decrement factors must be applied to the various terms in these expressions for field currents in the same way as to the armature currents except that the armature decrement factors apply to the odd harmonics and the field decrement factors to the even harmonics.

## Decrement Factors

In order to apply field decrement factors to the odd harmonic terms of the armature current, it is necessary to divide the armature current into portions, each of which is dependent only on the current flowing in a particular field circuit. The decrement factor for each portion is then the reciprocal of the time constant of its field circuit. Since this division will be the same at all times it will be sufficient to determine it at the initial instant.

At the initial instant the total direct current field excitation in the direct axis is:

$$e + eM\,(x_d - x_d'')(x_q'' + x_0 + bx_0)$$

from equations 25 and 26.

The field excitation due to direct currents flowing in the additional field in the direct axis is:

$$eM(x_d' - x_d'')(x_q'' + x_0 + b_{x0})$$

The fraction of the total armature current dependent on this additional field current, that is the subtransient part, is then the ratio:

$$K''i_{a0} = \frac{M(x_d' - x_d'')(x_q'' + x_0 + bx_0)}{1 + M(x_d - x_d'')(x_q'' + x_0 + bx_0)} i_{a0} \tag{27}$$

where $i_{a0}$ is the odd harmonic terms of $i_a$.

Similarly the fraction of the total armature current dependent on the transient current in the main field, that is the transient part, is:

$$K'i_{a0} = \frac{M(x_d - x_d')(x_q'' + x_0 + bx_0)}{1 + M(x_d - x_d'')(x_q'' + x_0 + bx_0)} i_{a0} \tag{28}$$

This leaves for the sustained part:

$$Ki_{a0} = \frac{1}{1 + M(x_d - x_d'')(x_q + x_0 + bx_0)} i_{a0} \tag{29}$$

The same factors of course serve to divide $i_{b0}$, the odd harmonic terms of $i_b$.

To calculate field time constants for a double-line-to-neutral short it is necessary to rely upon some physical reasoning rather than a strict mathematical derivation. When a short circuit of any kind occurs in a machine having 2 field circuits in the direct axis, the inductance of each field circuit is altered by the fact that there are 2 other closed circuits linking at least part of the flux linked by the circuit in question. However, the amortisseur circuit in most machines has such low reactance that its d-c component of current dies so rapidly that it is nearly zero for most of the time that a transient current is flowing in the main field. Therefore the amortisseur circuit may be considered open in calculating the time constant of the main field. Under these circumstances the per-unit self-inductance of the direct axis field circuit is $X_{ffd}$. The current flowing in the direct axis before the fault is equal to $E = e$. Shortly after the fault the average value of main field current is, from equation 25:

$$I = e + eM(x_d - x_d')(x_q'' + x_0 + bx_0)$$

Since the flux linkages remain constant the main field inductance after the fault must be:

$$\frac{1}{1 + M(x_d - x_d')(x_q'' + x_0 + bx_0)} X_{ffd}$$

The main field (transient) decrement factor will then be the ratio of the main field resistance to the main field inductance.

$$\alpha_d' = \frac{r_{fd}[1 + M(x_d - x_d')(x_q'' + x_0 + bx_0)]}{X_{ffd}} \tag{30}$$

The self-inductance of the additional field considering the main field as a closed circuit is:

$$X_{11d} - \frac{X_{1fd}^2}{X_{ffd}}$$

The average value of the current in the additional field immediately after the fault is, from equation 26:

$$I_{d1} = eM(x_d' - x_d'')(x_q'' + x_0 + bx_0)$$

Therefore the inductance of the additional field after the fault is:

$$\frac{1}{1 + M(x_d' - x_d'')(x_q'' + x_0 + bx_0)} \left(X_{11d} - \frac{X_{1fd}^2}{X_{ffd}}\right)$$

The additional field (subtransient) decrement factor is:

$$\alpha_d'' = \frac{X_{ffd}r_{1d}[1 + M(x_d' - x_d'')(x_q'' + x_0 + bx_0)]}{X_{11d}X_{ffd} - X_{1fd}^2} \tag{31}$$

The even harmonic terms of the armature current are grouped into 3 separate series. Each series may be considered as a current flowing in a closed armature circuit. The decrement factor to be used with each series is the ratio of the resistance of this circuit to its inductance. From an inspection of equation 11 the inductance met by the first even harmonic component of armature current is

$$\frac{1}{(x_d'' + x_q'')M}$$

The decrement factor for this component is therefore:

$$\alpha_{ap} = r(x_d'' + x_q'')M \tag{32}$$

Similarly for the other 2 components:

$$\alpha_{an} = r(x_q'' - x_d'')M \tag{33}$$

$$\alpha_{a0} = rx_0M \tag{34}$$

The final expression for the armature current in phase $a$ at any instant is:

$$i_a = \frac{1}{2}\sqrt{3}\,eM[(x_d'' + x_q'')\epsilon^{-\alpha_{ap}t}A_{ep} + (x_d'' - x_q'')\epsilon^{-\alpha_{an}t}A_{en} + x_0\epsilon^{-\alpha_{a0}t}A_{e0} + K''\epsilon^{-\alpha_{d''}t}(2x_q''A_{0p} + x_0A_{00}) + K'\epsilon^{-\alpha_{d'}t}(2x_q''A_{0p} + x_0A_{00}) + K(2x_q''A_{0p} + x_0A_{00})] \tag{35a}$$

The current in phase $b$ is:

$$i_b = \frac{1}{2}\sqrt{3}\,eM[(x_d'' + x_q'')\epsilon^{-\alpha_{ap}t}B_{ep} + (x_d'' - x_q'')\epsilon^{-\alpha_{an}t}B_{en} - x_0\epsilon^{-\alpha_{a0}t}A_{e0} + K''\epsilon^{-\alpha_{d''}t}(2x_q''B_{0p} - x_0A_{00}) - K'\epsilon^{-\alpha_{d'}t}(2x_q''B_{0p} - x_0A_{00}) + K(2x_q''B_{0p} - x_0A_{00})] \tag{35b}$$

The current in the main field is:

$$I = e + eMx_dA_{fd}[(x_d'' + x_q'')\epsilon^{-\alpha_{ap}t}C_{0p} + (x_d'' - x_q'')\epsilon^{-\alpha_{an}}C_{0n} + x_0\epsilon^{-\alpha_{a0}t}C_{00} + (x_q'' + x_0 + bx_0)\epsilon^{-\alpha_{d'}t} + K''\epsilon^{-\alpha_{d''}t}(2x_q''C_{ep} + x_0C_{e0}) + K'\epsilon^{-\alpha_{d'}t}(2x_q''C_{ep} + x_0C_{e0}) + K(2x_q''C_{ep} + x_0C_{e0})] \tag{35c}$$

The current in the additional field is the same except that the sustained d-c term is missing, and the transient d-c term has the decrement factor $\alpha_d''$, and the factor $A_{fd}$ is replaced by $A_d$.

If $x_0$ becomes infinitely large equations 35 become identical with the equations developed by Doherty and Nickle for a line-to-line fault, as should be expected.

## The Voltage Across the Open Phase

To get an expression for the voltage across the open phase the flux linkages can be found by setting $i_c = 0$ in

equation 7c. $i_a$ and $i_b$ can be eliminated from the resulting expression by substituting their values from equation 9. The result can then be expanded into a series and decrement factors applied as in the case of the currents and there is:

$$v_c = eM\,[3x_q''x_0K''\epsilon^{-\alpha_{d''}t}F_1 + 3x_q''x_0K'\epsilon^{-\alpha_{d'}t}F_1 + 3x_qx_0KF_1 + \frac{x_d - x_0}{2}(x_d'' + x_q'')\epsilon^{-\alpha_{ap}t}F_2 - \frac{(x_d'' - x_q'')^2}{4}\epsilon^{-\alpha_{an}t}F_2 - \frac{x_d'' + x_q'' - 2x_0}{4}(x_d'' - x_q'')\epsilon^{-\alpha_{an}t}F_4 - x_0(x_d'' - x_q'')\cos(\theta_0 + 30)\epsilon^{-\alpha_{a0}t}F_3] \quad (36)$$

To get the voltage equation 36 may now be differentiated with respect to time. It is much more convenient to expand the functions into Fourier series and then differentiate them term by term. This procedure is valid because the functions $F$ satisfy the rigid conditions under which the term by term derivative of a Fourier series is also the derivative of the function.[4]

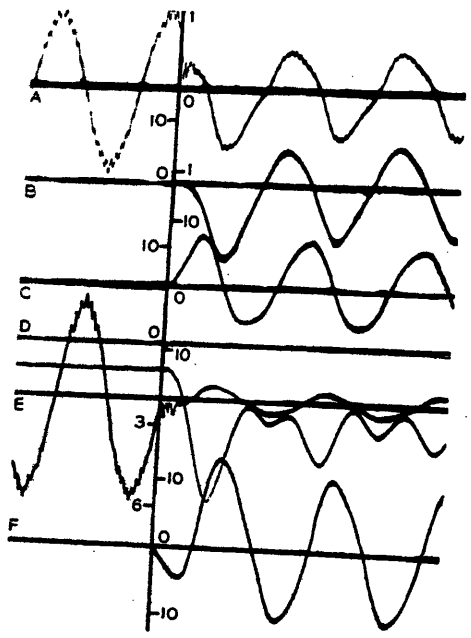



**Figure 1a.** $\theta = 0$

*A*—Voltage across the open phase

*C*—Current in line *b*

*E*—Voltage of phase *a*

*B*—Current in line *a*

*D*—Main-field current

*F*—Neutral current

The final expression for the voltage across the open phase a short time after a double-line-to-neutral fault is:

$$v_c = -eM[3x_q''x_0K''\epsilon^{-\alpha_{d''}t}(pF_1 - \alpha_{d''}F_1) + 3x_q''x_0K'\epsilon^{-\alpha_{d'}t}(pF_1 - \alpha_{d'}F_1) + 3x_q''x_0KpF_1 + \frac{x_d'' - x_0}{2}(x_d'' + x_q'')\epsilon^{-\alpha_{ap}t}(pF_2 - \alpha_{ap}F_2) - \frac{(x_d'' - x_q'')^2}{4}\epsilon^{-\alpha_{an}t}(pF_2 - \alpha_{an}F_2) - \frac{x_d'' + x_q'' - 2x_0}{4}(x_d'' - x_q'')\epsilon^{-\alpha_{an}t}(pF_4 - \alpha_{an}F_4) - x_0(x_d'' - x_q'')\cos(\theta_0 + 30)\epsilon^{-\alpha_{a0}t}(pF_3 - \alpha_{a0}F_3)] \quad (37)$$

where

$$F_1 = -(1-b)\sum_{n=1}^{\infty} b^{\frac{n-1}{2}}\sin n(\theta + 30)$$

$$pF_1 = -(1-b)\sum_{n=1}^{\infty} b^{\frac{n-1}{2}}\cos n(\theta + 30)$$

$$F_2 = -2\cos(\theta_0 - 60)\left[\sum_{n=2}^{\infty} b^{\frac{n}{2}}\cos n(\theta + 30) + \frac{1}{2}\right]$$

$$pF_2 = 2\cos(\theta_0 - 60)\sum_{n=2}^{\infty} nb^{\frac{n}{2}}\sin n(\theta + 30)$$

$$F_4 = b\cos(\theta_0 - 60) + \sin(\theta_0 - 60)(1 - b^2)\sum_{n=2}^{\infty} b^{\frac{n-2}{2}} \times \sin n(\theta + 30) + \cos(\theta_0 - 60)(1 + b^2)\sum_{n=2}^{\infty} b^{\frac{n-2}{2}}\cos n(\theta + 30)$$

$$pF_4 = \sin(\theta_0 - 60)(1 - b^2)\sum_{n=2}^{\infty} nb^{\frac{n-2}{2}}\cos n(\theta + 30) - \cos(\theta_0 - 60)(1 + b^2)\sum_{n=2}^{\infty} nb^{\frac{n-2}{2}}\sin n(\theta + 30)$$

$$F_3 = (1 - b^2)\sum_{n=2}^{\infty} b^{\frac{n-2}{2}}\sin n(\theta + 30)$$

$$pF_3 = (1 - b^2)\sum_{n=2}^{\infty} nb^{\frac{n-2}{2}}\cos n(\theta + 30)$$

## Steady-State Currents and Voltages

From equations 35 the sustained line currents are:

$$i_a = \frac{1}{2}\sqrt{3}\,eMK(2x_q''A_{0p} + x_0A_{00}) \quad (38)$$

$$i_b = \frac{1}{2}\sqrt{3}eMK(2x_q''B_{0p} - x_0A_{00}) \quad (39)$$

The neutral current is their sum:

$$i_N = \sqrt{3}\,eMKx_q''(A_{0p} + B_{0p}) \quad (40)$$

Substituting for $A_{0p}$ and $B_{0p}$ their values:

$$i_N = 3eMKx_q''(1 - b)\sum_{n=1}^{\infty} b^{\frac{n-1}{2}}\sin n(\theta + 30) \quad (41)$$

From equation 37 the sustained voltage across the open phase is:

$$v_c = -3\,eMKx_q''x_0(1 - b)\sum_{n=1}^{\infty} nb^{\frac{n-1}{2}}\cos n(\theta + 30) \quad (42)$$

If only the fundamental terms are considered, which can be done with very little approximation if $b$ is small, then the root-mean-square values of the time functions in equations 41 and 42 are equal. Therefore the ratio of the root-mean-square values is

$$\frac{V_c}{I_N} = x_0$$

which we would expect since this is one of the methods of measuring $x_0$.

## Comparisons of Calculated and Test Results

In order to check equations 35 and 37, oscillograms were taken of a number of short circuits on 2 different machines. Figure 1*a* is a typical oscillogram taken on the following machine: General Electric Company, 45 kva, type *ATB*, form P.B., frame 7,621, 118 amperes, 220 volts, 60 cycles, 1,200 rpm, serial number 302,689. The constants of this machine in per-unit on a 220-volt 118-ampere base are:

$x_d = 0.9$
$x_d' = 0.241$
$x_d'' = 0.220$
$T_{do}' = 339$
$x_q = x_q' = x_q'' = 0.470$
$x_0 = 0.07$
$r = 0.033$
$T_{do}'' = 7.6$

The amortisseur winding of the machine had been removed.

Figure 1*b* shows curves calculated from equations 35 and 37. The armature currents check very closely, especially in the first cycle where there is no difference of more than 8 per cent. The calculated curve of the field current

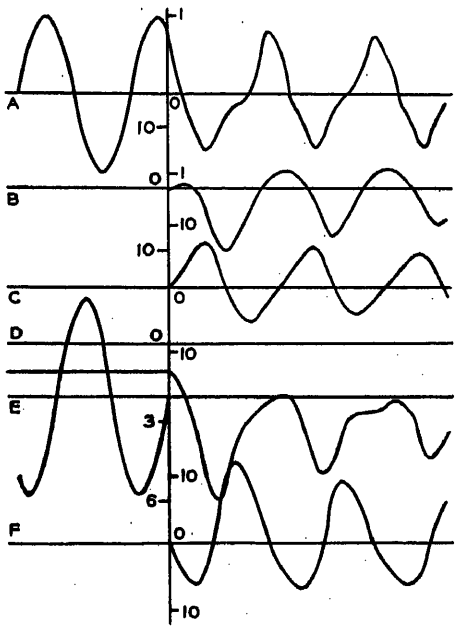



**Figure 1b.** $\theta = 0$

*A*—From equation 37

*C*—From equation 35*b*

*E*—e sin $\theta$

*B*—From equation 35*a*

*D*—From equation 35*c*

*F*—From equations 35*a* and 35*b*

shows too large a percentage of harmonics. This can be partly explained by the fact that in the actual calculation $A_{fd}$ was computed from equation 22 because all the constants in equation 18 were not available. All of the calculated curves show too large a percentage of even harmonics in armature quantities and odd harmonics in the field current, especially after the first cycle. This indicates that the values of the armature decrement factors as calculated from equations 32, 33, and 34 are somewhat too small. The short circuits were all made at normal voltage, so that saturation of the iron undoubtedly affected the test curves. The constants used in the calculations were measured under unsaturated conditions.

In order to find the largest possible value of current that can occur plots of both $i_a$ and $i_b$ were made for a number of different valus of $\theta_o$. These plots showed that the largest peak of $i_a$ occurred very near the point where $\theta_o = 0°$ and $\theta_o = 180°$. For $i_b$ the largest peak occurred near $\theta_o = 90°$ and $\theta = 270°$.

When these values are substituted in equations 9 there is:

$$i_a = \frac{6e(x_q'' + x_0)}{3x_d''x_0 + x_q''x_0 + 2x_d''x_q''} \tag{43}$$

$$i_b = \frac{2\sqrt{3}\,e(2x_q'' + x_0)}{x_d''x_0 + 3x_q''x_0 + 2x_d''x_q''} \tag{44}$$

These values do not give quite the theoretical maximum values of equations 9, but since actually we should consider the decrements as well, these expressions, are close enough and have the advantage of being relatively simple. In table I values of current calculated from equations 43 and 44 for the machine described and another similar machine are compared with the largest peaks for other types of faults calculated from analogous expressions. For line-to-neutral[2] fault:

$$i_a = \frac{6e}{2x_d'' + x_0} \tag{45}$$

For line-to-line fault:

$$i_a = \frac{\sqrt{3}\,e}{x_d''} \tag{46}$$

For 3-phase fault:

$$i_a = \frac{2e}{x_d''} \tag{47}$$

**Table I**

| Type of Fault | Current | Machine I | Machine II |
|---|---|---|---|
| $l - n$ | $i_a$ | 11.8 | 14.2 |
| $l - l$ | $i_a$ | 7.9 | 10.0 |
| $l - l - l$ | $i_a$ | 9.1 | 11.5 |
| $l - l - n$ | $i_a$ | 11.4 | 14.0 |
| $l - l - n$ | $i_b$ | 10.7 | 13.0 |

The table shows that for 2 typical machines the theoretical peak value of the line current in a double line-to-neutral fault is of about the same order of magnitude as that in a line-to-neutral fault.

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# Flywheels for A-C Generating Units

By F. K. BRAINARD
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SO MUCH has been written on the subject of flywheels and parallel operation of generating units, that the object of this paper is not to attempt to develop any entirely new method of flywheel calculation, but rather to collect and apply the available information and put it into convenient shape for practical use. The consideration of torsional vibrations in connection with the determination of flywheel sizes is frequently of the greatest importance, especially in the case of large multicylindered oil engines, and should not be overlooked. However it is beyond the scope of this paper and so will not be considered here.

In addition to the above, there are 3 quite distinct conditions which the flywheel of a proposed unit must satisfy.

The first is the very obvious condition that it must be large enough to prevent objectionable variations in frequency (and voltage) when the unit is the only generating unit on the system. Failure to provide for this will result in objectionable flickering of lighting handled by the generator. These variations may be (*a*) the result of violent changes in load combined with a somewhat sluggish prime mover or governor, or (*b*) the result of pulsating torque of the prime mover.

A convenient criterion for the (*a*) condition is the ratio of the kinetic energy of the rotating parts to the rated output of the unit. This will be the time required by the unit when operating at full load to develop energy equal to the kinetic energy of the rotating parts at full speed. There is nothing new about this as the equivalent of this has been used for many years. If this time is in seconds, then:

$$WR^2 = \frac{433\ kw\ T_1}{\left(\frac{\text{rpm}}{100}\right)^2} \qquad (1)$$

For hydroelectric units this effect is important, $T_1$ in this case varying between about 1.4 and 2.0 seconds, for a normal machine, depending upon the head, length of penstock, speed of operation of governor as well as gates, etc. For other applications this effect is, as far as the writer is aware, never the limiting feature, although it would seem that it might be in the case of certain multicylinder steam engines.

The (*b*) condition is important in the case of reciprocating engine units, on account of the varying turning effort developed by the engine for different crank angles. A convenient criterion for this condition is the well-known "irregularity factor." The use of this is also very old. It is the variation in speed expressed as a fraction of normal speed, during a power cycle, the load being assumed constant, e.g., an irregularity factor of $^1/_{200}$ means a variation in speed of 0.5 per cent during one revolution of a 2-cycle engine or 2 revolutions of a 4-cycle engine. It can be easily shown that the following is a very close approximation for flywheel effect in terms of irregularity factor:

$$WR^2 = \frac{130\ kw\ Z}{\left(\frac{\text{rpm}}{100}\right)^2} \times \frac{A_2}{A_1} \qquad (2)$$

Permissible values of irregularity factor depend upon the character of the load served and the frequency of the impulses causing the variations in speed, i.e., the number of power impulses per minute. For a miscellaneous factory load in which good lighting is not important an irregularity factor of $^1/_{100}$ will usually be satisfactory. However since office or residence lighting is almost always an important factor, and since low-wattage metallic filament lamps are used so generally, it is practically always necessary to make the irregularity factor low enough to avoid serious flickering of such lamps. The voltage variation necessary to produce an objectionable flicker varies with the frequency of the variation, being a maximum at about 500 cycles per minute. The available data are somewhat conflicting but it would seem that the following are reasonable values of irregularity factor:

| Frequency of impulses in cycles per minute | $\frac{1}{Z}$ |
|---|---|
| 100 | 1/125 |
| 300 | 1/175 |
| 500 | 1/225 |
| 700 | 1/175 |
| 1,000 | 1/125 |

The value of $A_2/A_1$ depends upon the shape of the tangential effort diagram, being the ratio of certain areas (see figure 1), and so varies widely for different engines. The following table gives approximate values for single acting oil engines:

| Number of Cylinders | $\frac{A_2}{A_1}$ 2 Cycle | $\frac{A_2}{A_1}$ 4 Cycle |
|---|---|---|
| 1 | | |
| 2 | 1.3 | |
| 3 | 0.40 | 1.4 |
| 4 | 0.19 | 0.45 |
| 5 | 0.11 | 0.20 |
| 6 | 0.075 | 0.14 |
| | 0.055 | 0.10 |

The second condition is that the flywheel must be suitable for satisfactory parallel operation of the unit with a very large system. This limitation can best be expressed in terms of the quantity $C$, which is the same as the "com-

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pressor factor'' as standardized by the National Electrical Manufacturer's Association. The expression for $WR^2$ in terms of $C$ is:

$$WR^2 = \frac{1.34\,P_r f\,C}{\left(\frac{\text{rpm}}{100}\right)^4} \tag{3}$$

The limiting values of $C$ can be determined from the tangential effort diagram of the engine as follows: Calculate the $CY$ ($Y$ = power pulsation of generator) curve by first assuming a reasonable unbalance between cylinders. Since the operation of internal combustion engines is somewhat irregular the amount of unbalance is largely a matter of judgment and hence the $CY$ curves cannot be calculated with the same accuracy as, for instance, compressor curves are calculated. For this reason and also because the flywheels are relatively large (which results in the effect of damping being relatively small) the damping can usually be neglected entirely. This results in a considerable simplification of the equations as follows:[2] For a 2-cycle engine

$$P = 100 + \sum y_n \frac{9.25}{9.25 - n^2 C} \sin(n\omega t + \phi_n)$$

and for a 4-cycle engine

$$P = 100 + \sum y_n \frac{37}{37 - n^2 C} \sin(n\omega t + \phi_n)$$

Then after having analyzed the tangential effort curve and determined the coefficients in the Fourier series representing the same, the procedure is to select a value of $C$ and calculate the curve of $P$ from $t = 0$ to $t = 2\pi$, i.e., over one power cycle which will be one revolution for a 2-cycle engine or 2 revolutions for a 4-cycle engine. Then $Y$ will be the maximum difference in the ordinates of this curve and the result one point on the $CY$ curve. Repeat for different values of $C$ until sufficient points are obtained to set limits of $C$ corresponding to the power pulsation desired.

The following are approximate values of $C$ based upon 66 per cent power pulsation and 10 per cent unbalance, for oil engines:

| Number of Cylinders | C: 2-Cycle Single-Acting | C: 4-Cycle Single-Acting |
|---|---|---|
| 1 | 100 or over | 500 or over |
| 2 | 20 or over | 150 or over |
| 3 | 16 or over | 75 or over |
| 4 | 3.5 to 4.5 or 14 or over | 60 or over |
| 5 | 3.3 to 5.0 or 13.5 or over | 57 or over |
| 6 | 3.0 to 6.0 or 12.5 or over | 55 or over |

The above values must not however be considered as final since as mentioned above they cannot be calculated with as much precision as would be desirable. Also the permissible values depend upon the maintenance of the engine. Hence the limits will have to be determined ultimately by experience, and so the above table must be considered as empirical and subject to some variation.

2. For all numbered references, see list at end of paper.

The third condition is that the flywheel must be suitable for parallel operation of the unit with certain particular units whose characteristics are known. A simple method of checking this after the other conditions are satisfied is to compute the natural frequency $F$ of each of the units with an infinite system using the AIEE formula:

$$F = \frac{35{,}200}{\text{rpm}} \sqrt{\frac{P_r f}{WR^2}}$$

Then if these natural frequencies are all well below the lowest forced frequency, say 20 per cent below, the operation will be satisfactory. This is because the combined natural frequencies of any combination of units is always between the natural frequencies of the individual units on an infinite system. However if the lowest forced frequency of one of the units is below the natural frequency of another unit, the combined natural frequencies of all combinations should be calculated and care taken to see that none of the forced and natural frequencies are dangerously close to each other.

The expression for combined natural frequency[1] of 2 units is

$$F_{1-2} = \frac{35{,}200}{\text{rpm}_1} \sqrt{\frac{P_{r1} f}{WR_1^2} \times \frac{1 + \left(\frac{\text{rpm}_1}{\text{rpm}_2}\right)^2 \times \frac{WR_1^2}{WR_2^2}}{1 + \frac{P_{r1}}{P_{r2}}}}$$

and in the case of 3 units, the expression is

$$F_{1-2 \text{ and } 3} = 9.55 \sqrt{\frac{N_2}{2N_1} \pm \sqrt{\left(\frac{N_2}{2N_1}\right)^2 - \frac{N_3}{N_1}}}$$

where

$$c_1 = 4.22 \times 10^5 \frac{P_{r1} f}{(\text{rpm}_1)^2}$$

$$d_1 = 5.74 \times 10^{12} f^2 \left[ \frac{P_{r1} P_{r2}}{(\text{rpm}_1)^2 (\text{rpm}_2)^2 WR_2^2} + \frac{P_{r1} P_{r3}}{(\text{rpm}_1)^2 (\text{rpm}_3)^2 WR_3^2} \right]$$

$$e_1 = 7.85 \times 10^{19} f^3 \left[ \frac{P_{r1} P_{r2} P_{r3}}{(\text{rpm}_1)^2 (\text{rpm}_2)^2 (\text{rpm}_3)^2 WR_2^2 WR_3^2} \right]$$

$$N_1 = c_1 + c_2 \left(\frac{\text{rpm}_2}{\text{rpm}_1}\right)^2 + c_3 \left(\frac{\text{rpm}_3}{\text{rpm}_1}\right)^2$$

$$N_2 = d_1 + d_2 \left(\frac{\text{rpm}_2}{\text{rpm}_1}\right)^2 + d_3 \left(\frac{\text{rpm}_3}{\text{rpm}_1}\right)^2$$

$$N_3 = e_1 + e_2 \left(\frac{\text{rpm}_2}{\text{rpm}_1}\right)^2 + e_3 \left(\frac{\text{rpm}_3}{\text{rpm}_1}\right)^2$$

Subscripts 1, 2, and 3 refer to units 1, 2, and 3 respectively.

For $c_2$, $d_2$, and $e_2$ interchange subscripts 1 and 2 in expressions for $c_1$, $d_1$, and $e_1$, respectively.

For $c_3$, $d_3$, and $e_3$ interchange subscripts 1 and 3 in expressions for $c_1$, $d_1$, and $e_1$, respectively.

It is sometimes assumed that parallel operation is always a more severe condition than operating alone and that if the flywheel is satisfactory from the former standpoint it will also be satisfactory from the latter. A few trials using equations 2 and 3 will show the fallacy of this,

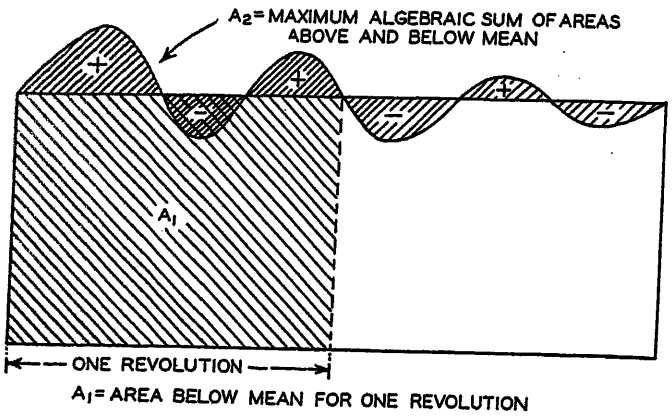



**Figure 1. Tangential effort diagram**

since sometimes it is one and sometimes the other which requires the greater flywheel effect. It is interesting to note that according to equation 1 the flywheel effect varies inversely as the square of the speed, according to equation 2 inversely as the cube of the speed, and according to equation 3 inversely as the fourth power of the speed. Hence the limiting feature depends to a considerable extent upon the speed of the unit. Also from equation 3 it is seen that the flywheel effect necessary on account of parallel operation varies directly with the frequency of the system. Hence parallel operation is relatively less important, and operation alone (which means irregularity factor) more important on 25 cycles than on 60 cycles.

## Appendix I. Symbols

$WR^2$ = flywheel effect of unit in (pound-feet)$^2$ (i.e., pounds weight multiplied by the radius of gyration in feet squared)

$kw$ = rated output of the unit in kilowatts

$T_1$ = time in seconds required by the unit when operating at full load to develop energy equal to the kinetic energy of the rotor at full speed. This is equal to the commonly accepted inertia constant $H$ divided by rated power factor

rpm = rated speed in revolutions per minute

$\frac{1}{Z}$ = irregularity factor = ratio of maximum variation in speed during a power cycle to normal speed

$A_1$ = area in tangential effort diagram below mean for *one revolution*

$A_2$ = maximum algebraic sum of small areas in tangential effort diagram above and below mean (see figure 1)

$P_r$ = synchronizing power in kilowatts per electrical radian as defined in AIEE rules

$f$ = frequency of system in cycles per second

$C$ = engine factor = $9.25\left(\frac{\text{rpm}}{F}\right)^2$

$F$ = frequency of oscillation of unit on an infinite system in cycles per *minute*

$y$ = $.100 + \Sigma y_n \sin(n\omega t + \phi_n)$ = Fourier analysis of tangential effort curve, in which

$n$ = order of harmonic

$y_n$ = amplitude of $n$th harmonic expressed as a percentage of rated output of unit

$\omega_n$ = 0.1045 $n$ rpm for 2-cycle engines, or 0.05225 $n$ rpm for 4-cycle engines

$t$ = time in seconds

$\phi_n$ = phase angle of $n$th harmonic

$P$ = power output of generator expressed as a percentage of the rating

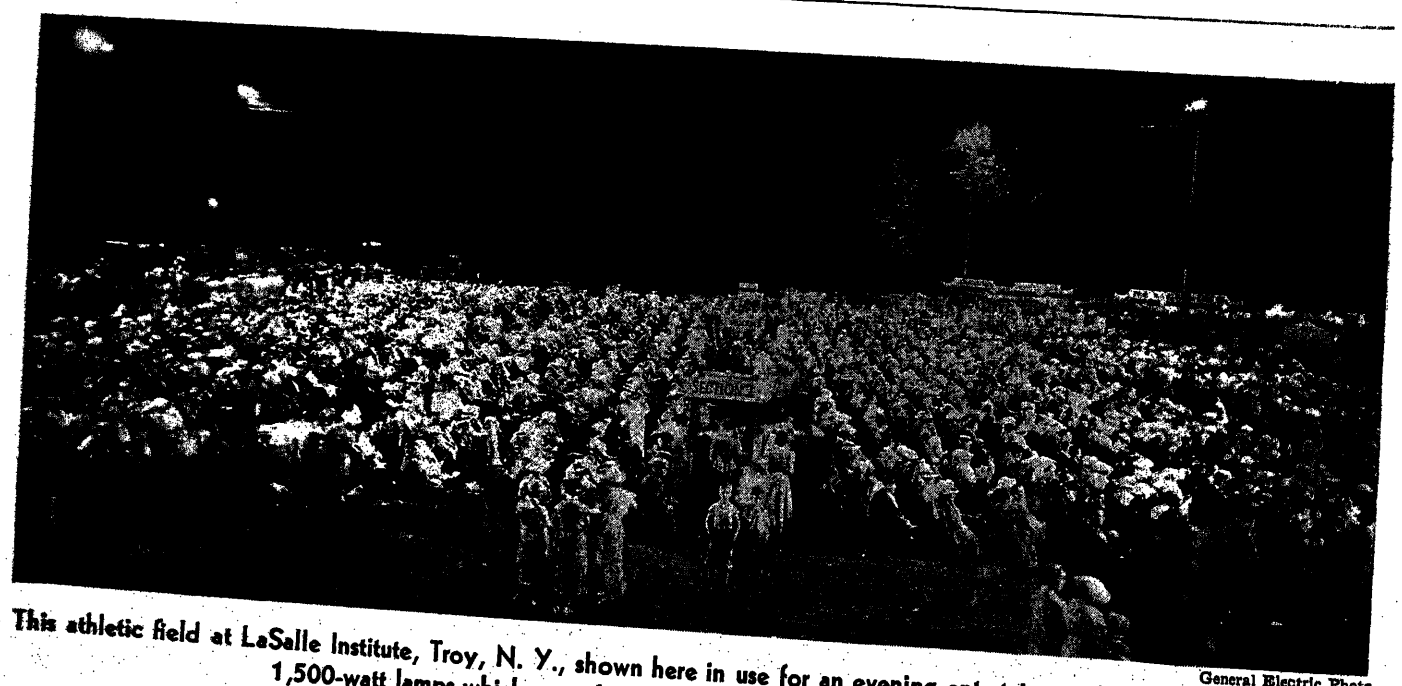
$Y$ = power pulsation of generator expressed as a percentage of the rating in kilowatts

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General Electric Photo

**This athletic field at LaSalle Institute, Troy, N. Y., shown here in use for an evening entertainment, is floodlighted by 40 1,500-watt lamps which provide an average illumination of 12 foot-candles**

# Coupling Between Parallel Earth-Return Circuits Under D-C Transient Conditions

By K. E. GOULD
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## Introduction

IN TESTS conducted in connection with several d-c railway electrifications, the induced voltages recorded in paralleling communication circuits at times of short circuit on the railway have shown marked divergences from values computed on the basis of uniform earth resistivity and a rate of change of earth current determined from measurements in trolley and rail circuits. Due to the numerous factors which might contribute to these divergences, such as nonuniform division of transient current along the tracks and associated return conductors, the presence of shielding conductors along or near the right-of-way, etc., it was felt that a better understanding of the problem of induction under d-c transient conditions could be obtained by experimental studies of the transient coupling between parallel earth-return circuits, free from the effects of shielding conductors, and with concentrated, rather than distributed, grounds. The study described in this paper was undertaken for this purpose.

The locations for the tests were selected to provide a reasonably large range of earth resistivity; also, at one location it was known that the earth structure departed substantially from uniformity. At each of these locations d-c transient coupling tests were performed in which transient currents, approximately of the form encountered during faults on d-c railway electrifications, were produced in an earth-return circuit, herein referred to as the primary, and measurements were made of the resultant voltages in earth-return circuits, herein called secondary circuits, parallel to and at separations from the primary circuit of from 50 or 60 to 2,000 feet. In addition to the d-c transient tests, measurements were made at each location of the steady state a-c coupling, in magnitude and phase angle, over a range of frequencies from 20 or 30 cycles to 3,200 cycles. From these a-c measurements the transient voltages were computed for a number of cases by evaluating the Fourier integral. The results of the a-c coupling tests were useful also in helping to explain, in a general way, the departures of the measured transient voltages from the voltages computed for uniform earth resistivity.

The measured transient voltages and voltages computed (1) from the a-c coupling measurements and (2) on the basis of a uniform earth resistivity, are shown for several representative cases in figures accompanying the paper.

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K. E. GOULD is a member of the technical staff of the Bell Telephone Laboratories, New York, N. Y. The author wishes to acknowledge the assistance of W. L. Gaines, J. H. Harding, and G. Wascheck in obtaining the experimental data and of Miss J. D. Goeltz, in supervising the extensive computations required to compute the transient voltages from the measured a-c coupling.

## Test Conditions

Three sets of tests were performed, near Savannah, Ga., Macon, Ga., and Jennings, La., respectively. The primary circuit was nearly straight in each case and was installed along a telephone line. The length of the primary circuit was 5.65 miles, 9.3 miles, and 4.7 miles at the respective locations, these lengths being great enough that end effects were not large even under the d-c transient conditions. The secondary circuits, 4,200 feet in length, were laid out parallel to and near the middle of the primary circuit, and at radial separations therefrom of 50 feet (Macon) or 60 feet (Savannah and Jennings), 200 feet, 500 feet, 1,000 feet, and 2,000 feet.

By means of a 500-volt gasoline-engine-driven d-c generator, and with the use of an air-core choke with taps giving inductances of roughly 1, $^3/_4$, $^1/_2$, or $^1/_4$ henry, it was possible to produce primary currents approximately of the form $I(1-e^{-at})$, with $a$ from about 40 to 110 for $t$ in seconds, and with $I$ somewhat less than 10 amperes. Conductors were brought in from each secondary so that the voltages produced in the secondaries under transient conditions could be recorded by a movie-type oscillograph, on 70-millimeter film moving at a speed of approximately 7 feet per second. Direct-coupled amplifiers were used to obtain the requisite sensitivity for the oscillograph, the over-all response of the measuring equipment being nearly constant for frequencies from zero to 4,000 cycles. The rate of change of primary current was recorded, simultaneously with the secondary voltages, by means of a search coil external to and coaxial with the primary choke.

For the a-c coupling tests a power amplifier driven by a variable frequency oscillator was used to energize the primary circuit and the voltages produced in the secondary circuits were measured with an a-c potentiometer, so that both components of the coupling could be determined. The continuity of the telephone conductors on the pole line carrying the primary circuit was interrupted during both the d-c transient tests and the measurements of a-c coupling to eliminate any possible shielding effects from these conductors.

## Typical Results

In figures 1 to 6, inclusive, are shown curves selected from the large amount of data collected as typical of the results of this study. The cases chosen for these illustrations are those in which the time constant of the pri-

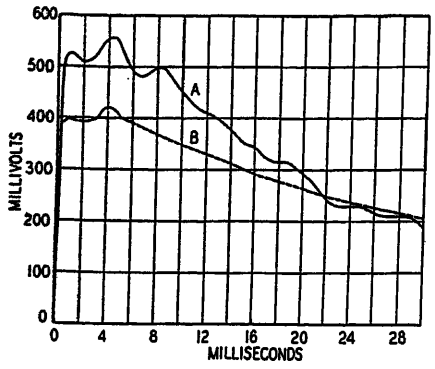



**Figure 1. Savannah tests—60-foot separation; rate of change of primary current approximately $440e^{-46t}$, amperes per second**

Curve *A*—Measured voltage
Curve *B*—Computed voltage for uniform earth resistivity of 100 meter-ohms

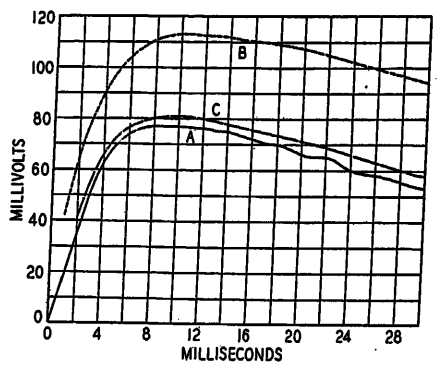



**Figure 2. Savannah tests—2,000-foot separation; rate of change of primary current approximately $440e^{-46t}$, amperes per second**

Curve *A*—Measured voltage
Curve *B*—Computed voltage for uniform earth resistivity of 100 meter-ohms
Curve *C*—Computed voltage from a-c coupling measurements

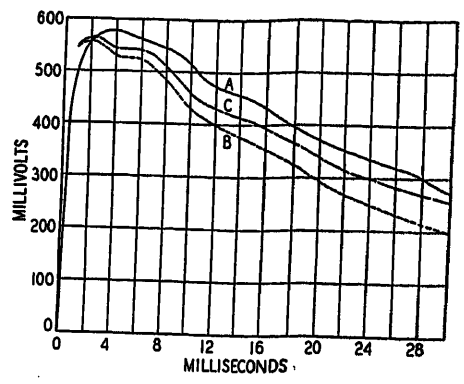



**Figure 3. Macon tests—50-foot separation; rate of change of primary current approximately $490e^{-60t}$, amperes per second**

Curve *A*—Measured voltage
Curve *B*—Computed voltage for uniform earth resistivity of 500 meter-ohms
Curve *C*—Computed voltage as for curve B, but with ground potentials corresponding to resistivity of 1,500 meter-ohms

mary circuit was most nearly representative for d-c railway electrifications, being about $^1/_{46}$, $^1/_{60}$, and $^1/_{45}$ second for the respective locations. The closest and widest separations were chosen for examples, and although the examples of the transient voltages computed from the a-c coupling measurements are thus limited to the cases of the 2,000-foot separation alone, the value of the illustrations is not significantly impaired thereby. As explained in a later section of the paper, it was not possible to compute the transient voltages for the closest separation from the a-c coupling measurements. Figures 1 to 6 illustrate the fact that with transient earth currents of the type considered here, the induced voltages not only decrease with increased separation, as in the steady-state a-c case, but also attain their maximum values later.

Figure 1 shows the measured transient voltage for the 60-foot separation in the Savannah tests and the computed voltage for a uniform earth resistivity of 100 meter-ohms, using the measured rate of change of primary current. This value of earth resistivity, chosen on the basis of the measured a-c coupling, was found to be about the best one as regards over-all agreement between the measured transient voltages and voltages computed on the basis of uniform earth resistivity.

Figure 2, for the 2,000-foot separation in the Savannah

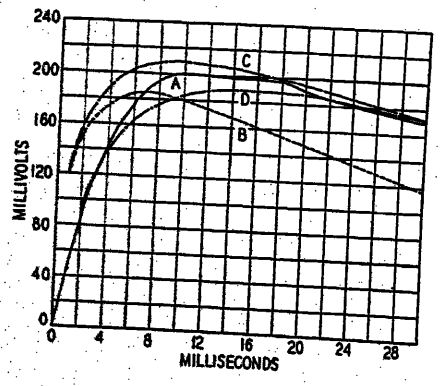



**Figure 4. Macon tests—2,000-foot separation; rate of change of primary current approximately $490e^{-60t}$, amperes per second**

Curve *A*—Measured voltage
Curve *B*—Computed voltage for uniform earth resistivity of 500 meter-ohms
Curve *C*—Computed voltage as for curve B, but with ground potentials corresponding to resistivity of 1,500 meter-ohms
Curve *D*—Computed voltage from a-c coupling measurements

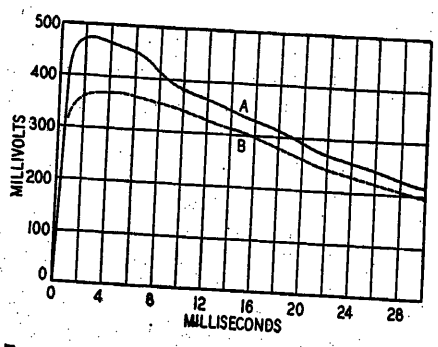



**Figure 5. Jennings tests—60-foot separation; rate of change of primary current approximately $535e^{-45t}$, amperes per second**

Curve *A*—Measured voltage
Curve *B*—Computed voltage for uniform earth resistivity of 10 meter-ohms

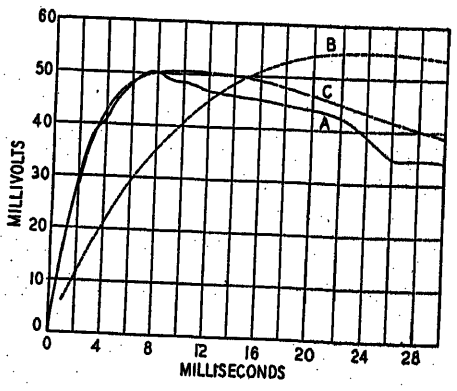



**Figure 6. Jennings tests—2,000-foot separation; rate of change of primary current approximately $535e^{-45t}$, amperes per second**

Curve *A*—Measured voltage
Curve *B*—Computed voltage for uniform earth resistivity of 10 meter-ohms
Curve *C*—Computed voltage from a-c coupling measurements

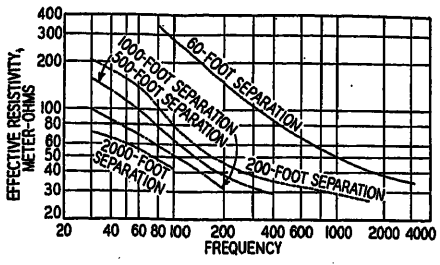



**Figure 7. Savannah tests; effective earth resistivity corresponding to measured quadrature coupling**

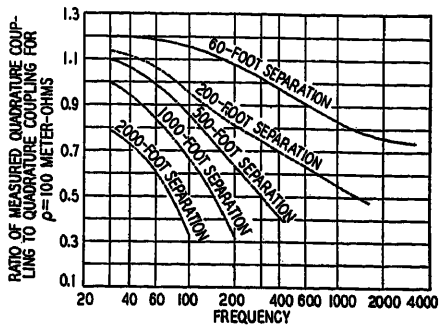



**Figure 8. Savannah tests; ratio of measured quadrature coupling to quadrature coupling for uniform earth resistivity of 100 meter-ohms**

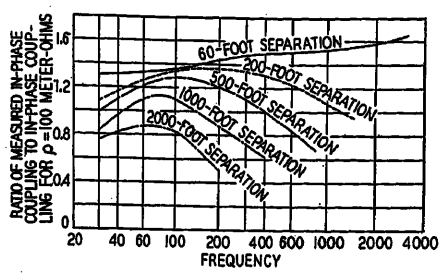



**Figure 9. Savannah tests; ratio of measured in-phase coupling to in-phase coupling for uniform earth resistivity of 100 meter-ohms**

tests, is similar to figure 1, except that the computed voltage from the a-c coupling measurements, using the measured rate of change of primary current, has been plotted also.

Figure 3, for the 50-foot separation in the Macon tests, is similar to figure 1, except that 2 computed curves are shown, one for a uniform earth resistivity of 500 meter-ohms, about the best single value which could be chosen, and the other for the same resistivity but with the ground potentials taken as corresponding to a resistivity of 1,500 meter-ohms. This was found to result in a fairly good approximation for the substantial increase observed in the effective earth resistivity at the low frequencies.

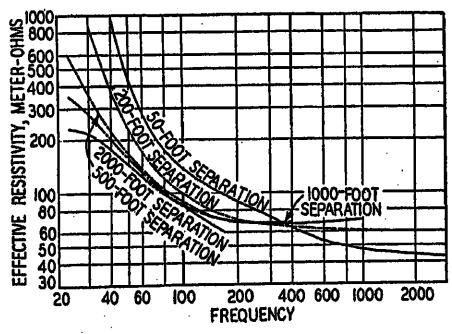



**Figure 10. Macon tests; effective earth resistivity corresponding to measured quadrature coupling**

Figure 4, for the 2,000-foot separation in the Macon tests, is similar to figure 2, except that computed curves are shown for the 2 conditions represented in figure 3. Figures 3 and 4 illustrate the fact that ground potentials were of greater relative importance at the wider separations.

Figure 5, for the 60-foot separation in the Jennings tests, is similar to figure 1, except that an earth resistivity of 10 meter-ohms was used for the computed voltage. Figure 6, for the 2,000-foot separation, is similar to figure 2, except for the change noted in the uniform resistivity used.

## Methods Used in Computing Transient Voltages

Two methods were used in computing the transient voltages for uniform earth resistivity, one a rigorous method, the other an approximate and simpler method giving sufficiently accurate results for the cases involved here. In the simpler method, which was used to obtain the curves in figures 1 to 6 for uniform earth resistivity, the transient voltage was computed for a primary circuit infinite in length, and to this voltage was added a term equal to the product of the primary current and the d-c mutual resistance, for uniform earth resistivity, of the actual primary and secondary circuits. For the case of an infinite length of primary circuit, the simple formal expression for $h(t)$, the voltage produced in the secondary circuit by unit step current (0 for $t < 0$, one ampere for $t > 0$) in the primary circuit, is given by[1]

$$h(t) = \frac{10^4\,\rho}{9.6x^2}\left[1 - \exp\left(\frac{-2.92 \cdot 10^{-8}x^2}{\rho t}\right)\right] \text{ volts per kilofoot}$$

where

$\rho$ = earth resistivity, meter-ohms
$x$ = separation, feet
$t$ = time, seconds

and thus a great part of the labor involved in exact computations for circuits of finite length is avoided.

A rigorous solution for $h(t)$, for circuits of finite length and with uniform earth resistivity, is available,[2] $h(t)$ so computed being but little different, in the present cases, from $h(t)$ for a primary circuit of infinite length, and only for large values of $(t)$. However, for the rigorous method, it appeared easier to compute $h(t)$ for the finite circuits involved by plotting the in-phase component, $a(\omega)$, of the coupling from curves based on the mutual impedance formulas,[1] in the form $a(\omega)/\omega$ and evaluating the Fourier integral[4] numerically, since previous computations made this process a simple one.

The voltage $V(t)$ produced in a secondary circuit by a primary current $I(t)$, the rate of change of which is $I'(t)$, is given by one form of the extension theorem[5] as

$$V(t) = \int_0^t h(t - \lambda)I'(\lambda)d\lambda$$

From this formula, using the measured rate of change of primary current, the transient voltage was computed for uniform earth resistivity.

1. For all numbered references, see list at end of paper.

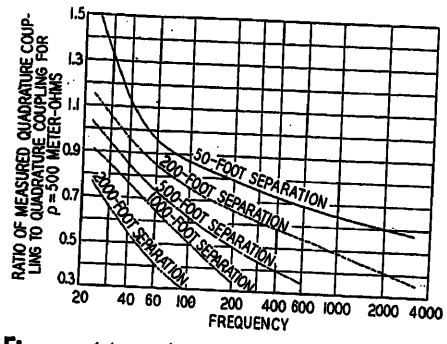



**Figure 11. Macon tests; ratio of measured quadrature coupling to quadrature coupling for uniform earth resistivity of 500 meter-ohms**

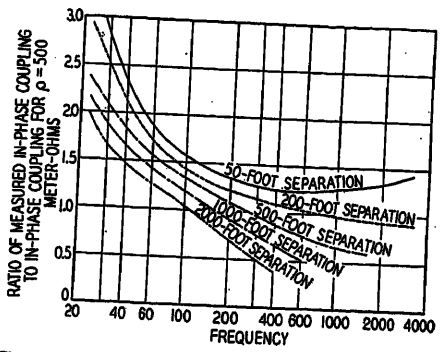



**Figure 12. Macon tests; ratio of measured in-phase coupling to in-phase coupling for uniform earth resistivity of 500 meter-ohms**

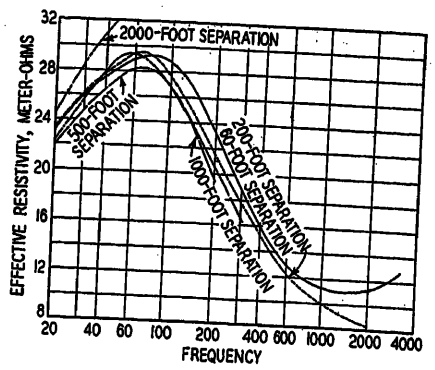



**Figure 13. Jennings tests; effective earth resistivity corresponding to measured quadrature coupling**

In computing the transient voltages from the in-phase and quadrature components, $a(\omega)$ and $b(\omega)$, of the measured a-c coupling, $a(\omega)/\omega$ and $b(\omega)/\omega$ were plotted from the experimental data and the Fourier integral[4]

$$h(t) = \frac{2}{\pi}\int_0^\infty \frac{a(\omega)}{\omega}\sin \omega t \cdot d\omega$$

$$= a(0) + \frac{2}{\pi}\int_0^\infty \frac{b(\omega)}{\omega}\cos \omega t \cdot d\omega$$

was evaluated numerically. The measured coupling was extrapolated to $\omega = 0$ on the assumption of the uniform resistivity used in computing the transient voltages. For the closest separation these computations could not be made with any significant degree of accuracy, largely because $b(\omega)/\omega$ did not converge with sufficient rapidity toward zero with increasing $\omega$, but for the other separations $h(t)$ could be computed with satisfactory accuracy from $b(\omega)$ for small values of $t$ and from $a(\omega)$ for larger values of $t$, up to about 10 milliseconds. The results from $a(\omega)$ and from $b(\omega)$ agreed within perhaps 10 per cent or less over a considerable range of $t$, thus providing a fairly conclusive check of the computations. For values of $t$ from 10 milliseconds to 30 milliseconds, the upper limit it seemed advisable to adopt, it was assumed that $[h(t) - a(0)]$ varied inversely with $t$. When end effects are negligible and the earth homogeneous, this relation is true for large values of $t$ and apparently represented a sufficiently accurate approximation here. The extension theorem was applied, as for the case of uniform resistivity, to obtain the transient voltages corresponding to the measured rate of change of primary current.

## Correlation of Results With Measured A-C Coupling

Figure 7 shows, for each separation in the Savannah tests, and as a function of the frequency, the effective earth resistivity corresponding to the quadrature component of the measured a-c coupling, that is, the value of uniform earth resistivity for which the quadrature component of the coupling, as determined from formulas for mutual impedance of grounded circuits of finite lengths,[3] would be equal to the measured quadrature coupling. The quadrature component was used in this connection because the effective earth resistivity could be determined more satisfactorily from it than from the in-phase component, although even from the quadrature component the effective resistivity could be determined satisfactorily only for the ranges of separation and frequency for which the resistivity is plotted in figure 7.

Figures 8 and 9 have been prepared to show the coupling data from the Savannah tests in a convenient form for correlating the behavior of the transient voltages with the behavior of the a-c coupling. Figure 8 shows the ratio of the measured quadrature coupling to the quadrature coupling corresponding to a uniform earth resistivity of 100 meter-ohms. Figure 9 shows the corresponding ratio for the in-phase coupling. The fact that the computed transient voltage for a resistivity of 100 meter-ohms was smaller than the measured voltage in the case of the 60-foot separation seems reasonable in view of the curves of figures 8 and 9 for this separation, since the ratios in this case are generally greater than unity, more than offsetting the smaller quadrature ratio at the higher frequencies. That the computed voltage for a resistivity of 100 meter-ohms was larger than the measured voltage in the case of the 2,000-foot separation is in accord with the fact that the ratios in figures 8 and 9 for this separation are considerably less than unity for the entire frequency range.

Figures 10, 11, and 12, for the Macon tests, are similar to figures 7, 8, and 9, respectively. Here the principal condition, illustrated in figures 3 and 4, to be correlated with the measured a-c coupling is that, for both separations, the computed voltages for a resistivity of 500 meter-ohms were greater than the measured voltages at small values of time and smaller at large values of time. The computations involving the Fourier integral showed clearly that at small values of time the transient voltages are closely related to the quadrature coupling at the higher frequencies, especially if the earth resistivity is not too low, whereas at large values of time the in-phase coupling at low frequencies is of most significance in predicting the transient voltages. Thus the above mentioned con-

dition regarding computed and measured voltages is seen to be consistent with the curves of figures 11 and 12. The high ratios shown in figure 12 for the low frequencies tend to substantiate the pragmatic approximation of taking the ground potentials to correspond to an earth resistivity of 1,500 meter-ohms.

Figures 13, 14, and 15, from the Jennings tests, are similar to figures 7, 8, and 9, respectively. On the basis of figure 13, it would appear that the best single earth resistivity to use in computing the transient voltages would be some 25 meter-ohms. However, as the computations involving the Fourier integral showed, the in-phase coupling at the low frequencies is of principal significance with regard to the maximum values of the transient voltages at wide separations, especially where the earth resistivity is as low as that indicated here, and an earth resistivity of 10 meter-ohms is seen, from figure 15, to be more nearly

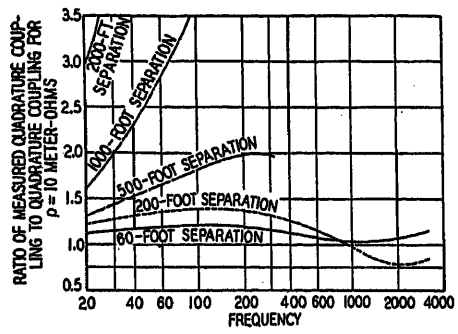



**Figure 14. Jennings tests; ratio of measured quadrature coupling to quadrature coupling for uniform earth resistivity of 10 meter-ohms**

consistent with this criterion. A resistivity of 10 meter-ohms was found to result in about as good an over-all agreement as could be obtained between the measured voltages and voltages computed on the basis of uniform earth resistivity.

As illustrated in figures 5 and 6, the use of an earth resistivity of 10 meter-ohms results in a maximum value for the computed voltage smaller than the maximum value of the measured voltage at the closest separation and greater than the maximum value of the measured voltage at the widest separation. Moreover, the computed voltages increased more slowly than the measured voltages, subsequent to the beginning of the transient, attained their maximum values later, and decreased more slowly at large values of time. These conditions are consistent with the curves of figures 14 and 15, since (1) for the close separations the transient voltages at small values of time can be predicted only from the measured quadrature coupling at the higher frequencies, whereas at large values of time the in-phase coupling at the lower frequencies is of most significance and (2) for the wide separations the transient voltages are related closely to the behavior of the measured in-phase coupling at low frequencies.

The computed voltages for the 2,000-foot separation, based on the measured a-c coupling, will be seen from figures 2, 4, and 6 to agree quite satisfactorily with the measured voltages and, although in some cases the agreement was not quite as good as that shown by these examples, it was found that in cases where the nonhomogeneity of the earth caused the transient voltages to depart considerably from the voltages which would have occurred with uniform earth resistivity, the computed voltages from the a-c coupling measurements took the effects of such nonhomogeneity into account fairly accurately.

## Summary

Widely different types of earth structure were indicated by the a-c coupling measurements at the 3 locations where these tests were performed, and by the behavior of the transient induced voltages. The departures of the measured transient voltages from the values which would have occurred with a uniform earth resistivity could generally be correlated satisfactorily with the measured a-c coupling.

At Savannah, Ga., a value of 100 meter-ohms was found to give about the best over-all agreement between the measured transient voltages and the voltages computed on the basis of uniform earth resistivity, this value being a reasonable one to choose from the standpoint of the measured a-c coupling. The voltages computed for this uniform resistivity were considerably lower than the measured voltages at the closest separation and, with increasing separation, the computed voltages gradually increased in comparison with the measured voltages, until at the widest separation they were substantially higher than the latter.

At Macon, Ga., the earth structure was apparently highly irregular, but with a reasonable value of uniform earth resistivity, 500 meter-ohms, as indicated by the a-c coupling measurements, the maximum values of the computed transient voltages agreed roughly with the maximum values of the measured voltages. However, these computed voltages increased more rapidly than did the measured voltages, subsequent to the beginning of the transient, and decreased more rapidly after the maximum values were attained. It was found that the approximation of taking the ground potentials to correspond to a resistivity of 1,500 meter-ohms improved the agreement between these computed voltages and the measured voltages. This constituted a crude way of taking into account the large in-phase coupling measured at the low frequencies.

At Jennings, La., the departures of the earth structure from homogeneity affected seriously the transient induced voltages, and careful examination of both components of the measured coupling was required to arrive at the

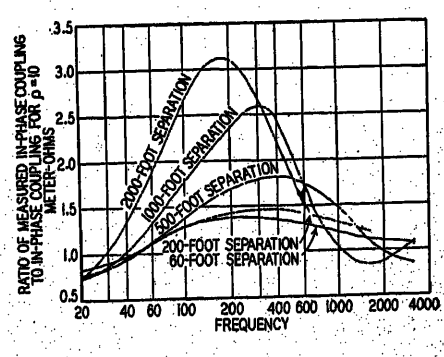



**Figure 15. Jennings tests; ratio of measured in-phase coupling to in-phase coupling for uniform earth resistivity of 10 meter-ohms**

value of earth resistivity, 10 meter-ohms, to give the best over-all agreement between the measured transient voltages and the voltages computed on the basis of uniform earth resistivity. Although the measured voltages and computed voltages for a resistivity of 10 meter-ohms were fairly well in accord as regarded maximum values, the wave shapes were considerably different. The computed voltages increased more slowly, subsequent to the beginning of the transient, than did the measured voltages, and decreased more slowly after the maximum values were attained.

The transient voltages computed from the measured a-c coupling were in satisfactory agreement with the measured voltages, indicating that in this method of computing transient voltages the effects of nonhomogeneities of the earth were taken into account where such effects were of importance.

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3. Mutual Impedance of Grounded Wires Lying on the Surface of the Earth, R. M. Foster. *Bell System Technical Journal*, volume 10, July 1931, pages 408–19.

4. Electric Circuit Theory and the Operational Calculus (a book), J. R. Carson. Chapter 11.

5. Reference 4, Chapter 2.


# Nuclear Physics Chart[1]

| Name | Picture Representation | Probable Composition | Charge | Approximate Mass | Remarks |
|---|---|---|---|---|---|
| Neutrino * | ± | Unknown | Zero | 1/2000 Unit | Undiscovered but theoretically necessary for conservation of mass energy in many nuclear transformations. |
| Electron | ⊖ | Elementary | 1 Unit Neg. | 1/2000 Unit | Carrier of electricity in wire conduction and vacuum tubes. |
| Positron ** | ⊕ | Elementary | 1 Unit Pos. | 1/2000 Unit | Discovered recently. Very unstable. Probably unites with electron and both disappear. ** Particle ejected during breakdown of a large number of artificially prepared radioactive substances. |
| Proton | ⊕ | Elementary | 1 Unit Pos. | 1 Unit | Ordinary hydrogen nucleus or ionized hydrogen atom. |
| Neutron | ± | Proton Electron | Zero | 1 Unit | Discovered recently. Electron and proton are closely bound so there is no external electric charge. This enables it to penetrate matter easily until it unties with a nucleus forming an isotope usually radioactive. |
| Deuteron Heavy Hydrogen Nucleus Diplon | ±⊕ | Neutron Proton | 1 Unit Pos. | 2 Units | Discovered recently. |
| Alpha Particle Helium Neucleus | ±⊕ ±⊕ | 2 Neutrons 2 Protons | 2 units | 4 Units | Given off in ordinary radioactivity. |
| Protium Hydrogen Atom | ⊕ ⊖ | Proton Electron | Zero | 1 Unit | Electron is separated from proton and loosely bound to it. May be ionized in discharges to form proton and free electron. |
| Deuterium *** Heavy Hydrogen Atom Diplogen Hydrogen Isotope | ±⊕ ⊖ | Proton Neutron Electron | Zero | 2 Units | Discovered recently. Occurs one part in ten thousand of ordinary hydrogen. May be easily ionized to form a deuteron. |
| Helium Atom | ⊖ ±⊕ ±⊕ ⊖ | 2 Protons 2 Neutrons 2 Electrons | Zero | 4 Units | Electrons loosely bound. May be ionized in discharges to form alpha particles and two free electrons. |

1. Compiled by Charles M. Lack, Westinghouse Electric and Manufacturing Company, and republished by permission from page 33 of *Electronics* for August 1937.

* In certain nuclear transformations it is necessary to postulate the ejection of small chargeless particles of 2 varieties or else abandon the laws of conservation of mass energy. One of these particles (neutrino) has a variable mass usually less than that of the electron and the other (anti-neutrino) a negative mass of the same amount.

** Modern physics believes mass and energy are different forms of the same thing and under certain conditions can be directly transformed one into the other. The mass of an electron, for instance, is equal to the energy of an electron or proton after being accelerated through 500 kv. When an electron and positron combine and disappear, 2 gamma rays are produced by the 500-kv type.

*** An isotope of an element is a form of the element having the same chemical properties but different mass. The chemical properties of all elements are determined by the number of outer loosely bound electrons. Thus to form an isotope it is necessary to increase or decrease the number of neutrons in the nucleus.

# Carbon Brushes for Steel-Mill Equipment

By W. C. KALB
MEMBER AIEE

*The problems associated with brush application on commutating-type equipment in the iron and steel industry are discussed in relation to type of equipment and conditions encountered in service.*

*The paper also discusses a newly defined measure of brush performance, termed "commutation factor," which provides an improved basis for control of the performance characteristics of brushes.*

*Mention is made of the development of electrographitic grades having mild polishing action, designed to prevent the formation of troublesome surface film on commutators exposed to the contaminating atmospheric conditions frequently encountered in steel mill applications.*

THE PROBLEMS associated with brush application in the iron and steel industry are fundamentally the same as those encountered wherever electrical generating equipment and motive power are used. However, service conditions in this particular industry are in some respects more severe than those usually encountered and, in certain instances, definitely unique. Discussion of the problems of brush application as related to this particular industry would therefore seem to be merited.

For the purpose of this discussion it is convenient to divide the types of equipment considered into 3 classes; first, industrial-type motors having shunt characteristics; second, series-type motors; third, generators and motors of large capacity used on mill drives. The application of brushes to slip rings will not be discussed since the number so used is small in comparison with those used on commutating equipment and the problems of application essentially the same as in other fields of service.

Undercutting of commutator mica has become an almost universal practice in steel mills. This practice removes the necessity for using brushes possessing decided abrasive characteristics. It also constitutes a valid reason for avoiding the use of so-called "self lubricating" brushes, i.e., brushes which have been impregnated with an oil or wax to maintain a film of lubrication on the commutator surface. The presence of such material tends to fill the slots of an undercut commutator with a conducting deposit which increases danger of commutator failure. Nearly all grades of brushes now manufactured have some graphite in their composition, either as a component of the original mix or imparted later by the process of graphitization. This graphite provides ample lubrication for the service conditions under which the brush is ordinarily used.

Industrial type motors of shunt characteristics present few serious problems in brush application. Apart from greater liability to troubles from conducting or abrasive dust and contaminated atmosphere, conditions of service are much the same in steel mills as in other industries. Where provision is made to insure cleanliness within the motor frame, nonabrasive electrographitic brushes give excellent service on this class of equipment. Atmospheric contamination of the commutator surface may require brushes possessing some cleaning action, the amount depending on local conditions. Under such conditions carbon-graphite brushes or special graphite brushes having a moderate cleaning action are often used. Because of variation in the amount of polishing effect required to maintain a clean commutator surface, a brush which works well on one motor may not give satisfactory performance on an identical motor in another part of the same mill. It is not advisable to attempt to offset the presence of abrasive or conducting dust by brush selection. The only sure remedy for troubles arising from this source is to prevent the dust entering the motor. This is best accomplished by piping clean, outside air to the interior of the motor frame. The dust cannot enter against an outward current of air from all openings in the frame.

Series type motors often encounter very severe operating conditions in steel-mill service. Some of the principal applications for this type of motor are on cranes, open-hearth chargers, mill screw-down, side guards, and table rolls. Heat and scale dust are almost always present in the vicinity of these motors, while oil vapor and other atmospheric contamination adds further complication on some applications. Piping in outside air will provide protection against heat, dust, and contaminated atmosphere for those machines which have a fixed location but this protection cannot be given to crane motors or others which are carried on moving equipment. In addition to the heavy load peaks, normally characteristic of the service on which series type motors are applied, the practice of "plugging" further increases the severity of operating conditions. By plugging is meant reversal of the controller before the motor comes to rest. Designers can build motors which will withstand the mechanical stresses resulting from this practice but it is impossible to provide the electrical compensation necessary to maintain good commutating conditions when direction of rotation and impressed voltage are reversed from their normal relationship. As a result, the burden of controlling commutation is thrown almost entirely onto the brushes.

Electrographitic brushes of the harder grades find extensive application on series-type motors in the steel mills. Brushes of this type, in general, have good commutating characteristics and, while not definitely abrasive, possess sufficient mass hardness to provide considerable cleaning action on the commutator. They are also highly resistant to the disintegrating effect of the sparking which inevitably occurs when motors are called upon to meet such extreme demands. In some instances, however, the

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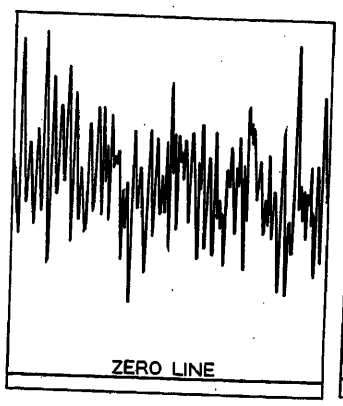



**Figure 1. Oscillographic record of contact drop on commutator with flat spot**

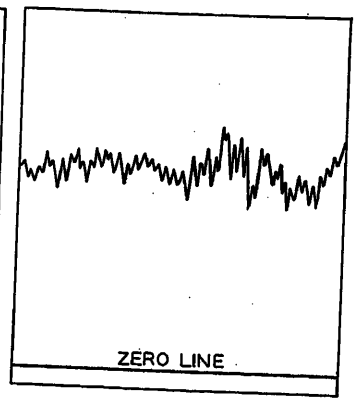



**Figure 2. Oscillographic record of contact drop on smooth commutator**

mass hardness of the electrographitic brush is not enough to overcome the burning of the commutator surface. The use of a carbon-graphite brush, having some abrasive action, is then indicated. While this abrasive action does result in some commutator wear, selection of a grade with the correct degree of abrasiveness will result in less commutator depreciation and lower maintenance expense than will be experienced if burned bars and flat spots are allowed to develop on the commutator. The latter condition may necessitate shutting down the mill for removal of the armature, an expense item of considerable moment. It may also result in more rapid loss of commutator capacity from returning than would be experienced from wear under a set of properly selected abrasive brushes.

The generators and large capacity motors used on modern steel mill drives constitute the third class of equipment on which brush application is considered in this discussion. Brushes of relatively high carrying capacity are required for this service since the motors are sometimes loaded almost to the stalling point and the current density in the brushes on both the motor and the generator rises to a very high value. In view of the sudden and extreme fluctuations of current resulting from the load conditions encountered it is also essential that brushes having exceptionally good commutating characteristics be applied. These requirements have led to the almost universal adoption of electrographitic brushes for motors as well as generators in this field of application.

Due to the industrial importance of heavy-duty electric drives in the steel mills and the fact that the demands there made upon the brushes are among the most severe encountered in heavy duty d-c power service, a thorough investigation of the brush requirements for this class of equipment has been carried on over the past few years. As a first step in this investigation, thousands of brush samples were obtained from service, together with accurate records of performance. Wherever possible these brushes were obtained in complete sets, with each brush identified as to polarity and location on the machine. A large proportion of these samples were taken from heavy duty steel mill drives, although brushes were also obtained from other heavy duty applications. Investigation was concentrated on brushes of the electrographitic type because of their predominance in this class of service. These brushes were then carefully studied in order to isolate some property common to those having good performance records and lacking in those which had failed in service.

It has long been recognized that the tests commonly applied to brush materials are not closely enough identified with the performance characteristics of the brush to provide a reliable basis for control. The tests referred to are specific resistance (electrical resistance per unit cube) hardness (as measured by the Schore scleroscope or other means) and apparent density (weight per unit of volume). These tests are simple to make and, since they do not destroy or impair the stock, they can be applied to each block of brush material. Unfortunately, however, they do not possess a well-defined relationship to the commutating properties of the brush. Contact drop and coefficient of friction are properties closely related to brush performance but tests of these characteristics require a great deal of time and it is impracticable to apply them to each block of brush material. Furthermore, the results obtained are influenced to a large extent by factors independent of the brush itself which affect the surface of the ring or commutator on which the test is being made.[1] Time, temperature, humidity, and atmospheric contamination are some of the factors which may influence the results obtained from tests of these properties. Brush manufacturers, as a class, have tried to control the performance characteristics of brushes by holding specific resistance, hardness, and apparent density within close limits but this plan has not been successful. Frequently 2 brushes which are almost identical in respect to these 3 properties will show entirely different performance characteristics.

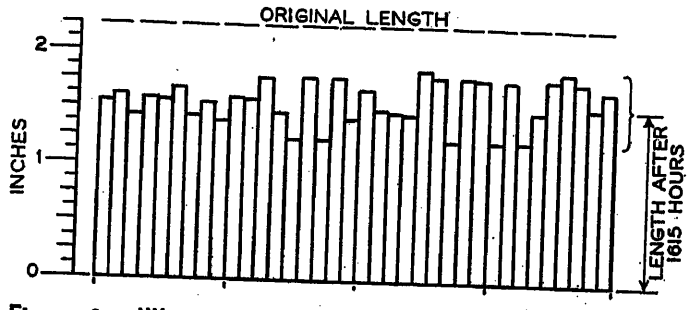



**Figure 3. Wear on brushes manufactured under customary basis of control, after 1,615 hours**

It is a well-known fact that one requisite to good brush performance is the maintenance of intimate contact between brush and commutator. Slight irregularities in commutator surface tend to impair this intimacy of contact thus causing sparking and resultant damage to commutator surface. Figure 1 is traced from an oscillographic record of the contact drop between a brush and a commutator on which a slight flat spot had developed. Figure 2 is a similar record from the same brush and commutator after the flat spot had been removed. Of course, the condition illustrated in figure 1 was accompanied by considerable sparking but no sparking occurred after re-

moval of the flat spot. It is known that irregularities in commutator surface as small as 0.0001 inch may seriously impair intimacy of contact with some grades of brushes while other grades are capable of maintaining firm contact in the presence of surface irregularities of considerably greater magnitude. In the study of this problem it soon became evident that commutating performance is closely associated with the ability of a brush to ride smoothly on the commutator and that property, in turn, with the elastic or, conversely, the shock absorbing properties of the brush.

A means was found to measure the shock-absorbing capacity of a brush and, as established by subsequent service tests, this also proved to be a measure of commutating performance. The test applied is essentially a measure of the elastic properties of the brush material. It disclosed that brushes having exceptionally good commutating properties possess a certain degree of elasticity while brushes less satisfactory in commutation show a different degree of elasticity. The characteristic so measured has been termed "commutation factor," indicating its close relationship to commutating performance. For practical purposes arbitrary numbers are assigned to indicate various commutation factors or differing degrees of elasticity. The test for this characteristic can be made quickly and does not injure the sample tested. It therefore affords an excellent basis for inspection, applicable to every block of brush material passing through production.

A practicable measure of brush performance having been found, methods were developed for the accurate control of materials and processes of production so that the required commutation factor can be imparted in accurately controlled degree to the finished product. By the methods developed it is possible to produce a series of several grades, similar in general characteristics but each having a different and sharply defined performance characteristic in respect to commutation.

This newly defined characteristic serves, not only as a measure of commutating performance, but also as a basis for obtaining improved uniformity in performance by making possible close control of one of the most important physical properties affecting performance. This is an accomplishment of major importance on applications as exacting as heavy-duty steel-mill drives. The superiority of control methods based on the use of "commutation factor" as the controlling property over methods designed to control resistance, hardness, and density, is shown by figures 3 and 4. Figure 3 shows the variation in wear among the brushes from 4 studs of a large synchronous converter after 1,615 hours of service. These brushes were of a well-known electrographitic grade and were all within close limits of tolerance in respect to resistance, hardness, and density. They did not, however, show corresponding uniformity when the test for commutation factor was applied. The brushes represented by figure 4 were manufactured under the commutation factor basis of control. They were placed on the same synchronous converter immediately after removal of the brushes represented by figure 3 and the record of wear was taken from the same 4 studs after 3,082 hours of service. The improvement in commutating performance was as marked as the improvement in uniformity of brush life which these charts indicate. A large number of carefully observed service tests confirm the evidence here presented that commutation factor is a dependable measure of brush performance and provides a reliable basis for production control.

This extensive comparison of brush performance and related physical properties also disclosed a reciprocal relationship between commutation factor and resistance to mechanical wear. Under mild commutating conditions, where electrical wear at the brush face is slight, a brush with comparatively low commutation factor will, as a rule, give longer life than one having high commutation factor. On the other hand, under severe commutating conditions the electrical wear of the brush with lower commutation factor may be so much more than that of one with high commutation factor that the latter will be superior in life as well as in commutating performance.

Atmospheric contamination is perhaps a greater source of difficulty on heavy-duty mill drive equipment than it is on the smaller series and industrial-type motors to which reference has been made in earlier paragraphs. In some mills elaborate air conditioning apparatus has been installed to remove acid fumes, oil vapor, and gaseous contamination which might cause the development of troublesome surface film on the commutators of mill-drive generators and motors. Most electrographitic brush grades are so free from all abrasive properties that they are incapable of polishing off the surface film resulting from contamination of the surrounding air. As a result, on some installations it is frequently necessary to resurface the commutators, an operation which may require shutting down the mill for an appreciable period of time. Naturally, this involves considerable expense and, if of frequent occurrence, may be a source of serious depreciation in commutator capacity. To better meet the needs of such operating conditions there has recently been developed a series of electrographitic grades possessing a mild polishing action. These have been tried out on a number of mill-drive installations and have proved capable of maintaining a clean, well-polished surface on many commutators previously troubled by film deposition when entirely nonabrasive brushes were used. The abrasive effect of these brushes is not great enough to be a source of appreciable commutator wear so that commutator de-

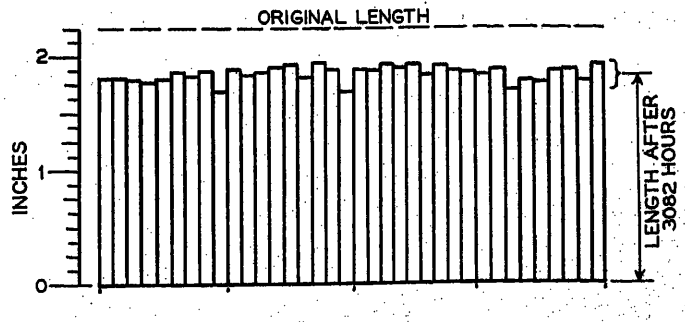



**Figure 4. Wear on brushes manufactured under "commutation factor" basis of control, after 3,082 hours**

preciation is less than that resulting from the necessity for frequent resurfacing. Furthermore, the liability to expensive shut downs and delays is reduced. Because their abrasive effect is so slight these brushes cannot be depended upon to remove existing surface faults such as burned bar edges or flat spots. Except for their slight polishing action these grades have the same general properties as the nonabrasive electrographitic grades and, like the latter, are produced with graduated and accurately controlled commutation factor.

Just why commutation factor should be a measure of the commutating performance of a brush is a point on which there may be diverse opinions. The relationship seems to be associated, at least in part, with the greater shock absorbing property possessed by a material showing high commutation factor and the resulting improvement in intimacy of contact when such a brush is subject to the impact of slight irregularities on the rapidly moving commutator surface. Whatever the explanation of this relationship may be, the fact of its existence has been demonstrated by service as well as laboratory tests. The discovery of this relationship represents another step of progress toward the solution of the many perplexing problems associated with commutation on equipment subject to such exacting conditions of service as are today encountered in the iron and steel industry.

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# Large Steel Pipe Welded by Improved Methods

IN preparation for completion of the Colorado River aqueduct, now scheduled for the winter of 1938–39, construction has been under way for some time on the distribution system which the Metropolitan Water District of Southern California is building for delivery of aqueduct water to member cities. The 242-mile main aqueduct from the Colorado River has its western terminus in Cajalco reservoir. Some 150 miles of distribution lines will be required to convey the water to the 13 cities of the District, located on the coastal plain between Cajalco and the sea. These distribution lines are the equivalent of a major water system in themselves, including a large mileage of tunnels, precast concrete pipe up to 12½ feet in diameter, and steel pipe in diameters up to 11½ feet. Because of the large diameter of the steel line, particular interest attaches to methods of fabrication in the shop and in welding metal as thick as $^{31}/_{32}$ inches under trench conditions, that is, where the pipe cannot be rotated during the welding process.

The steel pipe sections are all 33 feet 4 inches in length; diameters range from 10 feet 4 inches to 11½ feet except on the bridge across the Santa Ana River where pipe of 9 feet 8 inches diameter is used. The thickness varies, according to the head, from $^{17}/_{32}$ to $^{31}/_{32}$ inch. Correspondingly, the weight ranges from 18 to 28 tons per section.

*Shop Welding.* Each section is made up of 4 steel plates rolled to the proper curve and requiring only a single longitudinal weld in each plate to form a cylinder of the pipe diameter. The completed section is made up by putting together 4 of these cylinders and welding the 3 circumferential joints. In assembling a section, longitudinal welds are staggered. Circumferential welds are made in a large automatic electric welding machine which completes the weld, even in the $^{31}/_{32}$-inch thickness, with a single pass.

Two types of mounting are used for the welding machines: For longitudinal seams the welding equipment is on a carriage which moves lengthwise of the pipe as the weld progresses; a larger machine, used for making the circumferential welds, is stationary and the pipe is rotated as the weld progresses. Both welding machines operate on top of the pipe.

The adjoining edges of the plates to be welded are beveled so the molten metal flows in a V-shaped groove filled in advance with a flux. The flux is a silicious material applied in a powdered form resembling ground glass. The heat of the electric current, fusing the flux, forms a covering over the molten metal closely resembling glass in texture and brittleness. This glass-like covering is so brittle it is easily broken off with a hammer after the weld has cooled. The automatic welding machines work at about 40 volts and use a current of 1,100 or 1,200 amperes. In the longitudinal welds a pair of plates with a V groove similar to that in the joint itself are tack welded at the end of the joint where welding starts, thus affording a few inches for the welding operation to get well under way before reaching the joint in the pipe. Test coupons, attached at the end of the longitudinal weld, are taken every 800 linear feet of weld. All pipes with metal thicknesses exceeding $^{5}/_{6}$ inch are annealed, after welding, at temperatures of 1,100 degrees Fahrenheit after which they are cooled slowly.

*Welding Field Joints.* When a joint is fully entered ready for welding, it is tacked with welds 4 or 5 inches long spaced as required. This is done to prevent any tendency to creep as welding progresses around the circumference. The tack welding is done by one man on the inside and two on the outside.

Completion of the weld involves a number of passes varying with the thickness of the metal. With 7 passes for the thickest metal, the 11½-foot pipe requires 40 man-hours per joint or the equivalent of one man's time for a full week on the inside and outside of a single joint. With a crew of about 40 welders, joints in the trench are completed, inside and outside, at the rate of 8 sections per day.

All welds, in shop and field, are done electrically. In the field, current is supplied by portable motor-generator sets equipped for remote voltage control. The welder sets the control for any voltage he prefers from 40 to 80; the amperage is about 250.

From "Steel Pipe 11½ Ft. in Diameter Welded by Improved Methods" published in *Engineering News-Record* for May 20, 1937, pages 747–51.

# The Design of Inductances for Frequencies Between 4 and 25 Megacycles

By DALE POLLACK
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## Summary

The results of a study of the resistance of small single-layer inductances for use at frequencies between 4 and 25 megacycles are given. From experimental and analytical work a procedure has been deduced for the optimum design of such inductances.

## Introduction

WHILE IT HAS long been recognized that radio receiver performance is dependent upon the merit of the inductances employed in the tuned circuits, few data beyond 4 megacycles are available upon which to base the design of such inductances. Because of the lack of this information, design calculations at high frequencies have in general been limited to obtaining the correct inductance values. While some attention has been paid to obtaining low effective resistance, the efforts in this direction have usually been misdirected, with the emphasis on factors which actually are of little consequence in determining coil resistance.

A tuned circuit is represented to a first degree of approximation by the equivalent circuit shown in figure 1. For the small coils considered in this study, $C_0$ is very small,[1] less than 5 micromicrofarads, and it may be combined with the capacitance of the tuning condenser, $C$, with which the coil is associated, since $R_c$ is always small. The effective resistance of the inductance is usually considerably larger than the effective resistance of the condenser, but, at high frequencies, the condenser resistance may also be of importance.

The numerical value of the inductance, $L$, is determined by circuit considerations, and, consequently, is fixed by specification. This paper is concerned with the value of the effective resistance, $R$, of the coil, and with the design of coils to have a minimum effective resistance. It is usual to compare tuned circuits on the basis of the ratio of their reactance to their total effective resistance, $\omega L/R$ or $1/\omega CR$ denoted by $Q$. The highest $Q$ consistent with practical limitations—such as those of cost and space—is the desideratum. The importance of high $Q$ circuits in modern receiver design is well known.

The increase in resistance of an air-core solenoid at high frequencies over its d-c resistance is the result of:[2]

1. Skin effect in the wires, that is, the nonuniform current distribution over the cross section of the wire, caused by the internal flux of the wire itself.
2. Proximity effect, that is, the nonuniform current distribution over the cross section of the wire caused by the flux from neighboring turns of wire.
3. Dielectric losses, caused by hysteresis in the dielectric between turns of wire, or situated near the wire.
4. Eddy current losses in metallic bodies in the field of the coil.
5. Electromagnetic radiation losses.

As a consequence of these losses, the effective resistance of a coil may be many times its d-c resistance. The magnitude of these losses is determined by the construction of the coil, the factors which must be considered in designing a coil being:

1. Coil dimensions: length and diameter.
2. Wire: material, insulation, and size.
3. Coil form: material, insulation, and size.
4. Location of coil with respect to metallic and dielectric bodies.

The design problem is to proportion these factors, so that the resistance of the coil will be a minimum.

## Early Work

The most extended analytic work on coil resistance at high frequencies which can be applied to the types of coils used in radio equipment is that of Butterworth.[3] Butterworth's solution treated both skin effect and proximity effect in short solenoids and multilayer coils. The mathematical analysis made in this paper, in appendix II, is an extension and simplification of Butterworth's conclusions, as applied to short solenoids at frequencies above 4 megacycles. Butterworth's treatment is useful, in that the assumptions which were found necessary did not place any restriction on the frequency. However, his solution to this difficult problem was complicated, and has not received much practical attention. The conclusions were later reduced to a form better adapted to practical computations,[4] but the design method was still involved and has not been generally applied.

Published experimental information on coil resistance above 4 megacycles is meager. Hund and DeGroot[5] carried their measurements as far as 5 megacycles. Hall[6] describes tests at frequencies up to 6 megacycles, and Morecroft[7] presents data on measurements made up to 4 megacycles. A more recent paper, by Schwarz,[8] describes

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The experimental work involved in the study was carried out in the Marcellus Hartley Laboratory of the electrical engineering department of Columbia University. The writer wishes to thank Professors Walter I. Slichter, Edwin H. Armstrong, and John B. Russell, of Columbia University, for their kind supervision and assistance, and Doctor George P. Wadsworth, of the Massachusetts Institute of Technology, for checking the equations.

1. For all numbered references, see list at end of paper.

tests made at frequencies up to 10 megacycles. None of these data have been correlated for design purposes. Reference to work above 10 megacycles is almost entirely lacking, only one published paper having been found, by Barden and Grimes,[9] describing measurements at the single frequency, 15 megacycles.

## Experimental

Tests were performed on 2 sets of coils, having inductances of approximately 1.1 and 3.6 microhenrys. A large number of coils was wound, with groups in which one design parameter at a time was varied. The extremes over which the measurements were carried were:

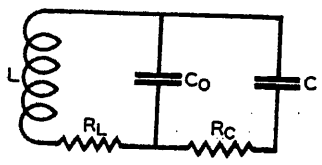



**Figure 1. Approximate equivalent circuit of coil and tuning condenser**

Frequency: 6 to 22 megacycles.
Wire size: 14 to 36, B. and S. gauge.
Coil diameter: 2.5 to 6.5 centimeters.
Coil length: 0.5 to 3.5 centimeters.

In addition, tests were made for a variety of coil form materials, and for several depths of winding grooves for the wire. Except where otherwise noted enameled copper wire was used.

The circuit resistance was measured by the reactance variation method,[10] using 2 condensers in parallel, as in figure 2, and a vacuum-tube voltmeter as the indicator. The condenser, $C_1$, is the tuning condenser, while $C_2$, with a total capacitance variation of only 6 micromicrofarads was employed to obtain the reactance change. The condensers were calibrated by a substitution method at a low radio frequency. The voltmeter was calibrated by comparison with a thermocouple, also at a low radio frequency.

Each of the coils was mounted on a pair of brass pins about 4 centimeters long, which fitted into mercury contact cups mounted in the center of a cubical copper compartment about 20 centimeters on each edge. The frequency of the oscillator used for a power source was maintained constant to within about 0.02 per cent by tuning to zero beat with harmonics of a crystal oscillator and maintaining a continuous audible check on the beat note with a radio receiver. In this way any frequency drift or reaction of the tuned circuit upon the oscillator source would have been detected, if it had occurred.

In the application of the reactance variation method of measurement, the total of all the circuit losses is obtained, including condenser and lead losses, tube input losses, and the coil losses. In this study, the data, except where otherwise noted, include the circuit and condenser resistance, but a correction has been made for the input impedance of the vacuum-tube voltmeter, as mentioned below. Despite the fact that some of the corrections have not been made, at any frequency for a given coefficient of self-inductance, the various experimental curves are comparable, because under such conditions the circuit and condenser losses are constant.

As a matter of interest, an attempt was made to determine the magnitude of the loss resulting from the input resistance of the vacuum-tube voltmeters.[11] In the tests of the 3.6 microhenry coils, a 24*A* tube was used in the voltmeter circuit, while, in the tests of the 1.1 microhenry coils, a 954 acorn tube was employed, in a triode connection. The tube losses were determined by shunting the circuit of figure 2 with a second identical vacuum-tube voltmeter, and remeasuring the $Q$. From the change in the overall $Q$ of the circuit, the effective resistance of the tube can be calculated. This method assumes that the condenser losses are independent of the small capacitance change necessary to retune the circuit to resonance, when the second vacuum tube is added.[12] From the data obtained for the effective input resistance of the voltmeters, correction factors for any $Q$ and any frequency have been plotted. These are shown in figures 3 and 4. While, as has been pointed out previously, it is not essential that these corrections be made, since the information was available, it was employed, and the experimental results presented in this paper have been corrected for the input resistance of the voltmeter.

## Results

In appendix II expressions are derived for the effective resistance and the $Q$ of a coil at high frequency, taking account of the wire losses, i.e., the skin effect and the proximity effect, only. When the frequency is well below the natural frequency of the coil, it is found, after certain assumptions are made, that the $Q$ of an inductance coil is

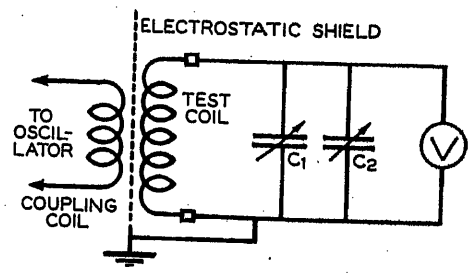



**Figure 2. Measurement circuit. A vacuum-tube voltmeter is used**

$$Q = \frac{f^{1/2}LdS^2D}{10^{3/2}\rho^{1/2}(S^2D^2N + 2N^3d^2)} \qquad (20)$$

or, the $Q$ is directly proportional to the square root of the frequency. For the coils employed in these tests (20) has been found to agree with Butterworth's equations, from which it is derived, by better than 10 per cent.

An exact experimental check on this equation is difficult because of the impracticability of separating precisely the skin and proximity effects from the circuit and coil losses which the equation does not include. Moreover, (20) was not used for design purposes and it consequently was not deemed essential to make a precise check. For illustration, however, a typical set of data are shown in figure 5, in which an attempt is made to break down the various loss components of the measurement circuit. Dielectric

losses in the coil form and wire insulation and vacuum-tube losses were corrected for by measurement, as described elsewhere in this paper. The distributed capacitance correction was made by (12). This correction is necessary, because the tuning condenser in the reactance variation method is calibrated without a coil in the circuit. Effectively, therefore, the addition of the distributed capacitance of the test coil constitutes an error in the calibration of the tuning condenser, and a correction must be made to the measured value. The approximate lead losses were calculated from the d-c lead resistance by applying the usual skin-effect formulas.

The condenser losses were estimated by assuming a condenser resistance of 0.02 ohm at 10 megacycles, increasing to 0.045 ohm at 20 megacycles. This is a conservative estimate. The condenser resistance was probably in excess of these figures, but could not be measured conveniently.

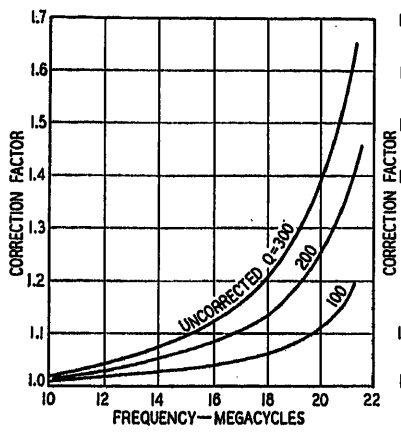



**Figure 3. Correction factor to correct for the input resistance of the 24A tube in the vacuum-tube voltmeter**

Corrected $Q$ = factor × uncorrected $Q$

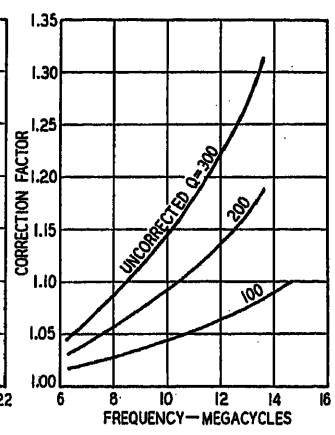



**Figure 4. Correction factor to correct for the input resistance of the triode-connected 954 tube in the vacuum-tube voltmeter**

The only loss components properly chargeable to the coil, besides the skin and proximity effects, are the dielectric losses and the unaccounted losses.

### Effect of Wire Size

An experimental set of curves illustrating the variation in $Q$ with wire size is shown in figure 6. The optimum wire diameter, as obtained in appendix II, is

$$d_0 = b\sqrt{\frac{D}{2L(102S + 45)}} \tag{16}$$

or

$$d_0 = \frac{b}{\sqrt{2N}} \tag{17}$$

In table I the values of the optimum wire size calculated from either of these expressions is compared with experimental values obtained from curves similar to those of figure 6. The test coils were wound on bakelite forms with enameled wire, typical of the construction used in practice. In most cases the agreement is better than the difference between diameters of successive wire sizes, namely, 12 per cent. The probable experimental error is about 8 per cent. It may be concluded that there is an optimum wire size for any given coil, and that this optimum size can be calculated from (16) or (17).

### Length-to-Diameter Ratio

The determination of the proper ratio of length to diameter for a solenoid is more difficult. Some confusion has resulted from the wide variations in conclusions which have been reached by various investigators.[3,9,14] The apparent inconsistencies result from the fact that different variables are considered in different studies. The solution which is reached must always depend upon the geometric or economic limitations which are assumed. The coil volume, surface area, wire length, or any of several other factors may be assumed constant, depending upon the nature of the problem. It should also be noted that either the wire size may be kept constant, or the optimum value may be employed, although, for design purposes, the latter is preferable.

**Table I. Experimental Verification of (16) and (17)**

| Coil Description | | | Optimum Wire Diameter (Centimeters) | | Percentage Difference From Experimental Figure |
|---|---|---|---|---|---|
| Inductance (Microhenries) | Diameter (Centimeters) | Length (Centimeters) | From Equation | From Experiment | |
| 3.6 | 2.5 | 1.55 | 0.090 | 0.102 | 12 |
| 3.6 | 3.8 | 1.45 | 0.108 | 0.115 | 6 |
| 3.6 | 2.5 | 1.55 | 0.090 | 0.115 | 22 |
| 1.1 | 2.5 | 0.89 | 0.105 | 0.100 | 5 |
| 1.1 | 2.5 | 0.56 | 0.079 | 0.093 | 15 |
| 1.0 | 1.3 | 0.69 | 0.055 | 0.064* | 13 |
| 1.0 | 3.8 | 0.79 | 0.142 | 0.134* | 6 |

* From data in Barden and Grimes's paper.[9]

The effect of changes in ratio of coil length to diameter, for a certain group of coils in which the coil diameter, wire size, inductance, and frequency are held constant, is shown in figure 7. A similar set of curves, except that the coil length is held constant, instead of the diameter, is given in figure 8. For the specifications for which these curves are obtained, namely, the wire size, inductance, frequency, and either the diameter or length constant, it appears that the optimum ratio of length to diameter is between 0.5 and 0.3. Fortescue[14] arrived at optimum values of the length: diameter ratio greater than unity, from an analytic treatment based upon similar assumptions, but Butterworth[14] has shown that an error must have been contained in the calculations. The curves also illustrate that the maxima obtained are flat, and values within a reasonably wide range may be employed without departing greatly from the maximum value of $Q$.

### Coil Dimensions

For design purposes the variation in $Q$ with the coil dimensions, when the optimum wire size of (16) or (17) is used, is of greater importance, since higher $Q$'s may be

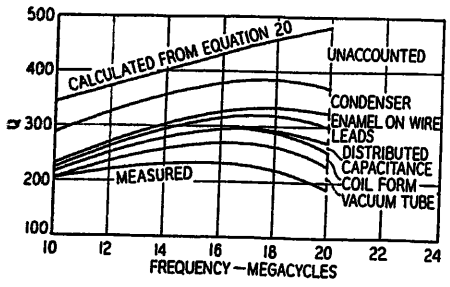



**Figure 5. Comparison of calculated and measured Q**

Coil dimensions for this figure: $L = 1.1$ microhenrys, $D = 2.5$ centimeters, $b = 3.4$ centimeters, wire size, 18 B. and S.

obtained in this way. In appendix II it is shown that, if the wire size is maintained at the optimum value, the figure of merit is given by,

$$Q_m = \frac{f^{1/2}\ Db}{\sqrt{2000}\ \rho^{1/2}\ (102b + 45D)} \tag{22}$$

For convenience in investigating the effect of changes in coil shape (22) is rearranged, giving

$$Q_m' \equiv \frac{Q_m}{\frac{f^{1/2}}{\sqrt{2000}\rho^{1/2}}} = \frac{Db}{102b + 45D} \tag{22a}$$

$$= \frac{D}{102 + \frac{45}{S}} \tag{22b}$$

$Q_m'$ is, of course, directly proportional to $Q_m$. These relations are plotted in figures 9 and 10. It is noted that, for a constant diameter of coil, the $Q$ increases as the coil length is increased, but the increase is less rapid as large values of $b/D$ are attained. Consequently, if an economic or a practical limitation is placed upon the design, there will be an optimum ratio.

Experimental data are shown in figure 11. The curve has been plotted from an equation of the form

$$Q_m = \gamma \frac{D}{102 + \frac{45}{S}} \tag{22c}$$

where $\gamma$ has been selected empirically to cause the curve to pass through one of the experimental points. The curve, therefore, shows the agreement of the experimental data with the shape of (22*b*). If (22*b*) had been plotted directly, it would have shown exactly the same shape as (22*c*), but displaced in the positive ordinate direction, since it does not take account of the circuit losses, radiation losses, and dielectric losses, which are all included in the experimental data.

Frequently, the maximum coil dimensions are fixed by the size of the coil shield, which, in turn, is limited in size by the space available in the apparatus. The presence of a coil shield usually reduces the $Q$, because of the increased eddy current loss. It has been shown by several experimental and mathematical studies[15] that, if the coil diameter is less than half the shield diameter, and the ends of the coil are separated by at least a coil diameter from the ends of the shield, the $Q$ of the tuned circuit is not reduced by more than 5 to 8 per cent. This restriction may be employed to determine the size of a coil enclosed in a shield.

It is of interest to note that, if the wire size, inductance, and length: diameter ratio are kept constant, an optimum diameter of coil can be obtained for which the $Q$ is a maximum. This is shown mathematically in appendix II, and the optimum diameter is found to be

$$D_0 = \sqrt[3]{\frac{10d^2L(102S + 45)}{S^2}} \tag{24}$$

A set of coils was wound which checks this relation very closely. The experimental results are plotted in figure 12, from which the maximum $Q$ is seen to obtain for a diameter of 4.0 centimeters. From (24) a value of 3.9 centimeters is obtained.

### Calculation of Number of Turns

The number of turns, for a given inductance, when the diameter and length of the coil are known, can be calculated from

$$N = \sqrt{\frac{L(102S + 45)}{D}} \tag{14}$$

which is derived in appendix II. This equation will usually give the correct value within about 5 per cent, and the coil, when wound, can be adjusted to the required value in any of the usual ways.

### Dielectric Losses

The magnitude of the dielectric losses in the coil form and in the enamel wire insulation for typical coils at high frequencies was investigated. Examples are given herewith. To measure the dielectric losses in the coil form 2 similar coils, of 2.5-centimeter diameter, were wound, one using a grooved bakelite form with a groove about 0.04 centimeters deep, the other wound self-supporting, except for 3 narrow celluloid strips to which the wire was fastened with collodion. The percentage loss in $Q$ resulting from the grooved bakelite form is shown in figure 13. At 14 megacycles the loss is less than 10 per cent.

The curves of figure 14 are for a set of 3 similar coils, of 5-centimeter diameter, one wound without any supporting material—similar to the coil described in the preceding paragraph—, one wound on a grooved bakelite form, and the third on a grooved cardboard form about one centimeter in thickness: worse than any case one would expect to find in practice. The groove in each case was about 0.04 centimeters deep. At 13 megacycles the reduction in $Q$ resulting from the heavy cardboard form was 27 per cent. A wood form, used for another coil, gave results similar to those obtained for the cardboard. The loss in $Q$ resulting from the grooved bakelite form was 19 per cent at 13 megacycles.

To measure the dielectric loss in the coil form at higher frequencies, a group of 1.1 microhenry coils was wound, one on a smooth bakelite form, one on grooved bakelite with a groove about 0.04 centimeter deep, and one without a supporting form, as described previously. The difference between the smooth bakelite and the air-core samples was smaller than the experimental error. The loss in $Q$ resulting from the groove in the bakelite is plotted in figure 15, and amounts to 13 per cent at 20 megacycles.

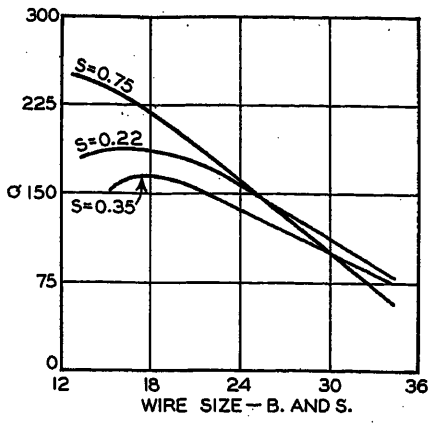



**Figure 6. Experimental curves illustrating variation in Q with wire size**

For this set of curves, $f$ = 20 megacycles, $L$ = 1.1 microhenrys, $D$ = 2.5 centimeters. Curves similar to these were used in preparing the data of table I

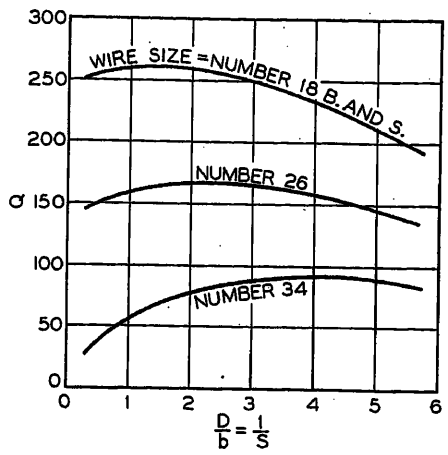



**Figure 7. Experimental curves illustrating the variation in Q with coil length : diameter ratio, when the diameter is constant**

For this set of curves, $f$ = 17 megacycles, $D$ = 2.5 centimeters, $L$ = 1.1 microhenrys

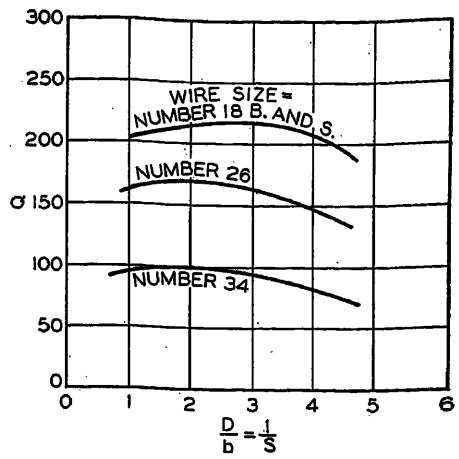



**Figure 8. Experimental curves illustrating the variation in Q with coil length : diameter ratio, when the length is constant**

For this set of curves, $f$ = 13 megacycles, $b$ = 1.5 centimeters, $L$ = 3.6 microhenrys

To investigate the dielectric loss in the enamel wire insulation, 2 similar coils were wound, on smooth bakelite forms, one using enameled wire, the other bare copper wire carefully cleaned to remove corrosion. The per-cent loss in $Q$ resulting from the enamel is plotted in figure 16 and amounts to about 6 per cent at 20 megacycles. This result is quite reasonable, since the dielectric path in a spaced winding is largely in air. Below 5 megacycles the dielectric loss in the wire insulation is difficult to detect. After a time bare copper wire corrodes and the dielectric loss in the enamel insulation may become smaller than the loss resulting from corrosion.

These data indicate the relative unimportance of the dielectric losses in determining coil performance. The choice of coil form material, within reason, and the use of enameled wire, have little effect on the merit of the coil. A loss of less than 10 or 20 per cent can be expected for small diameter coils, if a deeply grooved form is used. A shallower groove may be used with little sacrifice in rigidity and an improvement of a few per cent in the figure of merit. An ungrooved bakelite form causes very little loss in $Q$.

## Summary

The merit of coils for frequencies above 4 megacycles is determined largely by the winding design. A suitable procedure for the optimum design of coils for these frequencies is:

1. Coil diameter and length of winding: Make as large as is consistent with the shield being used. The shield diameter should be twice the coil diameter and the ends of the coil should not come within one diameter of the ends of the shield.

2. A bakelite coil form with a shallow groove for the wire, and enameled wire, may be used with little reduction in the $Q$. The groove should not be any deeper than is necessary to give the requisite rigidity. The use of special coil form constructions and special materials does not appear to be justified.

3. Number of turns: Calculate from

$$N = \sqrt{\frac{L(102S + 45)}{D}} \qquad (14)$$

4. Wire size: Calculate from

$$d_0 = \frac{b}{\sqrt{2}N} \qquad (17)$$

## Appendix I. Notation and Units

$b$ = length of winding, centimeters
$C$ = capacitance, micromicrofarads
$C_0$ = self-capacitance of coil, micromicrofarads
$d$ = diameter of wire, centimeters
$d_0$ = optimum wire diameter, centimeters
$D$ = diameter of coil, centimeters

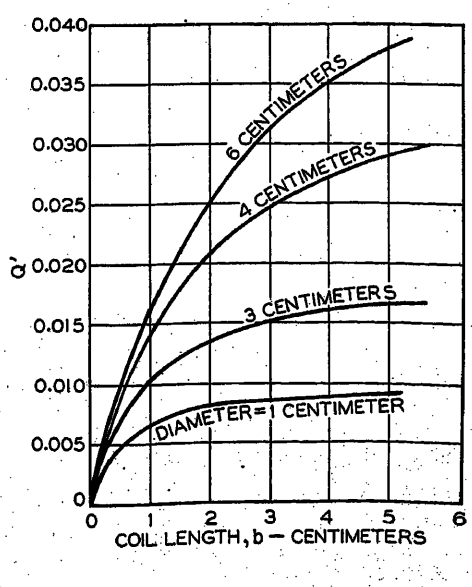



**Figure 9. Plot of (22a), showing the variation in Q with length and diameter of coil, when the wire size is kept at the optimum value**

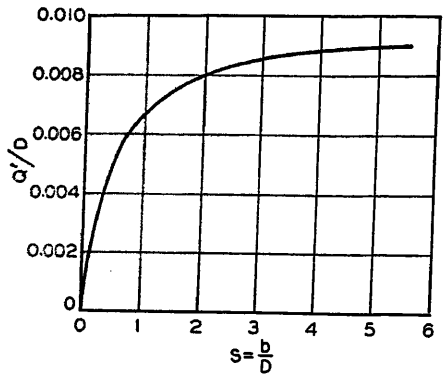



**Figure 10. Plot of (22b) showing the variation in Q with the length : diameter ratio, when the wire diameter is optimum and the coil diameter is constant**

$D_0$ = optimum coil diameter, centimeters
$f$ = frequency, cycles per second
$F$ = skin effect factor, see (1)
$G$ = proximity effect factor, see (1)
$j$ = $\sqrt{-1}$
$K$ = factor depending on $S$, see (1)
$L$ = inductance, microhenrys
$N$ = total number of turns of wire on coil
$Q$ = figure of merit of tuned circuit
$Q_m'$ = factor proportional to $Q_m$. See (22*b*)
$Q_m$ = figure of merit for optimum wire size
$R$ = effective resistance of tuned circuit or of coil, ohms
$R'$ = effective resistance of coil, including effect of self-capacitance
$R_c$ = effective resistance of condenser
$R_d$ = d-c resistance of coil, ohms
$R_L$ = effective resistance of coil
$S$ = ratio of length to diameter of coil = $b/D$
$X$ = reactance of coil, ohms
$z$ = skin effect coefficient, see (4)
$\gamma$ = empirical constant in (22*c*)
$\omega$ = angular velocity = $2\pi f$
$\rho$ = specific resistivity of conductor, in ohms per centimeter. For copper, $\rho = 1.72 \times 10^{-6}$ ohms per centimeter

## Appendix II. Derivation of Equations

Butterworth[3] has shown that the effective resistance of a coil, including the skin and proximity effects, may be expressed by the relation

$$R = R_d\left[1 + F + \frac{1}{4}\left(\frac{KNd}{D}\right)^2 G\right] \tag{1}$$

where, at high frequencies,

$$1 + F = \frac{\sqrt{2}z + 1}{4} \tag{2}$$

$$G = \frac{\sqrt{2}z - 1}{8} \tag{3}$$

and

$$z = \pi d\sqrt{\frac{2f}{10^9\rho}} \tag{4}$$

The quantities are expressed in practical centimeter-gram-second units. $K$ is a factor depending upon the ratio of coil length to diameter.

For copper wire

$$= 0.1d\sqrt{f} \tag{5}$$

, for No. 20 B. and S. wire

$$= 0.008\sqrt{f} \tag{6}$$

and, for frequencies greater than 4 megacycles,

$$z > 16$$

Consequently, for the high frequency case considered in this paper, (2) and (3) may be written, without much error

$$1 + F = \frac{\sqrt{2}}{4}z = \frac{\pi d}{2}\sqrt{\frac{f}{10^9\rho}} \tag{7}$$

$$G = \frac{\sqrt{2}}{8}z = \frac{\pi d}{4}\sqrt{\frac{f}{10^9\rho}} \tag{8}$$

Now, if the turns of the coil are assumed to be circular, which is not exactly true,

$$R_d = \frac{\rho l}{A} = \frac{4\rho DN}{d^2} \tag{9}$$

The factor, $K$, can be computed for any value of $S = b/D$ from series expansions. A simple empirical equation for $K$ has been found from the expansions. This relation is

$$K = \frac{4}{S} \tag{10}$$

For values of $S$ between 0.25 and 1.00 this simple expression gives $K$ to within 3 per cent of its correct value.

Equations 7, 8, 9, and 10 may be substituted into 1, giving an expression for the wire resistance of a coil at high frequencies, in terms of its physical dimensions,

$$R = 2\pi\sqrt{10^{-9}\rho f}\left[\frac{DN}{d} + \frac{2N^2d}{S^2D}\right] \tag{11}$$

If the coil is used at a frequency near its natural resonant frequency, its resistance is modified by its self-capacitance. The apparent resistance of the coil-self-capacitance combination of figure 1 is given by

$$R' = \frac{R}{(1 - \omega^2LC_0)^2} \tag{12}$$

assuming that the self-capacitance is lumped across the terminals of the coil. When the coil is shunted by an external capacitance, as in a tuned circuit, the self-capacitance becomes part of the shunt

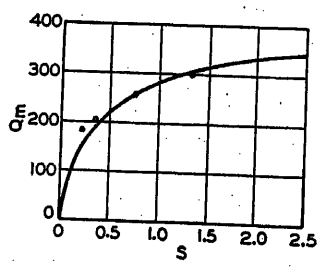



**Figure 11. Relation between the length : diameter ratio and Q, when the wire size is kept optimum. The points are from experimental data; the curve shown was drawn from (22c), after $\gamma$ had been selected to pass the curve through one of the experimental points**

For this curve, $D$ = 2.5 centimeters, $L$ = 1.1 microhenrys, $f$ = 11 megacycles

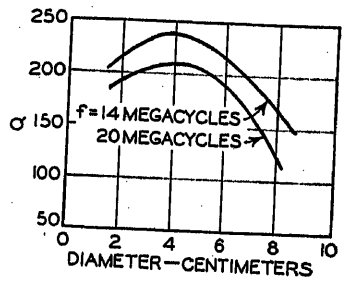



**Figure 12. Plot of Q against coil diameter, when the length : diameter ratio and the wire size are constant**

For these experimental data, $b/D$ = 2.8, $L$ = 1.1 microhenrys, $d$ = 0.081 centimeter

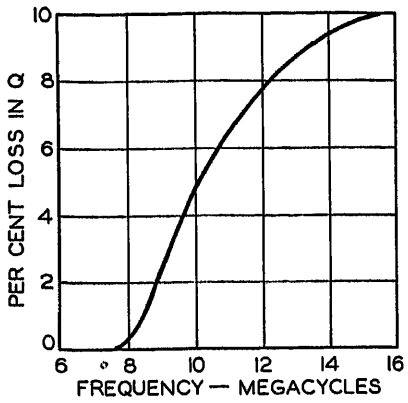



**Figure 13. Per cent loss in Q resulting from grooved bakelite form**

For this figure, $L$ = 3.6 microhenrys, $D$ = 2.5 centimeters, $b$ = 1.5 centimeters, wire size, number 18 B. and S.

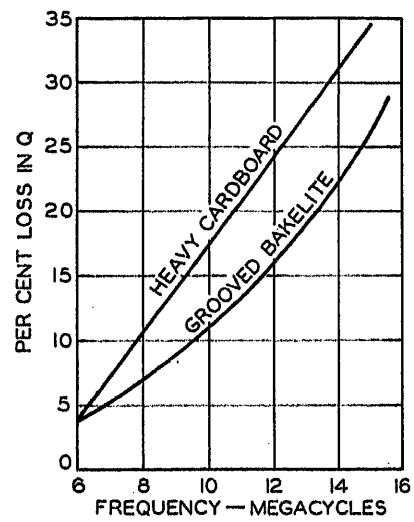



**Figure 14. Per cent loss in Q resulting from heavy cardboard form and grooved bakelite form**

For this figure, $L$ = 3.6 microhenrys, $D$ = 5 centimeters, $b$ = 1.5 centimeters wire size, number 32 B. and S.

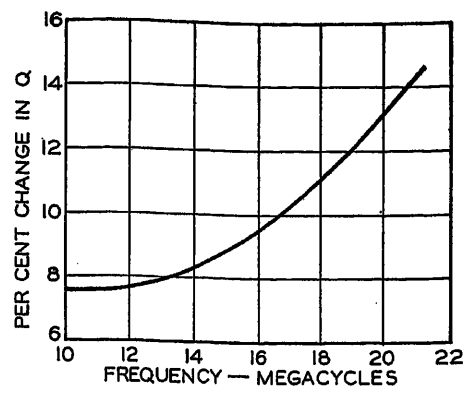



**Figure 15. Per cent loss in Q resulting from groove in bakelite form. No measurable loss resulted from the use of a smooth bakelite form**

For this figure, $L$ = 1.1 microhenrys, $D$ = 2.5 centimeters, $b$ = 1.9 centimeters, wire size, number 14 B. and S. Groove approximately 0.04 centimeter deep

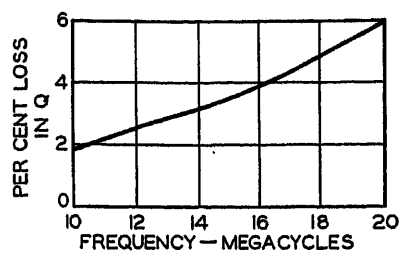



**Figure 16. Per cent loss in Q resulting from enamel wire insulation**

For this figure, $L$ = 1.1 microhenrys, $D$ = 2.5 centimeters, $b$ = 3.4 centimeters, wire size, Number 18 B. and S.

capacitance and the apparent increase in resistance resulting from the distributed capacitance does not represent a physical loss. Note that the reactance variation method of measurement gives the apparent resistance, $R'$, and the correction must be made to obtain the true coil resistance, $R$.

It was found convenient, also, to be able to express the inductance of a coil as a function of the coil dimensions. For this purpose, Rayleigh's equation[16]

$$L = DN^2\left[2\pi \ln \frac{4D}{b} - \frac{1}{2} + \frac{b^2\pi}{4D^2} \ln\left(\frac{4D}{b} + \frac{1}{4}\right)\right] \tag{13}$$

was found suitable. This equation, in common with most inductance formulas, was originally derived assuming the coil to have the form of a cylindrical current sheet, and consequently does not take account of the size of the wire or the frequency. A relatively simple empirical expression was found for the bracketed term, giving[17]

$$L = \frac{DN^2}{102S + 45} \tag{14}$$

This agrees with Rayleigh's equation within 2 per cent for values of $S$ between 0.25 and 1.00. Rayleigh's equation gives values of inductance within better than 3 per cent of their true values.

If the value of $N$ which is obtained from (14) is substituted in (11), the result is

$$R = 2\pi\sqrt{10^{-9}\rho f}\left[\frac{L^{1/2}D^{1/2}(102S + 45)^{1/2}}{d} + \frac{2dL^{3/2}(102S + 45)^{3/2}}{S^2D^{5/2}}\right] \tag{15}$$

To find the optimum wire size for fixed values of $L$, $S$, and $D$, (15) can be differentiated and the result equated to zero; that is, take

$$\frac{\partial R}{\partial d} = 0$$

If this operation is performed, the result obtained, for the optimum wire size to give minimum resistance, is

$$d_0 = b\sqrt{\frac{D}{2L(102S + 45)}} \tag{16}$$

If the value of $L$ from (14) is substituted in this equation, the particularly simple relation

$$d_0 = \frac{b}{\sqrt{2N}} \tag{17}$$

is obtained. Differentiating (11) would yield this result directly. These results can be substituted in (15) for $d$ to give the resistance of a coil, when the wire size is always optimum,

$$R_m = 4\pi\sqrt{2 \times 10^{-9}\rho f}\left[\frac{L(102b + 45D)}{Db}\right] \tag{18}$$

or

$$R_m = 4\pi\sqrt{2 \times 10^{-9}\rho f}\,\frac{N^2}{S} \tag{19}$$

These equations may be applied directly to the prediction of $Q$, as well as of $R$. Substituting the value of $R$ from (11) into

$$Q = \frac{X}{R}$$

gives, for any wire size,

$$Q = \frac{f^{1/2}LdS^2D}{10^{9/2}\rho^{1/2}[S^2D^2N + 2N^3d^2]} \tag{20}$$

The use of (15) yields

$$Q = \frac{f^{1/2}L^{1/2}S^2D^{5/2}}{10^{9/2}\rho^{1/2}[S^2D^3(102S + 45)^{1/2} + 2d^2L(102S + 45)^{3/2}]} \tag{21}$$

In the same way, the value of the figure of merit when the optimum

wire size is employed, $Q_m$, is, from (18),

$$Q_m = \frac{f^{1/2}\ Db}{20^{3/2}\rho^{1/2}(102b + 45D)} \tag{22}$$

or, from (19),

$$Q_m = \frac{f^{1/2}LS}{20^{3/2}\rho^{1/2}N^2} \tag{23}$$

Equation 15 may also be differentiated with respect to $D$, holding $L$, $S$, and $d$ constant, giving, for the optimum diameter

$$D_0 = \sqrt[3]{\frac{10d^2L(102S + 45)}{S^2}} \tag{24}$$

Note that the equations for the optimum wire size, (16) and (17), are not consistent with (24), because a different set of variables is assumed in each case. (24) is useful, practically, only because it affords an opportunity for an added experimental check on the analysis.

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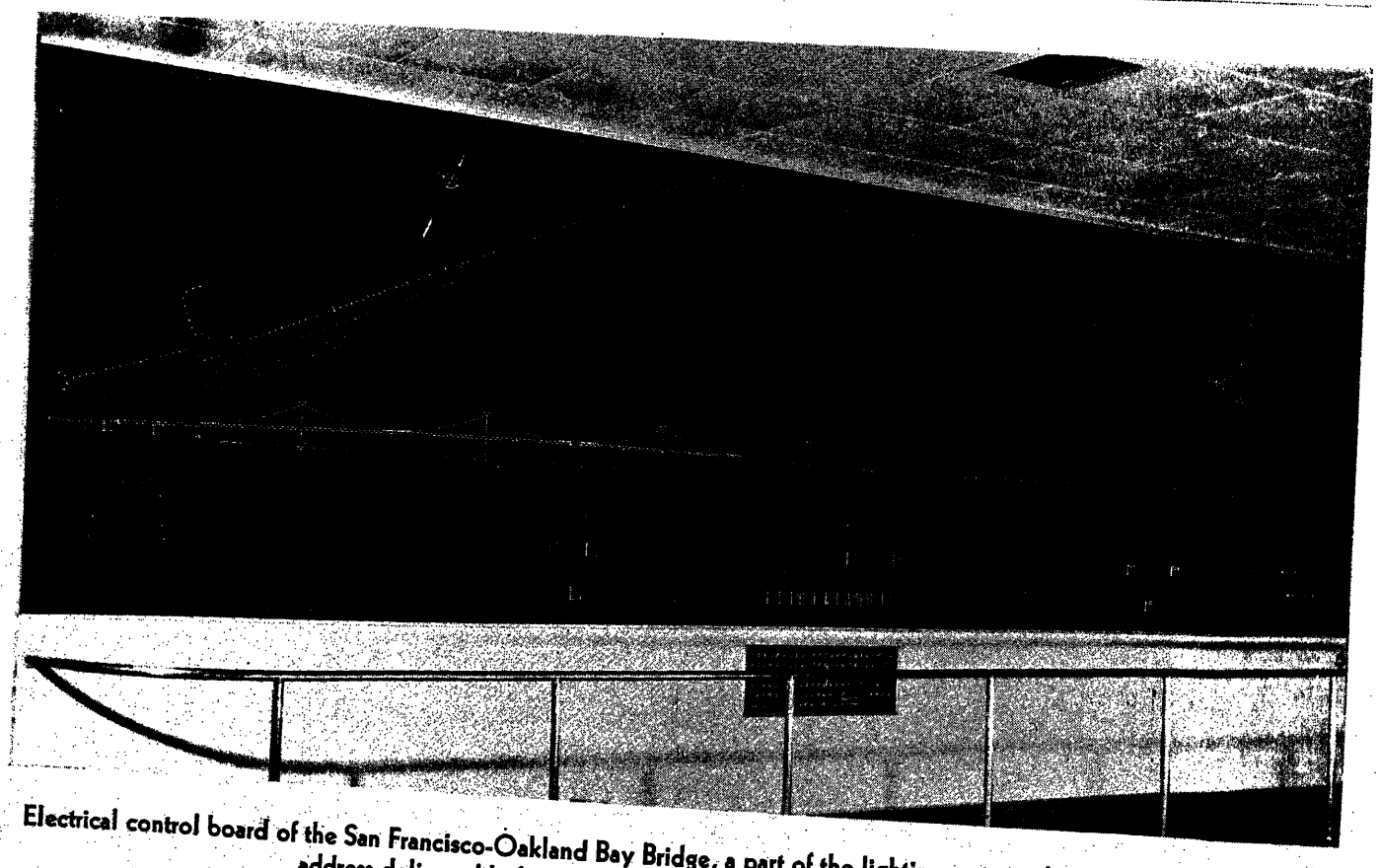
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Electrical control board of the San Francisco-Oakland Bay Bridge, a part of the lighting system which was described in an address delivered before the recent AIEE Pacific Coast convention

# Matrices in Engineering

By LOUIS A. PIPES
ASSOCIATE AIEE

## I. Summary

IT IS THE purpose of this paper to develop in a concise and simple manner the theory of matrix algebra from the foundations, and to emphasize the use of this powerful method in engineering problems.

It appears not to be a well-known fact among engineers that the matrix is not only a convenient notation that summarizes in a natural and convenient form whole groups of operations but that it is actually possible to solve the sets of differential or algebraic equations written in matrix form in a most convenient manner.

The method by which this is done is one of the utmost simplicity but makes use of some fundamental theorems on matrices not usually found in texts. The theory is scattered throughout the mathematical literature. It has, therefore, been considered worth while in the interest of unity and simplicity to build the subject from the foundations. It thus requires no previous knowledge of matrix algebra for the understanding of this paper.

The recent work of Kron, Sah, and others using the notation of tensors and dyadics in studying the behavior of circuits and machinery suggests the power and flexibility of more advanced mathematical methods in expressing the behavior of physical systems.

A perusal of this paper will illustrate that the matrix appears to be a natural tool to employ in the solution of certain classes of problems.

In the matrix notation we can actually solve the differential or algebraic equations involved without first unscrambling the variables and then proceeding in the conventional manner. The only restrictions on the differential equations is that they be linear and homogeneous. However, they may have variable or constant coefficients.

## II. The Fundamentals of Matrix Algebra

### 1. Definition of a Matrix

By a matrix is meant a system of $mn$ quantities arranged in a rectangular array of $m$ rows and $n$ columns. A matrix is usually denoted as:

$$\begin{bmatrix} a_{11} & a_{12} & \dots & a_{1n} \\ a_{21} & a_{22} & \dots & a_{2n} \\ \dots & \dots & \dots & \dots \\ \dots & \dots & \dots & \dots \\ a_{m1} & a_{m2} & \dots & a_{mn} \end{bmatrix} = [a]$$

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1. For all numbered references, see list at end of paper.

The subscript $m$ refers to the row and the subscript $n$ refers to the column.

The quantities $a_{ij}$ are called the elements of the matrix, they may be constants or functions of a variable.

This arrangement appears similar to that of a determinant. However, a matrix is not a determinant. A determinant has a certain definite value. A matrix, on the other hand, as we shall see, represents a set of operations that involve the elements of the matrix.

We note here that $n$ may differ from $m$. If $m = n$, we have a square matrix of order $n$. The square matrix is, as we shall see, the fundamental matrix. A rectangular matrix may be regarded as a square matrix whose missing rows or columns may be filled with elements whose value is zero.

### 2. Equality of Matrices

The question now arises, when may it be said that the matrix $[a] = [b]$? It is usual to define 2 things as equal when they cannot be distinguished from each other. We adopt this procedure in this case and define 2 matrices as equal when they have the same number of rows and of columns and if they have corresponding elements identical.

That is, if $a_{ij} = b_{ij}$ then, by definition $[a] = [b]$.

### 3. The Zero and Unit Matrices

We define a matrix $[a]$ to be a zero matrix denoted by $[0]$ if all of its elements $a_{ij} = 0$. That is, by definition if $a_{ij} = 0$ then $[a] = [0]$.

We define the square matrix $[I]$ all of whose elements are zero except those in the principal diagonal which are all unity as the unit matrix. As an example, for a third order matrix:

$$|I| = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

We shall see that the unit matrix plays the same rôle in matrix algebra that unity plays in ordinary algebra.

### 4. Square Matrix, the Fundamental Matrix

Suppose we have a matrix $[a]$ of $m$ rows and $n$ columns. For preciseness, let us say that $m > n$. If this condition holds, then our matrix $[a]$ is a rectangular matrix. We can, however, consider $[a]$ as a square matrix whose lacking columns are filled with elements of value zero.

As an example consider $m = 3$, $n = 2$, then:

$$[a] = \begin{bmatrix} a_{11} & a_{12} \\ a_{21} & a_{22} \\ a_{31} & a_{32} \end{bmatrix} = \begin{bmatrix} a_{11} & a_{12} & 0 \\ a_{21} & a_{22} & 0 \\ a_{31} & a_{32} & 0 \end{bmatrix}$$

We can, therefore, confine our discussion to square matrices. If $m < n$, the lacking rows would be filled with zeros.

## 5. The Fundamental Operations

### A. Addition and Subtraction

By definition $[a] + [b] = [c]$ provided that $c_{ij} = a_{ij} + b_{ij}$.

That is, the sum of the matrices $[a]$ and $[b]$ is defined as a new matrix $[c]$ whose elements are the sums of the corresponding elements of $[a]$ and $[b]$.

Similarly by definition $[a] - [b] = [c]$ provided that $c_{ij} = a_{ij} - b_{ij}$. Subtraction is merely a special case of addition.

### B. Multiplication

In matrix algebra an ordinary number or function is called a scalar in order to distinguish it from a matrix. If $[a]$ is a matrix and $k$ is some scalar quantity, we define $k[a] = [b]$ if $b_{ij} = ka_{ij}$.

That is, multiplication of a matrix by a scalar yields a new matrix whose elements are $k$ times the elements of the original matrix.

We have now to define the multiplication of one matrix by another. It must be realized that we are at liberty to define multiplication of matrices in any manner we please. However, of all possible methods of defining multiplication we select one because of its usefulness, as we shall see.

We define the multiplication of the two matrices $[a]$ and $[b]$ as being a matrix $[c]$ whose elements $c_{ij}$ are specified in a certain manner.

That is

$$[a][b] = [c]$$

if

$$c_{ij} = \sum_{k=1}^{n} a_{ik}b_{kj}$$

That is, if

$$[a] = \begin{bmatrix} a_{11} & a_{12} \\ a_{21} & a_{22} \end{bmatrix}$$

and

$$[b] = \begin{bmatrix} b_{11} & b_{12} \\ b_{21} & b_{22} \end{bmatrix}$$

then

$$[a][b] = \begin{bmatrix} (a_{11}b_{11} + a_{12}b_{21}) & (a_{11}b_{12} + a_{12}b_{22}) \\ (a_{21}b_{11} + a_{22}b_{21}) & (a_{21}b_{12} + a_{22}b_{22}) \end{bmatrix}$$

The rule is very simple. In words: "The product $[a]$ $[b]$ of 2 square matrices is a matrix $[c]$ in which the element which lies in the $i$th row and $j$th column is obtained by multiplying each element of the $i$th row of $[a]$ by the corresponding element of the $j$th column of $[b]$ and adding the results.

This rule is not as formidable as it looks. It can best be grasped by studying the example above. As a special case multiplication by the unit matrix $[I]$ gives $[a]$ $[I]$ = $[a] = [I]$ $[a]$. From this it is seen that the behavior of the unit matrix in multiplication is as if it were the number one in ordinary algebra.

Multiplication is not commutative in general. That is, $[a]$ $[b] \neq [b]$ $[a]$ in general.

This is obvious because

$$\sum_{n=1}^{n} b_{in}a_{nj} \neq \sum_{n=1}^{n} a_{in}b_{nj}$$

in general.

## The Singular Matrix

A matrix is said to be singular if the determinant of its elements is zero. If the determinant formed from the elements of a matrix does not vanish, the matrix is said to be a nonsingular matrix.

### C. The Inverse of a Matrix

If $[a]$ $[b] = [I]$, then, by definition, $[a]$ is called the inverse of $[b]$, and similarly $[b]$ the inverse of $[a]$. It is usual to denote the inverse of a matrix $[a]$ by $[a]^{-1}$. That is $[a]$ $[a]^{-1} = [I]$ and $[a]^{-1}$ $[a] = [I]$, the unit matrix. By actually multiplying out we arrive at the following rule for determining the elements of the inverse of a matrix $[a]$. The rule is analytically as follows:

Let $[b] = [a]^{-1}$, then the elements $b_{ij}$ of the matrix $[b]$ are given by $b_{ij} = A_{ji}/|A|$ where $|A|$ is the determinant formed from the elements of the matrix $[a]$ and $A_{ij}$ is the cofactor, or the minor with the appropriate sign of the element $a_{ij}$ in the determinant $|A|$. Since in order for $b_{ij}$ to have any values which are finite it is necessary that $|A| \neq 0$, it can be seen that only a nonsingular matrix has an inverse.

### D. Division of Matrices

Division is defined as the inverse of multiplication. However, since multiplication is not commutative, there are 2 kinds of division. That is, if $[c]$ $[b] = [b]$ $[d]$, we cannot infer that in general $[d] = [c]$. From the principles discussed so far, we can prove the following theorem: If $[a]$ is any matrix and $[b]$ is any nonsingular matrix, there exists only one matrix $[x]$ which satisfies $[a] = [b]$ $[x]$. The proof of this is as follows: Let us multiply both sides of the equation $[a] = [b]$ $[x]$ by $[b]^{-1}$ the inverse of $[b]$. Then we have $[b]^{-1}$ $[a] = [b]^{-1}$ $[b]$ $[x] = [I]$ $[x] = [x]$ since multiplication by the unit matrix always gives us back our matrix. We have thus found $[x] = [b]^{-1}$ $[a]$. However, if we had started with the relation $[x]$ $[b] = [a]$ then a similar process would have given $[x] = [a]$ $[b]^{-1}$. Since, in general $[a]$ $[b]^{-1} \neq [b]^{-1}$ $[a]$, we see that from $[c]$ $[b] = [b]$ $[d]$ we cannot infer that $[c] = [d]$. The order of multiplication in matrix algebra cannot be interchanged in general. In the case where it can be interchanged, that is if $[a]$ $[b] = [b]$ $[a]$, the matrices are called symmetric.

### E. The Vanishing of a Product of Matrices

If $[a] \cdot [b] = [0]$ that is, if the product of 2 matrices yields the zero matrix there are 3 possibilities. Either the

matrix $[a] = [0]$ or $[b] = [0]$ or if neither the matrix $[a]$ or $[b]$ is a zero matrix, the rule for multiplication tells us that

$$\sum_{n=1}^{n} a_{in}b_{nj} = 0$$

for all values of $i$ and $j$.

By expanding this set of equations out and making some elementary manipulations it is easily shown that the elements of the various rows of $[a]$ or of $[b]$ are proportional to the elements of the top row. As a special case let us consider $[a]$ and $[b]$ as matrices of the third order then on the supposition that neither is a zero matrix we can say that

$$[a] = \begin{bmatrix} a_{11} & a_{12} & a_{13} \\ \beta a_{11} & \beta a_{12} & \beta a_{13} \\ \omega a_{11} & \omega a_{12} & \omega a_{13} \end{bmatrix}$$

or

$$[b] = \begin{bmatrix} b_{11} & b_{12} & b_{13} \\ mb_{11} & mb_{12} & mb_{13} \\ nb_{11} & nb_{12} & nb_{13} \end{bmatrix}$$

where $\beta$, $\omega$, $m$, and $n$ are constants. That is, the elements of the lower rows are proportional to the elements of the top row.

This result, as we shall see, is of extreme usefulness.

### F. Powers of Matrices

We define powers of matrices in the following manner

Positive integral powers $[a]^p = [a][a] \ldots [a]$ to $p$ factors

Negative integral powers $[a]^{-p} = ([a]^{-1})^p$

$[a]^0 = [I]$ = the unit matrix

## 6. The Laws of Matrix Algebra

We see now with the exception that multiplication is not in general commutative, that is:

$$[a][b] \neq [b][a]$$

That our matrix algebra is similar to ordinary algebra, that is:

$$[a] + [b] = [b] + [a]$$
$$[a] + ([b] + [c]) + [c] = ([a] + [b]) + [c]$$

If $k$ is a scalar and $l$ is a scalar

$$k[a] + k[b] = k([a] + [b])$$
$$k[a] + l[a] = (k + l)[a]$$

If $[c]$ is a matrix and $[d]$ is a matrix

$$[c][a] + [c][b] = [c]([a] + [b])$$
$$[c][a] + [d][a] = ([c] + [d])[a]$$

The only precaution is that $[a]\,[b] \neq [b]\,[a]$ in general

## 7. The Characteristic Matrix of a Matrix

Let $[a]$ be a matrix whose elements are constants.

Then the matrix $[A] = \mu[I] - [a]$, where $\mu$ is a parameter and $[I]$ = the unit matrix, is called the characteristic matrix of $[a]$

## 8. The Characteristic Function of a Matrix [a]

Let $[A]$ be the characteristic matrix of $[a]$, then the determinant of the elements of the matrix $[A]$ $|A|$ is called the characteristic function of $[a]$

## 9. The Latent Roots of a Matrix [a]

Let $|A|$ = the characteristic function of $[a]$

$$\therefore |A| = \alpha(\mu)$$

Then the equation $|A| = 0$ is the characteristic equation of the matrix $[a]$

Now since

$$[A] = \mu[I] - [a]$$

The characteristic equation $|A| = 0$ is in general an equation of the $n$th degree in $\mu$ where $n$ is the degree of the matrix $[a]$.

The $n$ roots $\mu_1, \mu_2, \ldots . \mu_n$ of the characteristic equation are called the latent roots of the matrix $[a]$.

As an example consider

$$[a] = \begin{bmatrix} a_{11} & a_{12} \\ a_{21} & a_{22} \end{bmatrix}$$

The characteristic matrix is $[A] = \mu[I] - [a]$ or

$$[A] = \begin{bmatrix} (\mu - a_{11}) & -a_{12} \\ -a_{21} & (\mu - a_{22}) \end{bmatrix} = \text{characteristic matrix of } [a]$$

$$\begin{vmatrix} (\mu - a_{11}) & -a_{12} \\ -a_{21} & (\mu - a_{22}) \end{vmatrix} = 0$$

is the characteristic equation of $[a]$ or

$$\mu^2 - \mu(a_{11} + a_{22}) + (a_{11}a_{22} - a_{21}a_{12}) = 0$$

The roots of the equation

$$\mu_1 = \alpha_1 + jB$$
$$\mu_2 = \alpha_1 - jB$$

are the latent roots of $[a]$

## 10. The Cayley-Hamilton Theorem

This theorem, as we shall see, provides us with our most potent weapon in the solution of differential equations and circuit problems. The theorem: If $[a]$ is a matrix of constant elements and $\alpha(\mu) = 0$ is the characteristic equation of $[a]$, then $\alpha([a]) = [0]$ where $[0]$ is the zero matrix. In other words a matrix satisfies its own characteristic equation in a matrix sense. Example: As we have just seen if

$$[a] = \begin{bmatrix} a_{11} & a_{12} \\ a_{21} & a_{22} \end{bmatrix}$$

then

$$\alpha(\mu) = \mu^2 - \mu(a_{11} + a_{22}) + (a_{11}a_{22} - a_{21}a_{12}) = 0$$

is the characteristic equation of $[a]$. Then the Cayley-Hamilton theorem states that

$$\alpha([a]) = [a]^2 - [a](a_{11} + a_{22}) + [I](a_{11}a_{22} - a_{21}a_{12}) = 0$$

For a proof of this powerful theorem, see reference 2.

## 11. Functions of Matrices

How are we to define functions of the matrix $[a]$? In analysis, it is customary to define a function of $Z$ such as $\log Z$, $e^z$, sine $Z$, etc., in certain regions of the complex $Z$ plane by their power series expansions. In matrix algebra we shall adopt a similar procedure.

Consider a function of $Z$ $\alpha(Z)$ such as $e^z$, $\log Z$, sine $Z$, etc., which is definable as a power series in $Z$. That is:

$$\alpha(Z) = \sum_{n=0}^{n} C_n Z^n$$

Similarly we define a function of a matrix $[a]$ as

$$\alpha([a]) = \sum_{n=0}^{n} C_n [a]^n$$

with the proviso that $C_0 = C_0[I]$. From the fundamental definition, it is possible by repeated applications of the Cayley-Hamilton theorem to arrive at a simpler form for $\alpha([a])$.

It may be shown, see Duncan and Collar "Solution of Oscillation Problems by Matrices," *Philosophical Magazine*, volume 17, series 7, page 900, that the above definition reduces to the following one:

$$\alpha[a] = \sum_{r=1}^{n} \alpha(\mu_r)[Z_r]$$

where

$$[Z_r] = \frac{\prod_{s \neq r} (\mu_s[I] - [a])}{\prod_{s \neq r} (\mu_s - \mu_r)}$$

where $\mu_1 \ldots \mu_2 \ldots \mu_n$ are the latent roots of the matrix $[a]$.

This theorem is valid only if $[a]$ is a matrix of constant elements.

Professor H. F. Baker has given an alternative form which is sometimes more convenient in practice.[5] Baker's form is:

$$\alpha[a] = \frac{D_{n-1}}{D}[a]^{n-1} + \frac{D_{n-2}}{D} + [a]^{n-2} + \ldots + \frac{D_1}{D}[a] + \frac{D_0}{D}[I]$$

where $\mu_1, \mu_2, \ldots \mu_n$ are the latent roots of $[a]$

$$D = \begin{vmatrix} 1 & 1 & \ldots & 1 \\ \mu_1 & \mu_2 & \ldots & \mu_n \\ \ldots & \ldots & \ldots & \ldots \\ \mu_1^{n-1} & \mu_2^{n-1} & \ldots & \mu_n^{n-1} \end{vmatrix}$$

and $D_{r-1}$ is the determinant derived from $D$ by replacing the elements of the $r$th row by

$$\alpha(\mu_1) \ldots \alpha(\mu_2) \ldots \alpha(\mu_n)$$

Both forms are useful, as we shall see.

*Example:* Let it be required to find

$$e^{[n]} \text{ where } [n] = \begin{bmatrix} 1 & 0 \\ 0 & 2 \end{bmatrix}$$

The characteristic equation of $[n]$ is

$$\alpha(\mu) = \begin{vmatrix} (\mu - 1) & 0 \\ 0 & (\mu - 2) \end{vmatrix} = (\mu - 1)(\mu - 2) = \mu^2 - 3\mu + 2 = 0$$

The latent roots, are therefore, $\mu_1 = 1$, $\mu_2 = 2$

Now

$$D = \begin{vmatrix} 1 & 1 \\ \mu_1 & \mu_2 \end{vmatrix} = \begin{vmatrix} 1 & 1 \\ 1 & 2 \end{vmatrix} = 1$$

$$D_1 = \begin{vmatrix} 1 & 1 \\ e & e^2 \end{vmatrix} = e^2 - e$$

$$D_0 = \begin{vmatrix} e & e^2 \\ 1 & 2 \end{vmatrix} = 2e - e^2$$

$$e^{[n]} = \frac{D_1}{D}[n] + \frac{D_0}{D}[I] = (e^2 - e)\begin{bmatrix} 1 & 0 \\ 0 & 2 \end{bmatrix} +$$

$$(2e - e^2)\begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} = \begin{bmatrix} e & 0 \\ 0 & e^2 \end{bmatrix} \qquad e^{\left[\begin{smallmatrix} 1 & 0 \\ 0 & 2 \end{smallmatrix}\right]} = \begin{bmatrix} e & 0 \\ 0 & e^2 \end{bmatrix}$$

another matrix.

## 12. The Limiting Form of a Matrix When Raised to a Very High Power

A very useful result may be obtained from the above formulas if $\mu([a])$ is placed equal to $[a]^m$.

Let us substitute this in the above, then

$$[a]^m = \sum_{r=1}^{n} \mu_r{}^m [Z_r]$$

where $\mu_1 \ldots . \mu_n$ are the latent roots of $[a]$ arranged in descending order of magnitude. Let us suppose all roots are unequal. Now

$$[Z_r] = \frac{\prod_{s \neq r} (\mu_s[I] - [a])}{\prod_{s \neq r} (\mu_s - \mu_r)}$$

We see from this that $[Z_r]$ is independent of $m$.

Now if $m$ is very large and $\mu_1$ is the largest root, then

$$\lim_{m \to \infty} \sum_{r=1}^{n} \mu_1{}^m [Z_1] = \mu_1{}^m [Z_r]$$

This is true because $\mu_1$, being the largest of the roots, when it is raised to a very high power the term containing $\mu_1{}^m$ is much greater than the other terms and hence the other terms may be neglected in comparison with it. Therefore

$$\lim_{m \to \infty} [a]^m = \frac{\mu_1{}^m (\mu_2[I] - [a])(\mu_3[I] - [a]) \ldots (\mu_n[I] - [a])}{(\mu_2 - \mu_1)(\mu_3 - \mu_1) \ldots (\mu_n - \mu_1)}$$

*Example:* What is

$$\begin{bmatrix} 1 & 0 \\ 0 & 2 \end{bmatrix} ?$$

Here as before $\mu_1 = 2$, $\mu_1 = 1$

$$\begin{bmatrix} 1 & 0 \\ 0 & 2 \end{bmatrix}^{238} = \frac{2^{238}([I] - [a])}{-1}$$

$$= -2^{238}\left(\begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} - \begin{bmatrix} 1 & 0 \\ 0 & 2 \end{bmatrix}\right)$$

$$= -2^{238}\begin{bmatrix} 0 & 0 \\ 0 & -1 \end{bmatrix} \qquad = 2^{238}\begin{bmatrix} 0 & 0 \\ 0 & 1 \end{bmatrix}$$

This theorem is of extreme importance in raising matrices to high powers. It is valid only when the latent

roots are different. If the difference between the latent roots is great, the formula gives accurate answers even for rather small powers of a matrix.

## 13. The Differentiation of a Matrix

Suppose we have a matrix $[u]$ whose elements are functions of the variable $t$; that is, $u_{ij} = u_{ij}(t)$. We define

$$\frac{d}{dt}[u] = \begin{bmatrix} \frac{du_{11}}{dt} & \frac{du_{12}}{dt} & \cdots & \frac{du_{1n}}{dt} \\ \cdots & \cdots & \cdots & \cdots \\ \cdots & \cdots & \cdots & \cdots \\ \frac{du_{n1}}{dt} & \cdots & \cdots & \frac{du_{nn}}{dt} \end{bmatrix}$$

That is, if we let $D = \frac{d}{dt}$, then

$$D[u] = [Du]$$

## 14. Integration of a Matrix

Let $[u]$ be a matrix whose elements are functions of the variable $t$, that is, $\mu_{ij} = \mu_{ij}(t)$

Let

$$Q = \int_{t_0}^{t} (\,)dt$$

stand for the integral operator. We define

$$\int_{t_0}^{t} [u]dt = Q[u] = \begin{bmatrix} Qu_{11} & \cdots & Qu_{1n} \\ \cdots & \cdots & \cdots \\ \cdots & \cdots & \cdots \\ Qu_{n1} & \cdots & Qu_{nn} \end{bmatrix}$$

that is, $Q[u] = [Qu]$ or the integral of a matrix is a matrix whose elements are the integrals of the elements of the original matrix.

If $u_{ij}$ are constants, then

$$Q[u] = (t - t_0)[u]$$

## 15. Linear Transformation

Consider a set of variables $(e_1 \ldots e_n)$ related linearly to a set $(i_1 \ldots i_n)$ by the equations.

$$\begin{aligned} e_1 &= Z_{11}i_1 + Z_{12}i_2 + \ldots + Z_{1n}i_n \\ e_2 &= Z_{21}i_1 + Z_{22}i_2 + \ldots + Z_{2n}i_n \\ &\ldots\ldots\ldots\ldots\ldots\ldots\ldots \\ &\ldots\ldots\ldots\ldots\ldots\ldots\ldots \\ e_n &= Z_{n1}i_1 + Z_{n2}i_2 + \ldots + Z_{nn}i_n \end{aligned}$$

In matrix notation

$$[e] = [Z][i]$$

where

$$[e] = \begin{bmatrix} e_1 \\ \cdots \\ \cdots \\ \cdots \\ e_n \end{bmatrix} \qquad [i] = \begin{bmatrix} i_1 \\ \cdots \\ \cdots \\ \cdots \\ \cdots \\ i_n \end{bmatrix}$$

$$[Z] = \begin{bmatrix} Z_{11} \ldots Z_{1n} \\ \ldots\ldots\ldots \\ \ldots\ldots\ldots \\ Z_{n1} \ldots Z_{nn} \end{bmatrix}$$

That is, by our matrix notation, we may concisely write the above system of equations in the matrix form.

## III. The Most General Linear Network

If in the above linear transformation we allow the variables $(e_1 \ldots e_n)$ to represent the alternating voltages impressed in the various meshes of an $n$-mesh network and $[Z]$ and $[i]$ represent the impedance and current matrices, respectively, of the network, then the equation $[e] = [Z]\,[i]$ represents the matrix equation characterizing the behavior of the most general possible linear network.

If the voltages are alternating of angular frequency $\omega$, then

$$Z_{ij} = J\omega L_{ij} + R_{ij} - \frac{J}{\omega C_{ij}} \qquad J = \sqrt{-1}$$

As we shall see, in case we desire the solution for the transient state we may still use matrices.

In general $Z_{ij} = Z_{ji}$. Let us solve the matrix equation for the current. Let us multiply $[Z]\,[i] = [e]$ by $[Z]^{-1}$ the inverse of $[Z]$

$$[Z]^{-1}[Z][i] = [Z]^{-1}[e]$$
$$[i] = [Z]^{-1}[e]$$

where $[Z]^{-1} = [Y]$ the admittance matrix from II part 5c. The elements of $[Y]$ are given by

$$Y_{ij} = \frac{A_{ji}}{|Z|}$$

$A_{ij}$ is the cofactor of the element $Z_{ij}$ of the matrix $[Z]$.

Having determined the elements of the admittance matrix $[Y]$, we calculate the matrix

$$[i] = [Y][e]$$

The various elements of the current matrix $[i]$ give the various currents in the several branches.

Because $Z_{ij} = Z_{ji}$, therefore $A_{ij} = A_{ji}$, consequently, we have immediately the familiar reciprocity theorem as well as the superposition theorem directly from the equation

$$[i] = [Y][e]$$

## IV. Traveling Waves on Multiconductors

Suppose we have $n$ parallel conductors with electrostatic and electromagnetic coupling between them.

We may write the 2 matrix equations for the currents and voltages

$$-\frac{\partial}{\partial x}[e] = [Z][i] \quad \text{and} \quad -\frac{\partial}{\partial x}[i] = [Y][e]$$

Where the elements of the matrix $[e]$ represent the various voltages between the lines and the elements of the matrix $[i]$ represent the currents in the $n$ lines. The matrix

$$[Z] = \begin{bmatrix} Z_{11} & Z_{12} & \cdots & Z_{1n} \\ Z_{21} & Z_{22} & \cdots & Z_{2n} \\ \cdots & \cdots & \cdots & \cdots \\ Z_{n1} & \cdots & \cdots & Z_{nn} \end{bmatrix}$$

$$Z_{ii} = R_{ii} + L_{ii}\frac{d}{dt} \qquad Z_{ij} = M_{ij}\frac{d}{dt} \qquad i \neq j$$

$R_{ii}$ represents the resistances per unit length of the conductors, $L_{ii}$ the inductances per unit length of the conductors, and $M_{ij}$ represents the mutual inductance per unit length of the various conductors. The matrix

$$[Y] = \begin{bmatrix} Y_{11} & \dots & Y_{1n} \\ \dots & \dots & \dots \\ Y_{n1} & \dots & Y_{nn} \end{bmatrix}$$

$$Y_{ij} = G_{ij} + C_{ij}\frac{d}{dt} \qquad i \neq j$$

$G_{ij}$ = the leakage coefficient per unit length

$C_{ij}$ = mutual capacitance per unit length

$$\frac{-\delta^2[e]}{\delta x^2} = \frac{\delta}{\delta x}[Z][i] = [Z]\frac{\delta}{\delta x}[i]$$

Since $[Z]$ is a constant matrix

$$\frac{-\delta^2}{\delta x^2}[i] = [Y]\frac{\delta}{\delta x}[e]$$

Substituting in the original equation we obtain the fundamental equations for the voltages and currents

$$\frac{\delta^2}{\delta x^2}[e] = [Z][Y][e]$$

$$\frac{\delta^2}{\delta x^2}[i] = [Y][Z][i]$$

As we shall see, we can proceed to the solution of the actual differential equations in matrix form.[9]

## V. The 4-Terminal Network

From the general theory discussed in part III, it can be easily shown that for the case of a linear, passive, bilateral 4-terminal network shown diagrammatically as in figure 1.

$$E_1 = E_2A + BI_2$$
$$I_1 = E_2C + DI_2$$

where $AD - BC = 1$ or in the matrix form

$$\begin{bmatrix} E_1 \\ I_1 \end{bmatrix} = \begin{bmatrix} A & B \\ C & D \end{bmatrix} \cdot \begin{bmatrix} E_2 \\ I_2 \end{bmatrix}$$

Assume that 2 such circuits are connected in series as in figure 2.

If the 2 networks are identical, we have,

$$\begin{bmatrix} E_2 \\ I_2 \end{bmatrix} = \begin{bmatrix} A & B \\ C & D \end{bmatrix} \cdot \begin{bmatrix} E_3 \\ I_3 \end{bmatrix}$$

$$\begin{bmatrix} E_1 \\ I_1 \end{bmatrix} = \begin{bmatrix} A & B \\ C & D \end{bmatrix} \cdot \begin{bmatrix} A & B \\ C & D \end{bmatrix} \cdot \begin{bmatrix} E_3 \\ I_3 \end{bmatrix} = \begin{bmatrix} A & B \\ C & D \end{bmatrix}^2 \begin{bmatrix} E_3 \\ I_3 \end{bmatrix}$$

If there are $n$ such circuits in series,

$$\begin{bmatrix} E_1 \\ I_1 \end{bmatrix} = \begin{bmatrix} A & B \\ C & D \end{bmatrix}^n \begin{bmatrix} E_{n+1} \\ I_{n+1} \end{bmatrix}$$

If we wish to get the $(n + 1)$ currents and voltages in terms of the initial values, we have

$$E_2 = DE_1 - BI_1$$
$$I_2 = -CE_1 + AI_1$$

or

$$\begin{bmatrix} E_2 \\ I_2 \end{bmatrix} = \begin{bmatrix} D & -B \\ -C & A \end{bmatrix} \cdot \begin{bmatrix} E_1 \\ I_1 \end{bmatrix}$$

If we have $n$ identical networks in series then

$$\begin{bmatrix} E_{n+1} \\ I_{n+1} \end{bmatrix} = \begin{bmatrix} D & -B \\ -C & A \end{bmatrix}^n \cdot \begin{bmatrix} E_1 \\ I_1 \end{bmatrix}$$

If $n$ is very large, we may use the formula for raising a matrix to a very high power.

Because of the natural way in which matrix algebra enters into linear transformations, their application to circuit theory are seen to be unlimited.

## VI. The Solution of Differential Equations

The brief examples which are given above and obvious other applications are rather well known to some communication engineers. However, the powerful use which may be made of matrices in the actual *solution* of linear differential equations is not well known.

### 1. The Differential Equation in Matrix Form

In modern electrical and mechanical engineering there are a great class of problems in circuits, vibrations, etc., which lead either to linear equations of high order or to systems of linear equations. These equations may have either variable or constant coefficients.

Any differential equation or a set of differential equations can be changed into another involving only first order differential coefficients by writing the highest order coefficient as the differential coefficient of a new dependent variable.

All the other differential coefficients are regarded as separate dependent variables, and, for each new variable introduced, another equation must be added to the set.

These added equations are merely the mathematical statement that each new variable is the differential coefficient of the variable that represents the next differential coefficient of lower order. In this way the most general homogeneous linear equation or set of linear homogeneous equations with either constant or variable coefficients may be written as:

$$\frac{dx_1}{dt} = u_{11}x_1 + u_{12}x_2 + \dots + u_{1n}x_n$$
$$\frac{dx_2}{dt} = u_{21}x_1 \dots\dots\dots\dots + u_{2n}x_n$$
$$\dots\dots\dots\dots\dots\dots\dots\dots$$
$$\frac{dx_n}{dt} = u_{n1}x_1 \dots\dots\dots\dots + u_{nn}x_1$$

In matrix form: if $D = \frac{d}{dt}$

$$[Dx] = [u][x]$$

or

$$\frac{d}{dt}[x] = [u][x]$$

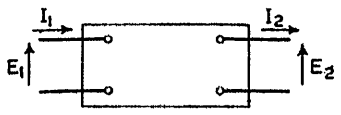



Figure 1

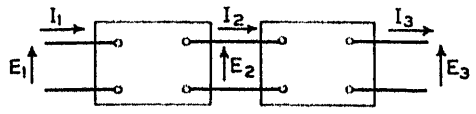



Figure 2

As a preliminary to the integration of this matrix differential equation let us consider the integration of the ordinary differential equation

$$\frac{dy}{dt} = \mu y \qquad \mu = \mu(t)$$

subject to $y = y_0$ at $t = t_0$ the boundary condition.

If we integrate, we obtain, on introducing the boundary conditions.

$$y = y_0 + \int_{t_0}^{t} \mu(t)\, y dt$$

This is an integral equation. We will solve it by successive approximations. Let $Q$ be the operator defined by

$$Q = \int_{t_0}^{t} (\,)\, dt$$

Then

$$y = y_0 + Q\mu y$$

Substitute $y$ in the second member and we obtain

$$y = y_0 + Q\mu[y_0 + Q\mu y] = y_0 + y_0 Q\mu + Q\mu Q\mu y$$

Repeating the process,

$$y = y_0(1 + Q\mu + Q\mu Q\mu + Q\mu Q\mu Q\mu + \ldots)$$

This series is very rapidly convergent.

### The Matrix Equation

We return now to our matrix equation

$$\frac{d}{dt}[x] = [u][x]$$

Let us require as a boundary condition that $[x] = [x^0]$ at $t = t_0$

Then carrying out the above process on the matrix equation, we obtain the matrix integral equation

$$[x(t)] = [x^0] + \int_{t_0}^{t} [u(t)][x(t)]dt$$

This may be solved by successive approximations.

$$[x(t)] = ([I] + Q[u] + Q[u]Q[u] + \ldots + \ldots)[x_0]$$

$[I]$ = unit matrix

$Q = \int_{t_0}^{t} (\,)dt$ operator

## 2. The Matrizant

We denote

$$\Omega^{t_0,t}[u] = ([I] + \int_{t_0}^{t} [u]dt + \int_{t_0}^{t} [u]dt \int_{t_0}^{t} [u]dt + \ldots)$$

and the solution of the equation is

$$[x(t)] = \Omega^{t_0,t}[u][x^0]$$

by the name of the "matrizant" of $[u]$.[3 4]

### Fundamental Properties of the Matrizant $\Omega^{t_0,t}[u]$

1. $\Omega^{t_0,t_0}[u] = [I]$
2. $\frac{d}{dt}\Omega^{t_0,t}[u] = [u]\Omega^{t_0,t}[u]$
3. If $[u]$ is a matrix of constant elements, then

$\Omega^{t_0,t}[u] = [I]e^{[u](t-t_0)}$

or, if we let $T = t - t_0$

$[I]$ = unit matrix

then,

$\Omega^{t_0-t}[u] = [I]e^{[u]T}$

$e$ = base of natural logarithms

These fundamental properties may all easily be deduced from the above definition of

$$\Omega^{t_0-t}[u] = ([I] + \int_{t_0}^{t} [u]dt + \int_{t_0}^{t} [u]dt \int_{t_0}^{t} [u]dt + +)$$

For a further set of properties, the above paper by Doctor Baker may be consulted.

## 3. Linear Equations With Constant Coefficients

As an example, let us consider the system:

$$dx_1/dt = u_{11}x_1 + u_{12}x_2$$
$$dx_2/dt = u_{21}x_1 + u_{22}x_2$$

where $u_{ij}$ are constants

Or in the short matrix form:

$$D[x] = [u][x]$$

Let the solution be subject to the boundary conditions that:

$x_1 = x_1^0$ and $x_2 = x_2^0$ at $t = t_0$

(Note: The superscripts here must not be confused with exponents, they are merely a convenient notation used to denote the initial values of $x_1$ and $x_2$ and, since the place for subscripts is already taken it is convenient to use superscripts.) By the foregoing theory, the solution under these initial conditions is:

$$[x] = \Omega^{t_0,t}[u][x^0]$$

In this case, since $[u]$ is a matrix of constants,

$$\Omega^{t_0,t}[u] = [I]e^{[u]T}$$

where $T = t - t_0$.

We must now compute the matrix function $e^{[u]T}$ by the rule given in part II, section 11. Following the procedure given there, we first compute the latent roots of $[u]$. The characteristic equation is:

$$|\mu I - u| = 0 \quad \text{or} \quad \begin{vmatrix} (\mu - u_{11}) & -u_{12} \\ (-u_{21}) & (\mu - u_{22}) \end{vmatrix} = 0$$

Or, expanding the determinant,

$$\mu^2 - \mu(u_{11} + u_{22}) + (u_{11}u_{22} - u_{12}u_{21}) = 0$$

Let us call the 2 roots of this equation $\mu_1$ and $\mu_2$. In general, the 2 roots will be complex numbers.
We can, therefore, in general denote the 2 roots as:

$$\mu_1 = \alpha + \beta \quad \text{and} \quad \mu_2 = \alpha - \beta$$

Computing $e^{[u]t}$ by Baker's rule (part II, section 11) we first must compute:

$$D = \begin{vmatrix} 1 & 1 \\ (\alpha+\beta) & (\alpha-\beta) \end{vmatrix} = (\alpha-\beta) - (\alpha+\beta) = -2\beta$$

$$D_1 = \begin{vmatrix} 1 & 1 \\ e^{\alpha T+\beta T} & e^{\alpha T-\beta T} \end{vmatrix} = -2e^{\alpha T}\sinh \beta T$$

$$D_0 = \begin{vmatrix} e^{\alpha t+\beta T} & e^{\alpha T-\beta T} \\ \alpha+\beta & \alpha-\beta \end{vmatrix} = 2e^{\alpha T}(\alpha \sinh \beta T - \beta \cosh \beta T)$$

We note that, by definition $[u]^0 = [I]$. We have, therefore, by Baker's rule:

$$e^{[u]T} = e^{\alpha T}\sinh \beta T \begin{bmatrix} u_{11} & u_{12} \\ u_{21} & u_{22} \end{bmatrix} - e^{\alpha T}/\beta\,(\alpha \sinh \beta T - \beta \cosh \beta T)[I]$$

Or, therefore, the matrizant, in this case is:

$$\Omega^{t_0,t}[u] = e^{\alpha T}\begin{bmatrix} (u_{11}-\alpha)/\beta \sinh \beta T + \cosh \beta T) & (u_{12}/\beta \sinh \beta T) \\ (u_{21}/\beta \sinh \beta T)\left(\dfrac{u_{22}-\alpha}{\beta}\right) & \sinh \beta T + \cosh \beta T) \end{bmatrix}$$

Therefore, the equation has the solution:

$$[x] = \Omega^{t_0,t}[u][x^0]$$

If we write

$$\Omega^{t_0,t}[u] = \begin{bmatrix} \Omega_{11} & \Omega_{12} \\ \Omega_{21} & \Omega_{22} \end{bmatrix}$$

$$\Omega^{t_0,t}[u] = e^{\alpha T}\begin{bmatrix} \left(\dfrac{u_{11}-\alpha}{\beta}\sinh \beta T + \cosh \beta T\right)\left(\dfrac{u_{12}}{\beta}\sinh \beta T\right) \\ \left(\dfrac{u_{21}}{\beta}\sinh \beta T\right)\left(\dfrac{u_{22}-\alpha}{\beta}\sinh \beta T + \cosh \beta T\right) \end{bmatrix}$$

where

$$\Omega_{11} = \left\{\frac{(u_{11}-\alpha)}{\beta}\sinh \beta T + \cosh \beta T\right\}e^{\alpha T}$$

$$\Omega_{12} = (u_{12}/\beta e)^{\alpha T}\sinh \beta T$$

$$\Omega_{21} = (u_{21}/\beta e)^{\alpha T}\sinh \beta T$$

$$\Omega_{22} = [(u_{22}-\alpha)/\beta \sinh] \beta T + \cosh \beta T)e^{\alpha T}$$

$$T = t - t_0$$

If $\beta$ is imaginary, sinh $\beta T$ and cosh $\beta T$ must be replaced by sine $\beta T$ and cos $\beta T$, respectively. If $\beta = 0$, we must obtain the limiting forms from these equations by the usual L'Hospital's rule of differentiation. We have now, the dependent variables in terms of the initial conditions.

## 4. Linear Equations With Variable Coefficients

The method of matrices is particularly well adapted to the solution of equations whose coefficients are functions of the independent variable $t$. The only restrictions on the variables is that they be finite and single valued functions of $t$ throughout the range of integration. This limitation is met by physical equations.

Let us consider the most general homogeneous linear differential equation with variable coefficients. This equation may be written:

$$Dx^n + a_1(t)Dx^{n-1} + \ldots + a_{n-1}(t)x = 0$$

where $D$ is the operator $d/dt$ and the coefficients $a_i(t)$ are single-valued analytic functions of $t$. That is, they do not become infinite in any part of the range for which we desire a solution.

As in the previous case with constant coefficients, we first break up the equation into a set of $n$ homogeneous equations of the first order. This is done by calling successive derivatives new variables. That is, we let $x = x_1$, $Dx = x_2$ and so forth. Our equation is then replaced by:

$$dx_1/dt = u_{11}x_1 + u_{12}x_2 + \ldots\ldots + u_{1n}x_n$$
$$\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots$$
$$\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots$$
$$dx_n/dt = u_{n1}x_1 + \ldots\ldots\ldots\ldots + u_{nn}x_n$$

where now the coefficients of $u_{ij}$ are functions of $t$.
In matrix form, we write this set of equations as before: $D[x] = [u][x]$. If we know the initial value of $x$ and the initial value of $(n-1)$th derivatives we denote them by $x_1^0$, $x_2^0$, etc., these initial values at $t = t_0$. Our solution is as before:

$$[x] = \Omega^{t_0-t}[u][x^0]$$

Where, unfortunately $\Omega^{t_0-t}[u]$ does not have the simple form it had when the elements of the matrix $[u]$ were constants instead of functions of $t$. In this case

$$\Omega^{t_0-t}[u] = ([I] + \int_{t_0}^{t}[u]dt + \int_{t_0}^{t}[u]dt\int_{t_0}^{t}[u]dt + + )$$

from the fundamental defining equation. It is most laborious to use this form to compute the matrizant. However we note that if $[u]$ is a matrix of constants, then

$$\Omega^{t_0-t}[u] = [I]e^{[u]T}$$

where $e$ is the base of the natural logarithms. This suggests that the following procedure be followed. Let the interval of time over which the equation is to be solved be broken up into $s$ small time intervals. The procedure may be more easily followed by the consideration of the following diagram:

| 1 | 2 | | 3 | 4 | | | | $s$ | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| $t_0$ | $t_1$ | $t_2$ | | | | | $t_{s-1}$ | $t_s$ | | | | | |

Let us assume that during the time interval from $t_0$ to $t_1$ the elements of the matrix $[u]$ are approximately constant and have the average value that they assume throughout the interval. Let us denote this matrix by $[u(1)]$. Let in general $[u(s)]$ represent the matrix whose elements are given the average values which they assume in the $s$th interval from $t = t_{s-1}$ to $t = t_s$. We may then proceed to the solution of our actual equation with variable coefficients by a sort of chain process. That is, assuming that throughout the first interval the elements of the matrix $[u]$ are constant and denoting the matrix of these constant values by $[u(1)]$, we may say that at the end of the first interval the solution is:

$$[x(t_1)] = [I]e^{[u]T}[x^0]$$

where

$$T = t_1 - t_0$$

This is the value that the variables have assumed at the end of the first interval, and hence these values provide the initial conditions for the second interval. That is, the initial conditions for the second interval are $[x(t_1)]$ instead of $[x^0]$. If the intervals are all equal let us call them $T$; that is

$$t_s - t_{s-1} = T$$

then

$$[x(t_1)] = [I]e^{[u(1)]T}[x^0]$$

and, at the end of the second interval, the solution is:

$$[x(t_2)] = [I]e^{[u(2)]T}[x(t_1)]$$

Since, however, we know $[x(t_1)]$, we can compute $[x(t_2)]$ by a matrix multiplication. The solution for the $s$th interval can be obtained similarly by a repeated chain of multiplication of the various values of the preceding intervals. The procedure appears laborious, but it is in reality quite simple. It may be noted that the intervals do not have to be of the same length $T$. It is usually more convenient to choose short intervals where the variations of the elements of the matrix $[u]$ is great and to choose larger intervals where the elements of $[u]$ are more or less constant.

## Illustration

This method may perhaps be brought out more clearly by means of an illustration. The example worked out by Frazer[6] will be given. It is particularly good as an illustration since it tests the method to the utmost in that the variables fluctuate widely and the values obtained may be compared with the exact solution.

Let us consider the motion of a pendulum of variable stiffness whose equation of motion may be taken as:

$$D^{2\alpha} + (16\pi^2 e^{-2t} - 1/4)\,\alpha = 0$$

It is easy to solve this equation in exact terms.

The exact solution is:

$$\theta = e^{t/2}\cos(4\pi e^{-t})$$

for the boundary conditions that $\alpha = 1.0$ and $d\alpha/dt = 0.5$ at $t = 0$. To solve this equation in the matrix form we place $\alpha = x_1$ and $d\alpha/dt = x_2$. Then the matrix equation is:

$$D[x] \begin{Vmatrix} 0 & 1 \\ u_{21} & 0 \end{Vmatrix} [x] = [u][x]$$

where

$$u_{21} = 1/4 - 16\pi^2 e^{-2t}$$

Let $u_{21}(s)$ be the average value of $^1/_4 - 16\pi^2 e^{-2t}$ for the $s$th interval from $t = t_{s-1}$ to $t = t_s$. Then, for that interval:

$$D[x] = \begin{bmatrix} 0 & 1 \\ u_{21}(s) & 0 \end{bmatrix} \cdot [x]$$

The characteristic equation is:

$$\begin{vmatrix} \mu & -1 \\ -u_{21}(s) & \mu \end{vmatrix} = 0$$

and the latent roots are:

$$\alpha_s = 0 \qquad \beta_s = \sqrt{u_{21}(S)}$$

The matrizant relation is as in VI part 3.

$$[x] = \begin{bmatrix} \cosh(\beta_s T) & \sinh(\beta_s T) \\ \dfrac{u_{21}(s)\sinh(\beta_s T)}{\beta_s} & \cosh(\beta_s T) \end{bmatrix} [x^{s-1}]$$

if $\beta_s$ is real. If, however, $\beta_s$ is imaginary, then circular functions must replace the above hyperbolic functions. The numerical values of the elements of $\Omega^{t_s - 1^{t_s}}$ are given in the table I.

The matrizant $\Omega^{t_{s-1},t_s}[u]$ is formed for each interval from the values given in the above table. From the value of the matrizant for the first interval and the initial conditions, the values of the dependent variables at the end of that interval and hence the initial conditions for the next interval can be found.

For example, the product $\Omega^{t_0,t_1}[x^0]$ may be carried out in table form. That is, the square matrix $\Omega t_0, t_1$ is multiplied by the line matrix $[x^0]$. This gives a line matrix

**Table I**

| Start of Interval t= | $u_{21}(s)$ | $\beta$ | $\cos \beta T$ $\cosh \beta T$ | $\sin \beta T$ $\sinh \beta T$ | $\sin \beta T/\beta$ $\sinh \beta T/\beta$ | $u_{21}(s)\sin \beta T/\beta$ $u_{21}(s)\sinh \beta T/\beta$ |
|---|---|---|---|---|---|---|
| $t = 0$ | $-129.9$ | $11.39j$ | $-0.6504$ | $0.7590$ | $0.0666$ | $-8.650$ |
| $t = 0.2$ | $-86.99$ | $9.327j$ | $-0.2900$ | $0.9570$ | $0.1026$ | $-8.926$ |
| $t = 0.4$ | $-58.23$ | $7.631j$ | $+0.0448$ | $0.9990$ | $0.1309$ | $-7.623$ |
| $t = 0.6$ | $-38.95$ | $6.241j$ | $0.3172$ | $0.9483$ | $0.1519$ | $-5.918$ |
| $t = 0.8$ | $-26.02$ | $5.101j$ | $0.5233$ | $0.8521$ | $0.1670$ | $-4.346$ |
| $t = 1.0$ | $-13.51$ | $3.675j$ | $-0.2636$ | $0.9650$ | $0.2626$ | $-3.546$ |
| $t = 1.5$ | $-4.469$ | $2.114j$ | $+0.4915$ | $0.8709$ | $0.4120$ | $-1.841$ |
| $t = 2.0$ | $-1.000$ | $1.000j$ | $0.5403$ | $0.8415$ | $0.8415$ | $-0.8415$ |
| $t = 3.0$ | $+0.0808$ | $0.284$ | $1.0405$ | $0.2880$ | $1.015$ | $+0.0819$ |

**Table II**

| Initial Value of t | The Matrizant $\Omega^{t_s - 1^{t_s}}$ | | Initial Conditions $\alpha$ and $D\alpha$ Stepped Solution | Exact Solution |
|---|---|---|---|---|
| 0 | $-0.6504$ | $0.0666$ | $1.0000$ | $1.0000$ |
| | $-8.650$ | $-0.6504$ | $0.5000$ | $0.5000$ |
| 0.2 | $-0.2900$ | $0.1026$ | $-0.6171$ | $-0.725$ |
| | $-8.926$ | $-0.2900$ | $-8.975$ | $-9.243$ |
| 0.4 | $0.0448$ | $0.1309$ | $-0.7419$ | $-0.657$ |
| | $-7.623$ | $0.0448$ | $+8.111$ | $+9.008$ |
| 0.6 | $0.3172$ | $0.1519$ | $1.0285$ | $1.11$ |
| | $-5.918$ | $-0.3172$ | $6.019$ | $5.855$ |
| 0.8 | $0.5233$ | $0.1670$ | $1.2405$ | $1.20$ |
| | $-4.346$ | $0.5233$ | $-4.1775$ | $-4.43$ |
| 1.0 | $-0.2636$ | $0.2626$ | $-0.0487$ | $-0.172$ |
| | $-3.546$ | $-0.2636$ | $-7.577$ | $-7.646$ |
| 1.5 | $-0.4915$ | $0.4120$ | $-1.977$ | $-1.99$ |
| | $-1.841$ | $0.4915$ | $+2.170$ | $+3.005$ |
| 2.0 | $0.5403$ | $0.8415$ | $-0.0776$ | $-0.35$ |
| | $-0.8415$ | $0.5403$ | $+4.706$ | $+4.745$ |
| 3.0 | $1.0405$ | $1.015$ | $3.918$ | $3.64$ |
| | $0.0819$ | $1.0405$ | $2.608$ | $3.46$ |
| 4.0 | | | $6.724$ | $7.19$ |
| | | | $3.035$ | $3.984$ |

which provides the initial conditions for the next interval. The same procedure is carried out for the next interval and repeated to the end of the range in $t$.

The process may be written symbolically as follows:

$$[x(t_n)] = \Omega^{t_{n-1},\, t_n}\Omega^{t_{n-2},t_{n-1}} \ldots \Omega^{t_0,t_1}[x^0]$$

or more briefly:

$$[x(t_n)] = \Omega^{t_{r-1},t_r}[x^0]$$

This is shown in table II.

It may be remarked that the approximate stepped solution differs quite considerably from the exact solution. However, in the example the variable stiffness fluctuates tremendously during the first interval.

The time intervals at the beginning of the solution should have been chosen shorter. Where the coefficients of the matrix $[u]$ vary considerably shorter time intervals must be taken.

The method here presented is only an approximate one and will give good results only in case the number of intervals during which the variable coefficients are to be considered constant is taken to be great. In the case of second order systems this method provides a rather quick method of arriving at the trend of the solution. In the example given here it is of course needless to calculate the process to 4 significant figures as has been done. It must be realized that the coefficient $(16\pi^2 e^{-2t} - 1/4)$ changes tremendously in the neighborhood of $t = 0$, and more accurate results would have been obtained had the number of intervals at the start of the solution been chosen in a different manner.

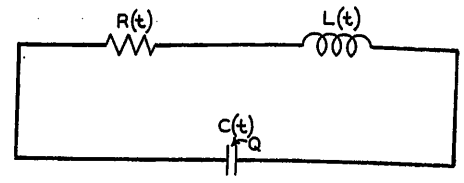
The method here presented is of particular value in second order differential equations whose coefficients do not vary greatly. It is true that when $t$ becomes large, errors will accumulate. Since, however, in most problems the variation of the dependent variable for small values of the independent variable $t$, is sought this method gives rather quickly the required information.

## VII. Variable Networks

The above-mentioned method enables one to obtain the solution for the free oscillations of a network whose parameters vary with the time. The solution may be made as accurate as desired by the correct choice of the time intervals $t_s - t_{s-1}$.

It is now proposed to discuss the transient solution of networks whose parameters vary with the time in a periodic manner. An example of this type of network is the alternator with the mutual inductance varying as a sine function of $t$. Another example is the telephone transmitter with internal resistance that varies periodically with the time. The condenser microphone is another example of this class of circuit. There are a host of important technical problems of this class. In the field of mechanical engineering the situation is the same. The torsional vibrations of the side-rods of electric locomotives and even the noisy vibrations of small synchronous clock motors may be brought under the heading of systems with periodically varying parameters. For other mechanical problems of this class the reader is referred to "Mechanical Vibrations," a book by Den Hartog. A most extensive bibliography of this class of problems is given by Van der Pol and Strutt.[8]

**Figure 3**




### 1. Free Oscillations of a Variable Network

The method will be illustrated by the use of a special case which is of great importance in electrical and mechanical engineering.

For definiteness, let us consider the most general possible series circuit containing a variable resistance, inductance, and capacitance. The circuit is shown in figure 3.

Suppose that at $t = t_0$ a charge is placed on the condenser and we inquire the subsequent behavior of the system. We specify that all the variable elements are periodic in time with the same frequency. That is,

$$R(t + T) = R(t)$$
$$C(T + t) = C(t)$$

and

$$L(t + T) = L(t)$$

where $T$ is the period of the variation. Let

$$R(t) = R_0 + r(t)$$
$$L(t) = L_0 + l(t)$$
$$R/C(t) = S(t) = S_0 + s(t)$$

where $S(t)$, the reciprocal of the capacitance is the elastance. $R_0$, $L_0$, and $S_0$ are the fixed constant resistance, inductance, and elastance of the circuit about which the circuit varies. $r(t)$, $l(t)$, and $s(t)$, are the variable elements of resistance, inductance, and elastance of the circuit. Let us suppose that the variations in the various elements is always smaller than the fixed portion of the various elements. That is,

$$|s| < R_0 \qquad |l| < L_0 \qquad \text{and} \qquad |s| < S_0$$

that is, the absolute values of the variable elements are always less than the fixed components. This is usually the case in actual physical systems.

The fundamental equation of the circuit is:

$$\frac{d^2Q}{dt^2} + \frac{dQ}{dt}\left(R + \frac{dL}{dt}\right)\frac{1}{L} + \frac{S(t)}{L(t)}\,Q = 0$$

where

$$D = d/dt$$

and $Q$ is the charge on the condenser in coulombs. Let

$$A(t) = \left(R + \frac{dL}{dt}\right)\frac{1}{L_0 + l(t)} \quad \text{and} \quad B(t) = \frac{S_0 + s(t)}{L_0 + l(t)}$$

In the above equation let us substitute

$$Q = e^{-1/2\int A(t)dt}y(t) \text{ for } Q$$

On making this substitution for $Q$ in the above differential equation we find that $y(t)$ must satisfy the uation $D^2y + (B - {}^1/_2DA - {}^1/_4A^2)y = 0$, if we call $- {}^1/_2DA - {}^1/_4A^2) = b^2 + \alpha(t)$; that is, we separate is expression into 2 parts, one a constant term and the ier a variable term. Our problem now reduces to the ution of $D^2y + [b^2 + \alpha(t)]y = 0$

It may be here noted that because of the periodicity of the rameters we must have: $\alpha(t + T) = \alpha(t)$

The above equation in $y$ is the equation of Hill. It has ceived extensive treatment particularly in astronomical nnections. All the methods published deal with the ution of the equation in series or contour integrals. ese solutions are most unsatisfactory from the practical int of view. A theorem will now be established which ll show the ease with which this equation may be solved nerically by the matrix method.

## The Stability of Hill's Equation

The following analysis is a general discussion on the de-rmination of the stability of the physical system whose havior is described by Hill's equation.

Consider Hill's equation:

$$y + [b^2 + \alpha(t)]y = 0$$

Now let $g_1(t)$ and $g_2(t)$ be 2 linearly independent solutions the differential equation. The general solution will en be a linear combination of $g_1$ and $g_2$ and may be ritten as:

$$= c_1g_1 + c_2g_2$$

here $c_1$ and $c_2$ are constants.

Let us write $y = x_1$ and $dy/dt = x_2$. We may then rite the matrix:

$$\begin{bmatrix} x_1 \\ x_2 \end{bmatrix} = \begin{bmatrix} g_1 & g_2 \\ Dg_1 & Dg_2 \end{bmatrix} \cdot \begin{bmatrix} c_1 \\ c_2 \end{bmatrix}$$

here $D = d/dt$ at $t = t_0$. Let

$$] = \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} = [x^0]$$

we now let

$$(t)] = \begin{bmatrix} g_1(t) & g_2(t) \\ Dg_1(t) & Dg_2(t) \end{bmatrix}$$

nd

$$] = \begin{bmatrix} c_1 \\ c_2 \end{bmatrix}$$

e may write the matrix relation $[x] = [A(t)]\,[c]$. Now determine the arbitrary constants we have,

$$^0] = [A(t_0)][c]$$

nd hence

$$] = [A(t_0)]^{-1}[x^0]$$

nd hence the solution becomes:

$$] = [A(t)][A(t_0)]^{-1}[x^0]$$

ow because of the periodicity of the variable coefficient $(t)$, that is, $\alpha(t + T) = \alpha(t)$, we may assume $[x(t_0 + T)] = k[x^0]$, where $k$ is some constant to be determined. But $[x(t_0 + T)] = [A(t_0 + T)]\,[A(t_0)]^{-1}[x^0]$, and hence substituting into the above equation we obtain:

$$k[x^0] = [A(t_0 + T)][A(t_0)]^{-1}[x^0]$$

If we let $[M] = [A(t_0 + T)]\,[A(t_0)]^{-1}$, then we have:

$$k[x^0] = [M][x^0]$$

or

$$[kI - M] = [0]$$

and the constant $k$ depends upon the 2 characteristic roots of the matrix $[M]$. That is if,

$$[M] = \begin{bmatrix} M_{11} & M_{12} \\ M_{21} & M_{22} \end{bmatrix}$$

then $k$ is given by the 2 roots of the equation

$$k^2 - k(M_{11} + M_{22}) + (M_{11}M_{22} - M_{12}M_{21}) = 0$$

Now if $|k_1| < 0$ and $|k_2| < 0$ the motion is stable while if $|k_1| > 0$ or $|k_2| > 0$, the motion is unstable.

By subdividing the interval from $t_0$ to $t_0 + T$ into small intervals throughout which the variable $v(t)$ may be assumed to have its mean value it is possible to arrive at a numerical value for the matrix $[M]$ and hence to compute the stability of the system. This method has recently been employed by the author to a simple system. The results are to appear in the *Journal* of the Franklin Institute shortly.

## 3. The Matrix Solution of Hill's Equation

It would be easy to give a numerical example. However, it is best to consider the general case.

We are to solve $D^2y + [b^2 + \alpha(t)]y = 0$ with the initial conditions of $y$ and $dy/dt$ known. Let $y = x_1$ and $dy/dt = x_2$. Our equation reduces to the system.

$$Dx_1 = x_2$$
$$Dx_2 = -[b^2 + \alpha(t)]x_1$$

Let $F(t) = -[b^2 + \alpha(t)]$

The equation in matrix form becomes,

$$D[x] = \begin{bmatrix} 0 & 1 \\ u_{21} & 0 \end{bmatrix} \cdot [x] \qquad u_{21} = F(t)$$

The solution is carried out as in the example of section VI, part 4. The time $T$ for one cycle of variation of $\alpha(t)$ is divided into several intervals of length $\Delta t$ and the various matrizants calculated.

The solution at the $n$th interval is given by

$$[x(t_n)] = \prod_{r=1}^{n} \Omega^{t_r - t_{r-1}}[x^0]$$

where, as before, $[x^0]$ is the matrix of the initial values of $y$ and $dy/dt$. If at the end of time $t = T$ or at the end of the completion of one cycle of variation of $\alpha(t)$ the variables $x_1$ and $x_2$ have increased to $kx_1^0$ and $kx_2^0$ or, in matrix form $[x(T)] = k[x^0]$, then we have solved the equation for any value of $t$ by the use of the formula $y(t + T) = ky(t)$. The important thing particularly in mechanical problems

is that we have determined the stability coefficient $k$ and can now predict whether the motion will increase and hence be unstable or die out or keep on without any increase or decrease. The author is in the process of applying this method to several special cases.

Having determined $y$, $Q$, the charge on the condenser is obtained from

$$Q = e^{-1/2\int(A_i)dt}y(t)$$

Whether $Q$ builds up or not depends on the relative magnitudes of the decrement factor

$$e^{-1/2\int A(t)dt}$$

and the value of $k$. In the absence of resistance, $A(t) = 0$. The behavior of $Q$ depends entirely on $k$ in such a case.

## VIII. The Solution of Oscillatory Networks

If in the most general linear bilateral network with lumped parameters discussed in part III, we place the resistance elements $R_{ij} = 0$. That is, the resistance in the various branches is negligible, we call the network an oscillatory network. In the conventional solution of such a network for the resonance frequencies and amplitudes it is necessary to solve a set of algebraic equations of high order. A method will now be given by which through the employment of matrices we do not have to solve any algebraic equations whatsoever. The method to be given here is a modification of a method developed by Duncan and Collar in treating mechanical problems.[7]

The fundamental equations for such a circuit in matrix form are:

$$[e] = [Z][i] \qquad \text{(See part III)}$$

where

$$Z_{ij} = J(\omega L_{ij} - 1/\omega C_{ij}) \qquad J = \sqrt{-1}$$

putting $R_{ij} = 0$.

Now, if we are interested in the various resonant frequencies, we place $[e] = [0]$.

Our matrix equation reduces to: $[0] = [Z]\ [i]$ or $[0] = (\omega[L] - 1/\omega[1/C])\ [i]$. The matrix

$$[L] = \begin{bmatrix} L_{11}\ldots L_{12}\ldots\ldots L_{1n} \\ \ldots\ldots\ldots\ldots\ldots \\ \ldots\ldots\ldots\ldots\ldots \\ L_{n1}\ldots L_{n2}\ldots\ldots L_{nn} \end{bmatrix}$$

may be termed the inductance matrix. The inductance matrix includes all the self-inductances ($L_{11}, L_{22}, \ldots L_{jj}$) and all the mutual inductances ($L_{ij}$ where $i \neq j$). The matrix

$$[1/C] = \begin{bmatrix} 1/C_{11}\ldots 1/C_{12} \quad \ldots\ldots 1/C_{1n} \\ \ldots\ldots\ldots\ldots\ldots\ldots \\ \ldots\ldots\ldots\ldots\ldots\ldots \\ 1/C_{n1}\ldots 1/C_{n2}\ldots\ldots 1/C_{nn} \end{bmatrix}$$

may be termed the elastance matrix. It includes the self- and mutual-elastances of the system.

If we multiply both sides of our above matrix equation by the scalar $\omega$, the angular frequency, we obtain:

$$(\omega^2[L] - [1/C])[i] = [0]$$

Multiplying by $[L]^{-1}$, the inverse of $[L]$ gives us,

$$(\omega^2[I] - [L]^{-1}[1/C])[i] = [0]$$

where $[I]$ is the unit matrix.

This may be considered as the generalization of the equation

$$(\omega^2 - 1/LC)i = 0$$

for the resonant frequency of a simple series circuit having an inductance $L$ and a capacitance $C$. In this simple case, the well-known solution for the angular resonant frequency is $\omega = 1/\sqrt{LC}$.

## 3. The Solution of the Matrix Equation

We must now solve the matrix equation:

$$(\omega^2[I] - [L]^{-1}[1/C])[i] = 0$$

For simplicity, let $\mu = \omega^2$ and $[M] = [L]^{-1}[1/C]$. Our equation now reduces to $[\mu I - M]\ [I] = [0]$. We note here (part II, section 7) that the matrix $[\mu I - M]$ is the characteristic matrix of the matrix $[M]$.

The latent roots $\mu_j$ of the matrix $[M]$ are related therefore, to the resonant frequencies by the equation

$$f_j = 1/2\pi\sqrt{\mu_j}$$

where the $f_j$ are the resonant frequencies.

We could, of course, evaluate these roots by finding the roots of the characteristic function

$$|\mu I - M| = 0$$

however, this is essentially the conventional procedure which one employs without the use of matrices. We are then confronted with an equation of degree $n$ for $\mu$. It is now proposed to give another method which avoids the solution of the algebraic equation.

Let us consider the matrix $[M]$ raised to a very high power. See part II, section 12. We have the equation

$$\lim_{n\to\infty}[M]^n = \frac{\mu_1{}^n\,[M_1]}{(\mu_2 - \mu_1)(\mu_3 - \mu_1)\ldots(\mu_n - \mu_1)}$$

where $\mu_1$ is the greatest of the latent roots of $[M]$, and $[M_1] = [\mu_2 - M]\ [\mu_3 - M]\ \ldots\ldots [\mu_n - M]$. We note that $[M_1]$ is the product in the Cayley-Hamilton relation with $[\mu_1 - M]$ absent. Therefore, by the Cayley-Hamilton theorem (part II, section 10), we have $[\mu_1 - M]\ [M_1] = [0]$

We now make use of the theorem on the vanishing of a product of matrices (part II, section $e$). Therefore

$$[M_1] = \begin{bmatrix} a_1A_1\ldots a_2A_2\ldots\ldots a_1A_n \\ \ldots\ldots\ldots\ldots\ldots\ldots \\ \ldots\ldots\ldots\ldots\ldots\ldots \\ a_nA_1 \quad a_nA_2\ldots\ldots a_nA_n \end{bmatrix}$$

That is, the matrix $[M_1]$ is such that the elements of any row are proportional to the corresponding elements of the top row of $[M_1]$. Therefore

$$\lim [M]^n = \frac{\mu_1{}^n}{\prod_{r\neq 1}(\mu_r - \mu_1)} \begin{bmatrix} a_1A_1\ldots\ldots\ldots a_1A_n \\ \ldots\ldots\ldots\ldots \\ \ldots\ldots\ldots\ldots \\ a_nA_1\ldots\ldots\ldots a_nA_n \end{bmatrix}$$

Now consider *any* line matrix $[X]$ and form the product

$$[M]^n[X] = \frac{{\mu_1}^n}{\prod_{r\neq 1}(\mu_r - \mu_1)} \begin{bmatrix} a_1A_1 \ldots\ldots a_1A_n \\ \ldots\ldots\ldots\ldots \\ \ldots\ldots\ldots\ldots \\ a_nA_1 \ldots\ldots a_nA_n \end{bmatrix} \begin{bmatrix} X_1 \\ X_2 \\ \ldots \\ X_n \end{bmatrix} =$$

$$\frac{{\mu_1}^n}{\prod_{r\neq 1}(\mu_r - \mu_1)} \begin{bmatrix} a_1R \\ a_2R \\ \ldots \\ a_nR \end{bmatrix}$$

where

$$R = A_1X_1 + A_2X_2 + \ldots + A_nX_n$$

If the values of $X_1, X_2 \ldots\ldots\ldots X_n$ are chosen so that $R$ is not zero, it follows that $[M]^{n+1}[X] = \mu_1[M]^n[X]$ that is, raising the power of the matrix $[M]$ from $n$ to $n+1$, gives a resulting matrix that is the same as before except that it is multiplied by $\mu_1$. Therefore, to obtain the fundamental frequency, any series of values are assumed for $X_1 \ldots\ldots X_n$ and, by continually multiplying $[M]^{n+1}[X]$ is obtained. After $n$ has reached a certain value, a limiting form is obtained when the ratio of successive multiplications is equal to $\mu_1$. When $\mu_1$ has been obtained, the fundamental frequency is obtained from

$$f_1 = 1/2\pi\sqrt{\mu_1}$$

It remains now to find the relative amplitude of the currents in the various meshes when the system is oscillating in its fundamental mode. We return to

$$[\mu I - M][i] = [0]$$

and

$$[\mu_1 - M][M_1] = [0]$$

Let $(i_1^0\ i_2^0 \ldots\ldots\ldots i_n^0)$ be the amplitudes of the currents corresponding to the fundamental mode $\mu_1$. Then

$$[\mu_1 - M][i^0] = [0]$$
$$[\mu_1 - M][M_1] = [0]$$

hence $[i^0] = K_1[M_1]$, where $K_1$ is some constant; or, therefore,

$$[i^0] = K_2 \begin{bmatrix} a_1R_1 \\ a_2R_2 \\ \ldots \\ \ldots \\ a_nR \end{bmatrix}$$

Therefore the amplitudes of the various currents are proportional to the quantities $a_1, a_2, \ldots\ldots\ldots a_n$. The method will be illustrated by means of a numerical example.

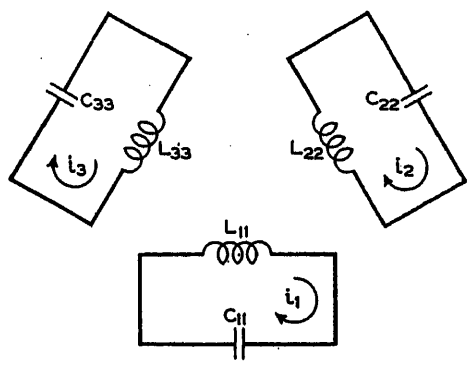



**Figure 4**

## 4. Example, Free Vibrations of a Coupled Circuit

The method will be made clear by the following example. Consider the coupled circuit shown in figure 4. In the circuit, let $C_{11} = C_{22} = C_{33} = 10^{-6}$ farads. Let $C_{ij} = 0$ if $i \neq j$. Let $L_{11} = {}^5/_6H$, $L_{22} = {}^1/_2H$, $L_{33} = {}^1/_6H$, $L_{12} = -{}^1/_3H = L_{21}$, $L_{31} = 0 = L_{13}$, $L_{23} = -{}^1/_3H = L_{32}$. In matrix form

$$[L] = \begin{bmatrix} 5/6 & -1/3 & 0 \\ -1/3 & 1/2 & -1/6 \\ 0 & -1/6 & 1/6 \end{bmatrix}$$

$$[1/C] = 10^6 \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} = 10^6[I]$$

We first calculate $[M] = [L]^{-1}[1/C]$

$$[L] = 1/36 \begin{bmatrix} 30 & -12 & 0 \\ -12 & 18 & -6 \\ 0 & -6 & 6 \end{bmatrix}$$

$$[L]^{-1} = \begin{bmatrix} 2 & 2 & 2 \\ 2 & 5 & 5 \\ 2 & 5 & 11 \end{bmatrix}$$

$$[M] = 10^6 \begin{bmatrix} 2 & 2 & 2 \\ 2 & 5 & 5 \\ 2 & 5 & 11 \end{bmatrix}$$

We choose

$$[X] = \begin{bmatrix} 1 \\ 1 \\ 1 \end{bmatrix}$$

for simplicity. Therefore

$$[M][X] = 10^6 \begin{bmatrix} 2 & 2 & 2 \\ 2 & 5 & 5 \\ 2 & 5 & 11 \end{bmatrix} \begin{bmatrix} 1 \\ 1 \\ 1 \end{bmatrix} = 10^6 \begin{bmatrix} 6 \\ 12 \\ 18 \end{bmatrix} = 18 \times 10^6 \begin{bmatrix} 1/3 \\ 2/3 \\ 1 \end{bmatrix}$$

$$[M]^2[X] = 18 \times 10^{12} \begin{bmatrix} 2 & 2 & 2 \\ 2 & 5 & 5 \\ 2 & 5 & 11 \end{bmatrix} \begin{bmatrix} 1/3 \\ 2/3 \\ 1 \end{bmatrix} = (18)(15)(10^{12}) \begin{bmatrix} 4/15 \\ 9/15 \\ 1 \end{bmatrix}$$

It may be noted that since we are only interested in the ratio of successive multiplications we may dispense with the numerical factors in front of the matrix. Continuing the process we soon reach:

$$\begin{bmatrix} 4/15 \\ 9/15 \\ 1 \end{bmatrix} \begin{bmatrix} 2 & 2 & 2 \\ 2 & 5 & 5 \\ 2 & 5 & 11 \end{bmatrix} = 14.533 \begin{bmatrix} 0.256{,}881 \\ 0.584{,}762 \\ 1 \end{bmatrix}$$

and

$$\begin{bmatrix} 2 & 2 & 2 \\ 2 & 5 & 5 \\ 2 & 5 & 11 \end{bmatrix} \begin{bmatrix} 0.256{,}881 \\ 0.584{,}762 \\ 1 \end{bmatrix} = 14.4495 \begin{bmatrix} 0.255{,}238 \\ 0.584{,}762 \\ 1 \end{bmatrix}$$

The ratio is settling down to a number nearly equal to 14.45. By continuing further it is found that the value of $\mu_1 = 14.431 \times 10^6$ and the ratios of the amplitudes of the currents for the fundamental oscillation are about 0.255, 0.584, and 1.000 as given by the final matrix. A similar mechanical problem is discussed by Duncan and Collar in the above-mentioned paper in the *Philosophical Magazine.*

It is seen that the convergency of the process is very high and the calculations are easily made with a comptometer. The results are

$\mu_1 = 14.431(10^6)$

hence

$_1 = 1/2\pi\sqrt{\mu_1} = 607$ cycles per second

This is the fundamental frequency. When the system is oscillating at the fundamental frequency the ratios of the currents are $i_1 = 0.225$, $i_2 = 0.584$, and $i_3 = 1.000$; that is, with respect to $i_3$ as unity the other currents have the above values.

For a more complete discussion of this method in similar mechanical problems the reader is referred to "Solution of Oscillation Problems by Matrices" by Duncan and Collar. In this paper a method of obtaining the higher resonant frequencies is also given. The author is working on some more applications of the method.

It must be noted that the method here given while it avoids the direct solution of the detrimental equation makes use of a process which is related to the well-known root-squaring method of Graeffe. Graeffe's method has been shown to be equivalent to the method of Daniel Bernoulli. An excellent discussion and an extension of Bernoulli's method which may be reduced to the method here presented may be found in A. C. Aitken's paper "On Bernoulli's Numerical Solution of Algebraic Equations" Proceedings of the Royal Society, Edinburgh, volume 46, page 289, 1926.

## X. Conclusion

It has been the purpose of this paper to show the inherent simplicity and power of the matrix method once the fundamental operations have been grasped.

The theory of matrices as presented in part II has been the result of searching the international literature and it is hoped that the concise presentation may give an impetus to the use of this method. The author is at present attacking the problem of simultaneous partial differential equations by this method and the results thus far show that the matrix method will be more powerful in this connection (See reference 9).

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# The Next 50 Years

IN THE 50-year period before us there will be an accelerated advance in the accomplishments of engineering, which, broadly speaking, is the application of science. New discoveries in science, and their use by means of new inventions, will follow one another with ever increasing rapidity. Often one discovery will reveal a score or more of new opportunities which speedily will be developed and made useful to man.

This acceleration in the speed of engineering advancement will be due in part to the increase in the number of workers in this field, made available through the competition of engineering colleges to gain students, and especially through the growing conviction among parents, whether well-founded or not, that an engineering education carries with it an improved economic and social status. The public has become "engineering minded."

No one can foretell with accuracy what specific results will ensue from this intensified development along engineering lines; but a few accomplishments are clearly evident:

1. Space, already so greatly reduced, will, practically speaking, be well nigh eliminated by the conquest of the air.

2. Mass-production will be extended to far more industries.

3. Agriculture will yield more and more to combination-control and mechanization. With the aid of new methods of processing and the discovery of synthetic foods, the necessary agricultural products for a unit of population will be provided with a fraction of the labor and land now used.

4. Automatic control of production and operation will further greatly reduce the need for manual control.

5. New scientific discoveries, new sources of power, and the development of new processes and inventions, will make necessities and many luxuries more generally available.

Such changes will inevitably shorten the work-time required to satisfy the demands of the public. In Canada and the States it has been reduced $^1/_3$ during the last 50 years. Is it not probable that an equal reduction will result in the next 50 years? If so, the required work-time will become only half what it is at present. Probably 20 hours a week is a conservative estimate.

Whatever this reduction may be, it will result largely from the activities of the engineer. Credit for lightening the human burden, however, will be accompanied by liability for any unfortunate results which may ensue, and the public will look to the engineer to provide the means to avoid them.

From an address by the late Harrison P. Eddy, past-president of the American Society of Civil Engineers, prepared for presentation at the recent semicentennial celebration of the Engineering Institute of Canada, upon which occasion Mr. Eddy was to have been made an honorary member of that society. The address was posthumously delivered at a luncheon meeting on June 16, and was published in the August 1937 issue of *Civil Engineering*, pages 545–6.

# Short-Circuit Protection of Distribution Networks by the Use of Limiters

By C. P. XENIS
MEMBER AIEE

A LARGE PERCENTAGE of secondary cable faults in distribution networks "burn clear" rapidly. In such cases, the short-circuit current to the fault has not persisted for a sufficiently long period of time to raise the temperature of the cable conductor on either side of the fault to a high enough temperature to fuse, or permanently damage adjacent cable insulation. However, not even the most optimistic treatises on "burnoff" have ever asserted that all secondary cable faults are of this accommodating type. Furthermore, the fault consists of an electric arc between a number of energized copper conductors confined in the small space of the duct, surrounded by masses of molten metal and with water frequently present. Under such a combination of conditions, who can contend that the fault can be depended upon to always clear in time to protect the insulation of cables supplying the fault current?

Companies operating extensive distribution networks have experienced cases of cable failure "spreading" beyond the initial point of fault, and the prevention of extensive damage in such cases depends on the prompt arrival of the operating crews who cut network cables "around" the faulted area. This type of fault is frequently accompanied by fires and explosions for apparent reasons.

This problem is not new, and the development of noncombustible cable insulation represents one angle of attack. The development of cable joining connectors, lugs, etc., which incorporate fusible elements, so that in addition to their normal splicing functions, they provide adequate fuse protection to the cables to which they are attached, represents another angle of attack to the problem. Undoubtedly other solutions will present themselves in the future.

## The Limiter

The limiter consists of a reduced metallic section incorporated in a connector, lug, or other connecting device used in normal cable installation procedure. It has a time-current characteristic calculated to protect the cable to which it is connected over a wide range of short-circuit currents, by interrupting the faulty circuit before the cable insulation reaches the "roasting" point; in other words, the limiter selects with cable insulation. It is so designed as to form an integral part of the joint or cable terminal without the necessity of the additional enclosures, terminal blocks, packing glands, etc. that conventional underground fusing systems require. In short, it is a fuse made into an inconspicuous part of the cable it is intended to protect.

Figure 1 step number 1 shows a connector-type limiter used for protecting number 4/0 nonleaded cables on the distribution systems of the Consolidated Edison Company of New York, Incorporated. This limiter is made from a single piece of copper tubing by flattening the middle portion of the tube and punching out the excess metal, thus leaving the desired fusible section. Step number 2 shows the ends of the number 4/0 cables inserted in the tubular ends of the limiter, while step number 3 shows the assembly after the tubular ends are indented to form a permanent connection between the cables. Step number 4 shows the fireproofing shells assembled around the limiter, while step number 5 shows the limiter installation completed by covering the assembly with a rubber sleeve and taping the ends to the cable insulation. Figure 2 gives the corresponding steps taken in installing a limiter lug on the end of a 500,000-circular-mil nonleaded cable. Note that in this case no rubber covering is provided over the fireproofing shells on the lug since it is used for indoor installations. The limiter lug is also constructed from a single piece of

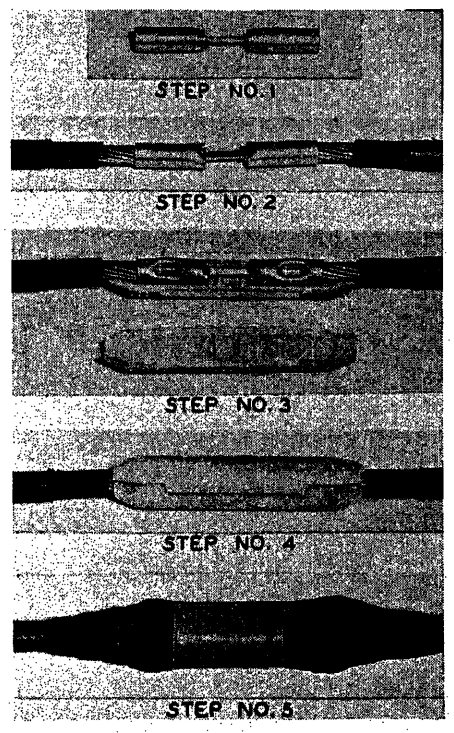



**Figure 1. Installation of connector type limiter**

A paper presented at the Edison Electric Institute transmission and distribution committee meeting, Chicago, Ill., May 5, 1937, and recommended for publication by the AIEE committee on power transmission and distribution. Manuscript submitted May 21, 1937; released for publication July 9, 1937.

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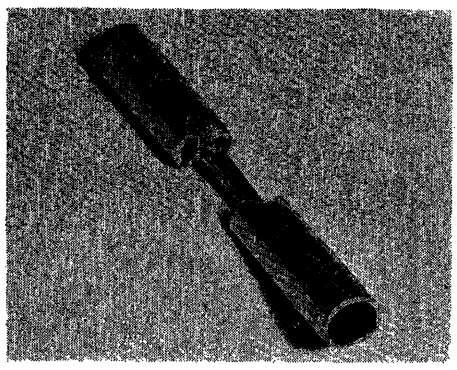


**Figure 1A. Connector type limiter**

copper tubing, a portion of which has been flattened, bent, and punched out to form the lug and fusible section.

The fireproofing shell (figure 3) plays an important part in the proper operation of the limiter by providing the means of confining the arc developed during the interruption of the circuit. It is molded from a noncombustible dry mixture of asbestos and cement. Note the barriers which further tend to confine the arc and keep it from striking across the large cylindrical portions of the limiter. With the limiter assembly as described, it is possible to interrupt short-circuit currents met in practice without any external indication of arc or flame.

In connecting the above limiters to cables, it should be noted that compression-type mechanical connections were used. Various types of powder driven, hydraulically operated, and screw-type devices are now available which make satisfactory connections. Solder must be avoided in the proximity of limiters because of its low melting point. While in the above illustrations we have indicated the use of limiters on nonleaded cables, their application to rubber-insulated lead-covered cables is equally practical and lead sleeves may be installed over the limiters if desired. However, the use of limiters on paper-insulated lead-covered cables becomes relatively difficult since it is necessary to take additional steps to keep the impregnating oil from entering the fuse chamber of the limiter.

The use of limiters at multiple points of a network system results in the protection of each cable section between such points. The cable fault shown in figure 4 draws its supply of short-circuit current from 3 directions at each multiple point. However, the total short-circuit current from each multiple point must pass through the limiter which is connected to the faulty cable. In other words by installing limiters of the same type at each multiple point of a network system, the selection between limiters is automatically secured, and since the faulty section is equipped with limiters at both extremities, it will be isolated from the rest of the network. This presumes that the limiter is designed so that it will blow at the minimum values of short-circuit current encountered in that network.

## Limiter Characteristics

The limiter, like any other type of fuse, has a time current characteristic which defines its performance at various overloads. From previous discussions, it is evident that the ideal characteristic for a limiter is one slightly faster than the insulation damage characteristic of the cable it is intended to protect. In other words, the limiters on the faulted section should fuse before the insulation of the cables feeding the short-circuit reaches a dangerous condition as the result of the total heat generated by all cables in the duct. It therefore follows that limiter design should be preceded by the determination of cable damage characteristics. This has been done experimentally using various rubber-insulated cables, for a single cable in open air and again for a set of main cables installed in concrete duct. Figures 5, 6, and 7 show time-temperature characteristics for various types of cable installations encountered in the network distribution systems of the Consolidated Edison Company of New York, Incorporated. It will be noticed that after the copper conductor reaches a temperature of approximately 265 degrees centigrade the rubber reaches the point of permanent visible damage. Although tests were made on cables insulated with 2 types of rubber base compounds, namely, intermediate rubber compound, ASTM performance rubber compound, some lead-covered, others not, it was found that the slight differences in the results obtained did not justify separate treatment in this report and therefore one set of curves have been plotted. It will also be noted that in cases of rapid temperature rise in the copper conductor, somewhat higher copper temperatures are necessary to cause the same extent of damage to cable insulation. This is the result of the lag in the temperature

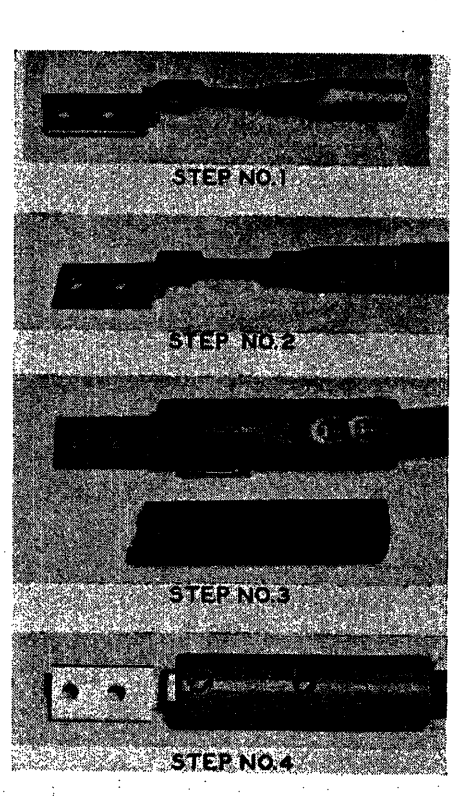



**Figure 2. Installation of lug type limiter**

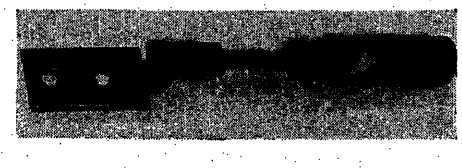


**Figure 2A. Lug type limiter**

rise of the insulation behind the rise of copper temperature. Figure 8 summarizes the cable damage characteristics for rubber insulation in a more convenient form for comparison with limiter characteristics.

In figures 9 and 10 we have shown cable damage characteristics together with the characteristics of limiters of types illustrated in the first part of this paper. The intersection of the limiter characteristic with the cable damage characteristic indicates the value of current below which the limiter offers no protection to cable insulation. However, if this critical current is below the minimum value of short-circuit current obtainable in the network, this limitation loses all practical importance. A wide range of limiter characteristics is possible by varying the cross section and the length of the fusible section. This phase of the limiter design problem is not much different than that of general fuse link design and therefore, no useful purpose can be served here by going into detail. On figure 9, 2 limiter characteristics have been shown to illustrate possible variations in design.

An additional point to be kept in mind in selecting or designing limiters is that the limiter generates heat at a higher rate than the cable conductor and therefore some of this heat is conducted to the cable to which it is attached. This presents a problem only for currents near the minimum at which the limiter is designed to fuse. Higher currents fuse the limiter before the heat generated has time to affect the adjacent cable insulation. Substantially lower currents (than the minimum fusing values for the limiter) do not generate a sufficient amount of heat to affect the adjacent cable insulation. It is therefore desirable that this particular point be investigated as the last step of design to insure that no overheating of the cable insulation adjacent to the limiter results from heat conducted from the limiter. By judicious change of the length and cross section of the fusible section and by proper selection of the minimum blowing point of the limiter, this condition can be overcome. In this connection the fact that the limiter and adjacent cable insulation are located in the manhole where ambient temperatures are substantially lower than those in the duct in which the overloaded cables are located, assists in arriving at the desired thermal balance. At rated loads the temperature of the fusible section (located within the asbestos shell) is approximately 5 degrees centigrade higher than that of the cable conductor.

With the aid of the above analysis and reference to the data presented in curve form, it is possible to design limiters which will properly select with the cable insulation. In the a-c distribution system of the Consolidated Edison Company of New York, Incorporated, limiter type *AC-2R* has been used extensively for protecting number 4/0 nonleaded network cables in Manhattan and the

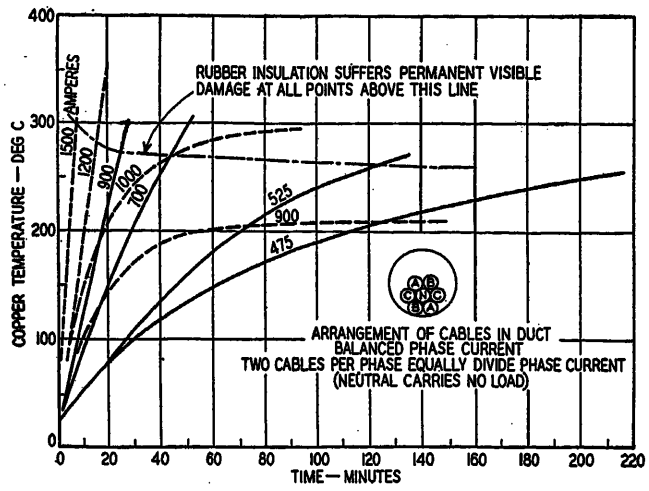



**Figure 5. Time-temperature characteristics, rubber-insulated cables**

Solid curves—Six number 4/0 cables in duct
Dashed curves—One number 4/0 cable in open air

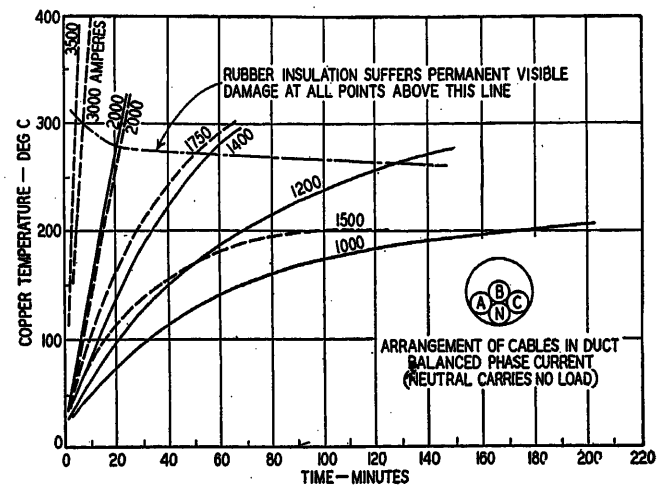



**Figure 6. Time-temperature characteristics, rubber-insulated cables**

Solid curves—Three 500,000-circular-mil cables in duct
Dashed curves—One 500,000-circular-mil cable in open air

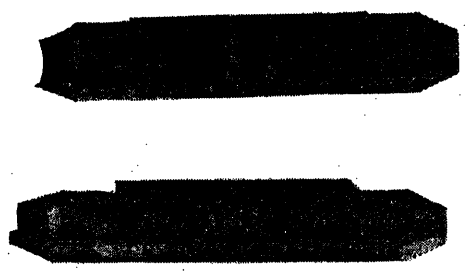


**Figure 3. Fireproofing shells for connector type limiter**

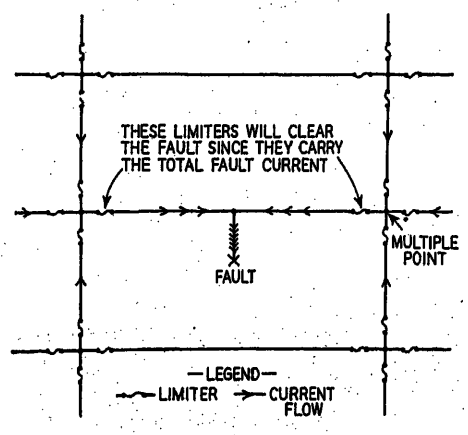



**Figure 4. Schematic current distribution diagram under condition of a secondary network fault**

Note: All limiters in this network are of the same type and characteristic

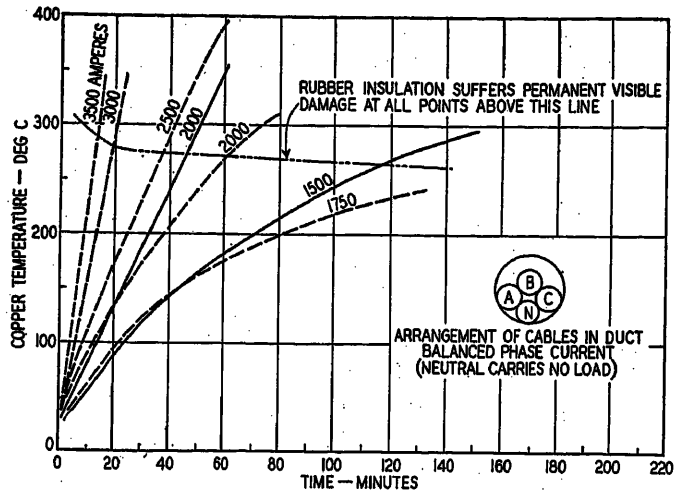



**Figure 7. Time-temperature characteristics, rubber-insulated cables**

Solid curves—Three 750,000-circular-mil cables in duct
Dashed curves—One 750,000-circular-mil cable in open air

Bronx. Their use is now being extended to other sizes of cables and at other points of the distribution networks.

## Selectivity Between Limiters and Network Protector Fuses

Our discussion heretofore has been confined to the proper protection of network cables by means of limiters installed at multiple points. Where the multiple point happens to be also a supply point, 2 additional considerations for the proper design of the system must receive attention:

(*a*) The supply cables (connecting the network protector to the street mains) may be protected by means of limiters.

(*b*) The network protector fuse should properly select with the combination of limiters on the supply cables and those on the network mains at the multiple point.

With reference to consideration (*a*) the desirability of protecting supply cables varies with the type of installation. If, for example, the supply cables represent a very short run between a network protector installed in an underground manhole and the multiple point, the need for protecting the supply cables is questionable. If, however, the supply cables are of considerable length as in the case of transformer banks installed within customer's buildings, the protection of such supply cables and secondary ties is of considerable importance since a serious case of cable failure within the customer's premises is liable to entail unpleasant consequences. This protection can be accomplished in accordance with the methods previously explained. Where the cable terminates at a bus, as would be the case where secondary ties connect to the customer's bus, limiter lugs are used for the purpose. Figure 11 is a schematic diagram representing a network completely equipped with limiters at multiple points and with supply cables protected at both extremities. Figure 12 shows a transformer vault installation with secondary ties, as well as cables connecting the transformer secondary side to the network switch, completely protected by means of limiters. This type of protection has been recently adopted by the Consolidated Edison Company of New York, Incorporated.

Figure 12 also serves to illustrate the problem of obtaining the proper selection between network protector fuse and associated limiters. In the event of a high-voltage feeder failure, if the network protector fails to open because of some defect, it is desirable to have the circuit interrupted by the network protector fuse because of the relative ease of replacement of the latter, in comparison with the replacement of limiters. Hence, it is necessary to consider the characteristic of the network protector fuse in conjunction with that of the associated limiters, taking into consideration the fact that a number

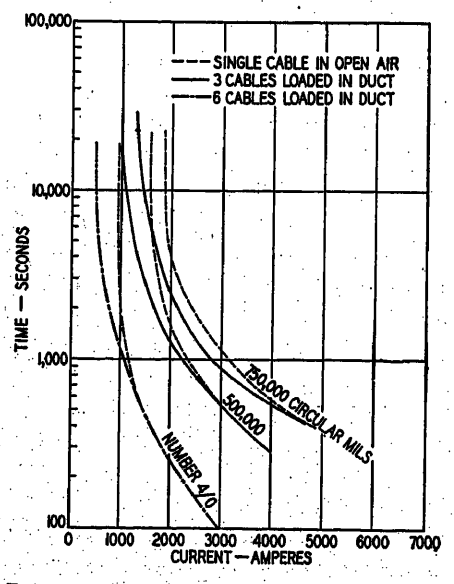



**Figure 8. Cable insulation damage characteristics, rubber-insulated cables**

Note: Visible damage occurs at points on and above each characteristic curve

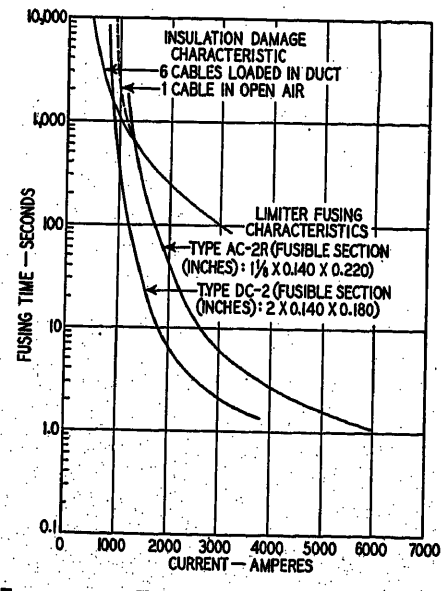



**Figure 9. Time-current characteristic, 4/0 cable limiter**

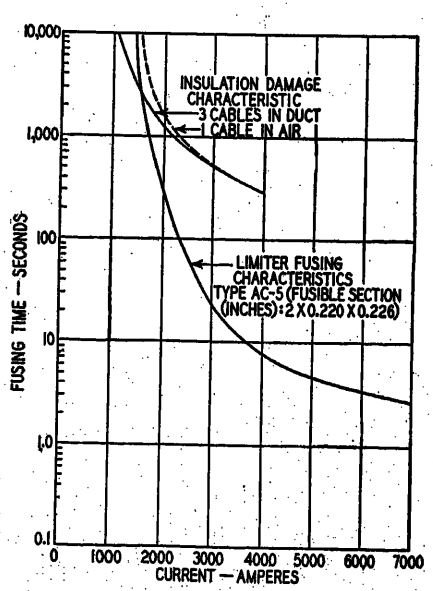



**Figure 10. Time-current characteristic, 500,000-circular-mil cable limiter**

of limiters in parallel (4 per phase in the case of figure 12) divide the total current flowing through each network protector fuse. Because of differences in length between the street ties and variations in the network layout, it is possible that in the case of backfeed the 4 street ties shown in figure 12 may not equally divide the total backfeed current. It has therefore been decided that the proper selection should be obtained even when one of the 4 secondary ties carries as much as 40 per cent of the total backfeed current. An unbalance of this magnitude is extremely unlikely to occur on the system. Figure 13 shows the characteristic of network protector fuse type $Z$-25 and that of limiter type $AC$-5 when carrying various percentages of the total fuse current. It will be noticed that even when a limiter on one of the secondary ties carries as much as 40 per cent of the total backfeed current, a comfortable margin of selectivity is obtained. The characteristic of the limiter considered on figure 13 ($AC$-5) is shown on figure 10. With a range of selection such as indicated above, the network protector fuse continues to be the weakest link in the chain of network protection.

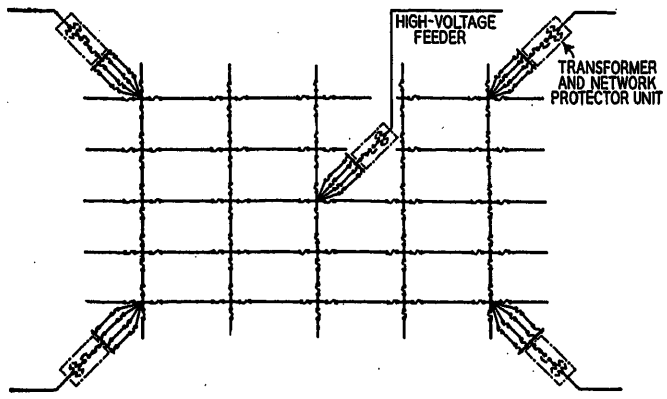



**Figure 11. Schematic diagram of distribution network completely equipped with limiters**

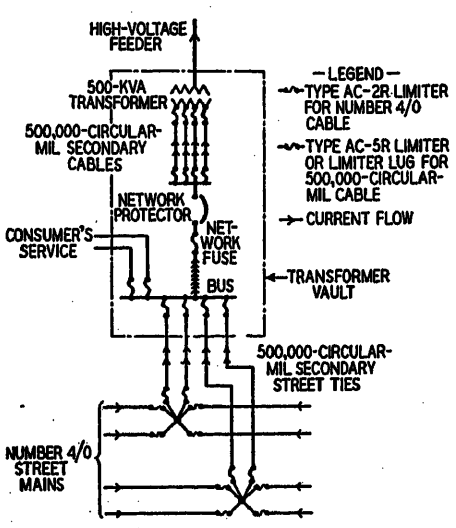



**Figure 12. Schematic current distribution diagram under condition of backfeed**

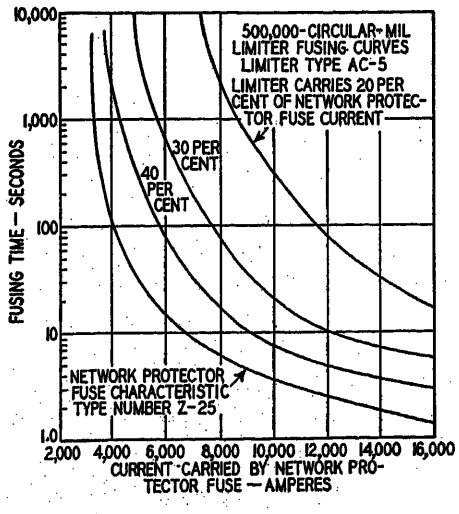



**Figure 13. Selectivity between network protector fuse and associated limiters**

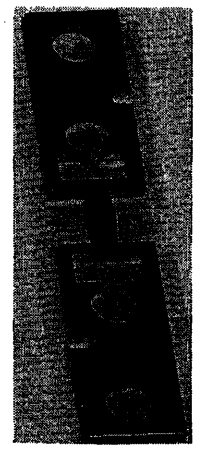


**Figure 14 (above). Type Z network protector fuse**

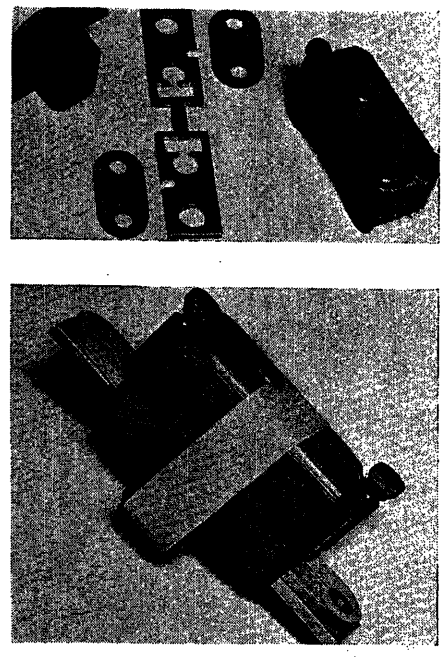


**Figure 15 (right). Details of type Z network protector fuse and enclosure (top) and assembly of type Z network protector fuse and enclosure (bottom)**

Since the network protector fuse is in series with a group of limiters which are in parallel, the 2 types of devices must necessarily possess time-current characteristics of the same general shape. Hence it was decided to review network fuse design and bring it in line with limiter design so as to obtain the desired selection. The result of this work was a copper fuse, illustrated on figure 14, which provides proper selection with limiters, protects the transformer over a broader range of overload currents than other conventional network protector fuses, and is of a type that can be readily punched out of flat sheet copper. An individual fireproof arc-suppressing enclosure (see figure 15) is provided with each fuse. These enclosures serve to protect men who may happen to be standing in front of an open network protector when the fuse blows, and to prevent damage to equipment and communication of trouble. These fuse assemblies have successfully interrupted currents of the order of 30,000 amperes at full restoration voltage with no restriking, and with the arc sufficiently confined to protect workmen in the immediate vicinity. The fuse characteristic on figure 13 is that of a fuse of this type, and of the size used with a 500-kva bank.

The development outlined in this paper may be briefly summarized as an attempt to revise cable splicing procedure so as to incorporate fuse protection for the large amounts of cable insulation exposed to high copper temperature in the vicinity of short-circuited distribution-

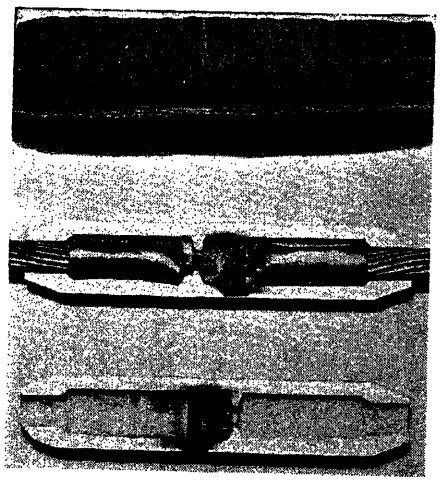


**Figure 16. Kerite and friction tape covering (top) and limiter fusing with separation of 1/4 inch (bottom)**

network mains. With such a system, those faults which "burn clear" in less time than that required to clear the limiter (see limiter characteristic) will continue to "burn clear" as heretofore. The faults which do not "burn clear" very readily are the ones that endanger insulation on cables supplying the fault current. Such faults will be cleared by limiter action.

The selection of the proper limiter for any distribution system should be based on a study of conditions obtaining in that system, with particular reference to (*a*) insulation damage characteristic of network cables, (*b*) minimum short circuit current, (*c*) selection with network protector fuses. Standardization in limiter design must necessarily be preceded by standardization in distribution network design.

The Consolidated Edison Company of New York, Incorporated, has installed 16,000 limiters in the past year. During this period there have been 2 cases of faults on cables equipped with limiters (35th Street and Sixth Avenue and 40th Street and Sixth Avenue). Both cases were caused by cables being "bull-pointed" by subway construction contractors. In each case the limiters properly cleared and protected the cables to which they were attached. Figure 16 shows a limiter which has blown in the field and cleared a short-circuit.

## Pooling Power in a Large Industrial Center

A PROBLEM of The Detroit (Mich.) Edison Company incident to the provision of reserve capacity against the exigencies of power plant operation and against outages occasioned by routine maintenance, and the provision of excess capacity to meet the unpredictable and sudden demands of a vigorously expanding industrial community, was discussed in a paper presented at the semiannual meeting of The American Society of Mechanical Engineers, Detroit, Mich., May 17–21, 1937, by J. W. Parker and R. E. Greene (A'26) respectively, vice-president and member of the engineering division of the company. The paper was published in *Mechanical Engineering* for May 1937, pages 335–9.

Diversity in time of use constitutes the major advantage in pooling the power requirements of any community, inasmuch as the peak load of residential and commercial users does not occur at the same hour as the peak industrial load. If each wholesale user of power operated its own isolated power plant, the installed capacity required would be much greater than is needed if all plants in an area are interconnected. Reserve capacity in a large system can be less than the aggregate reserve capacity in a series of isolated plants for the same load, where one spare unit may be a relatively large part of the total capacity.

In the Detroit system, reserve capacity in machines running and on the line is maintained at least equal to the capacity of the largest machine on the line. In case a machine must be shut down in an emergency, the running reserve should be restored at once, and, therefore, a second large machine is kept standing ready for an immediate start.

Pooling of power resources benefits the community because freedom is allowed in the choice of sites for manufacturing establishments, inasmuch as large quantities of water for condensers may be obtained by locating central stations on rivers, rather than requiring all manufacturers to build plants on the rivers. Such concentration in large stations, however, requires considerable investment in a transmission and distribution system, amounting in the Detroit system to approximately 56.6 per cent of the total property. The territory served is divided into 4 areas, each with a major generating station. Interconnection may be described as "loose linked," for limited-capacity ties are provided which may or may not normally carry load but which are sufficient in capacity to compensate for any losses in generating capacity which can be reasonably anticipated. If an uncontrollable fault develops in one area, the remainder of the system cuts clear.

The authors conclude that: "With all its advantages of both reliability and economy, the central system cannot, under certain circumstances, compete with certain types of load. Combining electric generation with a supply of steam required in some industrial process, produces power as a by-product at a much lower cost than can be attained by the best of condensing turbines. Seldom, however, does the requirement of steam for process work and building heating coincide with the manufacturer's own use of power. Paralleling such by-product generation with the central system may be, and often is, good economy rather than providing spare capacity against breakdown or being compelled to generate power under costly conditions in periods when no corresponding demand for steam exists. In a sense, the central system becomes a broker ready to sell or buy power as the circumstances of the moment may dictate."

# Extension of 2-Reaction Theory to Multiphase Synchronous Machines

By Y. H. KU
MEMBER AIEE

An extension of the 2-reaction theory of synchronous machines as developed by R. H. Park is given in this paper for machines with any number of phases.

AT THE 1929 AIEE winter convention, Park[1] and Ku[2] presented simultaneously 2 papers on the analysis of 3-phase synchronous machines. While Ku's method was based on Heaviside's operational calculus and Stokvis-Fortescue's symmetrical components, Park generalized the work of Blondel, Dreyfus, Doherty, and Nickle and gave a complete analysis of the salient-pole machine with any number of rotor circuits. Ku's work has since been extended to the salient-pole case with inductive and capacitive load[3] and also to the asynchronous operation[4] of synchronous machines. The 2-reaction theory has been further extended by Park[5] to the consideration of synchronizing and damping torque during continuous and transient oscillations. The 2-reaction operational impedances of machines with field collars are given by Waring and Crary,[6] and, more recently, the effect of condenser load is considered by Crary.[7] The present paper is a further extension of the 2-reaction theory as developed by Park to the general case of $n$-phase salient-pole synchronous machines. It may be pointed out that the 2-reaction components can also be simply related to the symmetrical components[8,9] and a similar extension based on operational calculus and symmetrical components[10] may serve as a good comparison between the 2 methods of attack.

## Fundamental Circuit Equations

Consider an ideal synchronous machine with $n$ phases, and let

$i_A, i_B, i_C \ldots i_N$ = per-unit instantaneous phase currents
$e_A, e_B, e_C \ldots e_N$ = per-unit instantaneous phase voltages
$\psi_A, \psi_B, \psi_C \ldots \psi_N$ = per-unit instantaneous phase linkages
$t$ = time in electrical radians
$p$ = $d/dt$

Then there is

$$\left.\begin{aligned} e_A &= p\psi_A - ri_A \\ e_B &= p\psi_B - ri_B \\ e_C &= p\psi_C - ri_C \\ &\cdots\cdots \\ e_N &= p\psi_N - ri_N \end{aligned}\right\} \quad (1)$$

A paper recommended for publication by the AIEE committee on electrical machinery. Manuscript submitted June 2, 1937; released for publication July 22, 1937.

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1. For all numbered references, see list at end of paper.

The phase linkages of an $n$-phase salient-pole synchronous machine may be given as follows (see appendix I):

$$\psi_A = I_d \cos\theta - I_q \sin\theta - x_0 i_A + \left[x_0 - \left(\frac{x_d + x_q}{2}\right)\right]\left(\frac{2}{n}\right) \times [i_A + i_B \cos\theta_0 + i_C \cos 2\theta_0 + \ldots + i_N \cos\{(n-1)\theta_0\}] - \left(\frac{x_d - x_q}{2}\right)\left(\frac{2}{n}\right)[i_A \cos 2\theta + i_B \cos(2\theta - \theta_0) + i_C \cos(2\theta - 2\theta_0) + \ldots + i_N \cos\{2\theta - (n-1)\theta_0\}]$$

$$\psi_B = I_d \cos(\theta - \theta_0) - I_q \sin(\theta - \theta_0) - x_0 i_B + \left[x_0 - \left(\frac{x_d + x_q}{2}\right)\right]\left(\frac{2}{n}\right)\left[i_A \cos\theta_0 + i_B + i_C \cos\theta_0 + \ldots + i_N \cos(n-2)\theta_0\right] - \left(\frac{x_d - x_q}{2}\right)\left(\frac{2}{n}\right) \times [i_A \cos(2\theta - \theta_0) + i_B \cos(2\theta - 2\theta_0) + i_C \cos(2\theta - 3\theta_0) + \ldots + i_N \cos(2\theta)]$$

$$\cdots\cdots\cdots\cdots$$

$$\psi_N = I_d \cos\{\theta - (n-1)\theta_0\} - I_q \sin\{\theta - (n-1)\theta_0\} - x_0 i_N + \left[x_0 - \left(\frac{x_d + x_q}{2}\right)\right]\left(\frac{2}{n}\right)[i_A \cos(n-1)\theta_0 + i_B \cos(n-2)\theta_0 + i_C \cos(n-3)\theta_0 + \ldots + i_N] - \left(\frac{x_d - x_q}{2}\right)\left(\frac{2}{n}\right)[i_A \cos\{2\theta - (n-1)\theta_0\} + i_B \cos 2\theta + i_C \cos\{2\theta - (n+1)\theta_0\} + \ldots + i_N \cos\{2\theta - (n-2)\theta_0\}] \quad (2)$$

where $\theta$ = position of rotor axis in electrical radians measured from the axis of phase $A$, and $\theta_0 = 2\pi/n$. Let the transformations from the phase quantities to 2-reaction components be given by the following (see appendix II):

$$f_d = \frac{2}{n}[f_A \cos\theta + f_B \cos(\theta - \theta_0) + f_C \cos(\theta - 2\theta_0) + \ldots + f_N \cos\{\theta - (n-1)\theta_0\}] \quad (3)$$

$$f_q = -\frac{2}{n}[f_A \sin\theta + f_B \sin(\theta - \theta_0) + f_C \sin(\theta - 2\theta_0) + \ldots + f_N \cos\{\theta - (n-1)\theta_0\}] \quad (4)$$

where $f$ may stand for $e$, $i$, or $\psi$. It may be verified that

$$\psi_d = I_d - x_d i_d \quad (5)$$

$$\psi_q = I_q - x_q i_q \quad (6)$$

From previous work of Park,[1] Waring and Crary,[6] and others,[9] we know that $I_d$ can be expressed in terms of $E_d$ and $i_d$, and, similarly, $I_q$ can be expressed in terms of $E_q$ and $i_q$. Hence by extending to the $n$-phase case, we have

$$\psi_d = G_d(p)E_d - x_d(p)i_d \quad (5a)$$

$$\psi_q = G_q(p)E_q - x_q(p)i_q \quad (6a)$$

Let also

$$f_0 = \frac{1}{n}[f_A + f_B + f_C + \ldots + f_N] \quad (7)$$

Then

$$\psi_0 = -x_0 i_0 \quad (8)$$

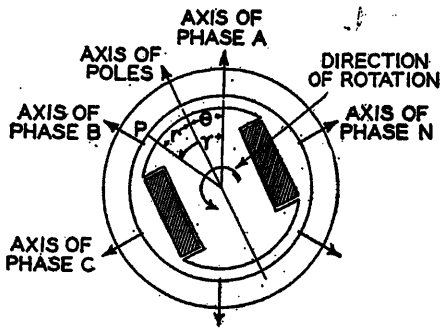



Figure 1

For the transformation of other variables, we have in general,

$$f_{u(k)} = \frac{2}{n}\,[f_A + f_B \cos(k+1)\theta_0 + f_C \cos\{2(k+1)\theta_0\} + \ldots + f_N \cos(k+1)\theta_0] \quad (9)$$

$$f_{v(k)} = \frac{2}{n}\,[0 + f_B \sin(k+1)\theta_0 + f_C \sin\{2(k+1)\theta_0\} + \ldots - f_N \sin(k+1)\theta_0] \quad (10)$$

where $(k)$ has the values from one to $(n-3)/2$ for $n$ odd and to $(n-4)/2$ for $n$ even. For $n$ even, we have also

$$f_w = \frac{1}{n}\,[f_A - f_B + f_C - \ldots - f_N] \quad (11)$$

Then it can be shown that

$$\psi_{u(k)} = -x_{0i} i_{u(k)} \quad (12)$$

$$\psi_{v(k)} = -x_{0i} i_{v(k)} \quad (13)$$

$$\psi_w = -x_{0i} i_w \quad (14)$$

The equations for the phase voltages can now be transformed to the following:

$$e_d = p\psi_d - r i_d - \psi_q p\theta \quad (15)$$

$$e_q = p\psi_d - r i_q + \psi_d p\theta \quad (16)$$

$$e_0 = p\psi_0 - r i_0 \quad (17)$$

$$e_{u(k)} = p\psi_{u(k)} - r i_{u(k)} \quad (18)$$

$$e_{v(k)} = p\psi_{v(k)} - r i_{v(k)} \quad (19)$$

$$e_w = p\psi_w - r i_w \quad (20)$$

Notice that since $\psi_d$ and $\psi_q$ only involve the current components $i_d$ and $i_q$, $i_d$ and $i_q$ can be obtained by solving 15 and 16 simultaneously. Equations 17 to 20 are even simpler as linkages are functions of their own current components, hence each equation only contains one current component corresponding to the voltage component, and the common impedance function is $z_0(p) = r + x_0 p$.

The reverse transformations from the "2-reaction" components to the phase quantities are as follows:

$$f_A = f_d \cos\theta - f_q \sin\theta + f_{u(1)} + 0 + \ldots + f_w$$

$$f_B = f_d \cos(\theta - \theta_0) - f_q \sin(\theta - \theta_0) + f_{u(1)} \cos 2\theta_0 + f_{v(1)} \sin 2\theta_0 + \ldots - f_w$$

$$f_C = f_d \cos(\theta - 2\theta_0) - f_q \sin(\theta - 2\theta_0) + f_{u(1)} \cos 4\theta_0 + f_{v(1)} \sin 4\theta_0 + \ldots + f_w$$

$$\cdots\cdots\cdots\cdots$$

$$f_N = f_d \cos(\theta + \theta_0) - f_q \sin(\theta + \theta_0) + f_{u(1)} \cos 2\theta_0 - f_{v(1)} \sin 2\theta_0 \quad (21)$$

## Appendix I. Armature Flux Linkages

The machine will be assumed to be "ideal" as defined by Park.[11] The no-load per-unit space fundamental flux density at the armature surface will be (see figure 1)

$$\beta_0 = I_d \cos\Gamma + I_q \sin\Gamma \quad (1)$$

where

$\Gamma$ = angle along the armature surface measured in electrical radians from the rotor axis

$I_d$ = per-unit rotor excitation or rotor current in direct axis

$I_q$ = per-unit rotor excitation or rotor current in quadrature axis magnetizing ahead of the poles

The per-unit magnetomotive force due to armature phase currents $i_A, i_B, i_C \ldots i_N$ will be

$$A = -\frac{2}{n}\,[i_A \cos(\Gamma+\theta) + i_B \cos(\Gamma+\theta-\theta_0) + i_C \cos(\Gamma+\theta-2\theta_0) + \ldots + i_N \cos(\Gamma+\theta+\theta_0)]$$

$$= -\frac{2}{n}\cos\Gamma\,[i_A\cos\theta + i_B\cos(\theta-\theta_0) + i_C\cos(\theta-2\theta_0) + \ldots + i_N\cos(\theta+\theta_0)] + \frac{2}{n}\sin\Gamma\,[i_A\sin\theta + i_B\sin(\theta-\theta_0) + i_C\sin(\theta-2\theta_0) \times + \ldots + i_N\sin(\theta+\theta_0)] \quad (2)$$

where $\theta$ is the position of rotor axis measured from the axis of phase $A$, $\theta_0 = 2\pi/n$, $n$ = number of phases.

As the armature linkages for all space harmonics are assumed to be zero for the ideal machine, we have for the wave of per-unit flux,

$$\beta = I_d \cos\Gamma + I_q \sin\Gamma - \frac{2}{n} p_d \cos\Gamma\,[i_A\cos\theta + i_B\cos(\theta-\theta_0) + i_C\cos(\theta-2\theta_0) + \ldots + i_N\cos(\theta+\theta_0)] + \frac{2}{n} p_q \sin\Gamma\,[i_A\sin\theta + i_B\sin(\theta-\theta_0) + i_C\sin(\theta-2\theta_0) + \ldots + i_N\cos(\theta+\theta_0)] \quad (3)$$

The per-unit linkages in phase $A$ due to the flux are equal to the value of $\beta$ at $\gamma = \Gamma + \theta = 0$ or $\Gamma = -\theta$, i.e.,

$$\psi_{A(\beta)} = I_d\cos\theta - I_q\sin\theta - \frac{p_d+p_q}{n}\,[i_A + i_B\cos\theta_0 + i_C\cos 2\theta_0 + \ldots i_N\cos\theta_0] - \frac{p_d-p_q}{n}[i_A\cos 2\theta + i_B\cos(2\theta-\theta_0) + i_C\cos(2\theta-2\theta_0) + \ldots + i_N\cos(2\theta+\theta_0)] \quad (4)$$

The total per-unit linkages in phase $A$ are then

$$\psi_A = I_d\cos\theta - I_q\sin\theta - x_{l\sigma} i_A - x_m'\,[i_B\cos\theta_0 + i_C\cos 2\theta_0 + \ldots + i_N\cos\theta_0] - \frac{p_d+p_q}{n}\,[i_A + i_B\cos\theta_0 + i_C\cos 2\theta_0 + \ldots + i_N\cos\theta_0] - \frac{p_d-p_q}{n}\,[i_A\cos 2\theta + i_B\cos(2\theta-\theta_0) + i_C\cos(2\theta-2\theta_0) \times + \ldots + i_N\cos(2\theta+\theta_0)] \quad (5)$$

where

$x_{l\sigma}$ = per-unit self leakage reactance of any phase

$x_m'$ = maximum possible value of per-unit mutual leakage reactance between the phases. When $n$ is even, this is equal to the actual value between diametrically opposite phases. For 3-phase case, this is equal to twice the actual value between any 2 phases

Under balanced conditions of operation with normal armature current flowing, there is

$$i_A = \cos t$$
$$i_B = \cos (t - \theta_0)$$
$$i_C = \cos (t - 2\theta_0)$$
$$\cdots\cdots$$
$$i_N = \cos (t + \theta_0)$$
$$\theta = t + t_0$$

where $t_0$ = the value of $\theta$ at $t = 0$.
Then, for $I_d = I_q = 0$ there is

$$\psi_A = -\left[x_{l\sigma} + x_m'\left(\frac{n}{2} - 1\right) + \frac{p_d + p_q}{2}\right]\cos t - \left[\frac{p_d - p_q}{2}\right]\cos (t + 2t_0) \quad (6)$$

When $t_0 = 0$ there is

$$\psi_A = -(x_{l\sigma} + x_m + p_d)\cos t = -x_d \cos t \quad (7)$$

where

$$x_m = x_m'\left(\frac{n}{2} - 1\right)$$

$x_d$ = direct synchronous reactance[11,12]

When $t_0 = \pi/2$ there is

$$\psi_A = -(x_{l\sigma} + x_m + p_q)\cos t = -x_q \cos t \quad (8)$$

where $x_q$ = quadrature synchronous reactance
With zero phase-sequence currents impressed there is

$$i_A = i_B = i_C \ldots = i_N$$
$$\psi_A = -(x_{l\sigma} - x_m')i_A = -x_0 i_A \quad (9)$$

where $x_0$ = zero-sequence reactance
Thus we have obtained the following relations:

$$x_{l\sigma} + x_m + p_d = x_d$$
$$x_{l\sigma} + x_m + p_q = x_q$$
$$x_{l\sigma} - x_m' = x_0$$
$$p_d - p_q = x_d - x_q$$
$$p_d + p_q + 2(x_{l\sigma} + x_m) = x_d + x_q$$

Equation 5 can now be rewritten in the form

$$\psi_A = I_d \cos\theta - I_q \sin\theta - x_0 i_A - \left[\left(\frac{x_d + x_q}{2}\right) - x_0\right] \times \left(\frac{2}{n}\right)[i_A + i_B \cos\theta_0 + i_C \cos 2\theta_0 + \ldots + i_N \cos\theta_0] - \left(\frac{x_d - x_q}{2}\right)\left(\frac{2}{n}\right)[i_A \cos 2\theta + i_B \cos (2\theta - \theta_0) + i_C \cos (2\theta - 2\theta_0) + \ldots + i_N \cos (2\theta + \theta_0)] \quad (10)$$

Similarly we can write down the equations for the other phases.

## Appendix II. Transformation of Variables

The transformations between the phase quantities and the 2-reaction components will be given in the form of matrices as below:

$C_d{}^A =$

| | $A$ | $B$ | $C$ | $D$ | ..... | $N$ |
|---|---|---|---|---|---|---|
| 0 | $\frac{1}{n}$ | $\frac{1}{n}$ | $\frac{1}{n}$ | $\frac{1}{n}$ | ..... | $\frac{1}{n}$ |
| $d$ | $\frac{2}{n}\cos\theta$ | $\frac{2}{n}\cos(\theta - \theta_0)$ | $\frac{2}{n}\cos(\theta - 2\theta_0)$ | $\frac{2}{n}\cos(\theta - 3\theta_0)$ | ..... | $\frac{2}{n}\cos(\theta + \theta_0)$ |
| $q$ | $(-)\frac{2}{n}\sin\theta$ | $(-)\frac{2}{n}\sin(\theta - \theta_0)$ | $(-)\frac{2}{n}\sin(\theta - 2\theta_0)$ | $(-)\frac{2}{n}\sin(\theta - 3\theta_0)$ | ..... | $(-)\frac{2}{n}\sin(\theta + \theta_0)$ |
| $u_1$ | $\frac{2}{n}$ | $\frac{2}{n}\cos 2\theta_0$ | $\frac{2}{n}\cos 4\theta_0$ | $\frac{2}{n}\cos 6\theta_0$ | ..... | $\frac{2}{n}\cos 2\theta_0$ |
| $v_1$ | 0 | $\frac{2}{n}\sin 2\theta_0$ | $\frac{2}{n}\sin 4\theta_0$ | $\frac{2}{n}\sin 6\theta_0$ | ..... | $(-)\frac{2}{n}\sin 2\theta_0$ |
| : | : | : | : | : | ..... | ..... |
| : | : | : | : | : | ..... | ..... |
| $w$ | $\frac{1}{n}$ | $-\frac{1}{n}$ | $\frac{1}{n}$ | $-\frac{1}{n}$ | ..... | ..... |

For example, from the first row, we have $i_0 = \frac{1}{n}(i_A + i_B + i_C + i_D + \ldots + i_N)$

$C_A{}^d =$

| | 0 | $d$ | $q$ | $u_1$ | $v_1$ | ..... | $w$ |
|---|---|---|---|---|---|---|---|
| $A$ | 1 | $\cos\theta$ | $-\sin\theta$ | 1 | 0 | .... | 1 |
| $B$ | 1 | $\cos(\theta - \theta_0)$ | $-\sin(\theta - \theta_0)$ | $\cos 2\theta_0$ | $\sin 2\theta_0$ | ..... | $-1$ |
| $C$ | 1 | $\cos(\theta - 2\theta_0)$ | $-\sin(\theta - 2\theta_0)$ | $\cos 4\theta_0$ | $\sin 4\theta_0$ | ..... | 1 |
| $D$ | 1 | $\cos(\theta - 3\theta_0)$ | $-\sin(\theta - 3\theta_0)$ | $\cos 6\theta_0$ | $\sin 6\theta_0$ | ..... | $-1$ |
| : | : | : | : | : | : | ..... | ... |
| : | : | : | : | : | : | ..... | ... |
| $N$ | 1 | $\cos(\theta + \theta_0)$ | $-\sin(\theta + \theta_0)$ | $\cos 2\theta_0$ | $-\sin 2\theta_0$ | ..... | ... |

For $n$ odd, row $w$ or column $w$ should be omitted.
As a check, we have

$$C_A{}^d C_d{}^A = 1$$

The foregoing transformations may be derived in another way as follows:

According to the method of symmetrical components, we have

$C_1^A =$

| | $A$ | $B$ | $C$ | $D$ | ... | $N$ |
|---|---|---|---|---|---|---|
| 0 | $\frac{1}{n}$ | $\frac{1}{n}$ | $\frac{1}{n}$ | $\frac{1}{n}$ | ... | $\frac{1}{n}$ |
| 1 | $\frac{1}{n}$ | $\frac{a}{n}$ | $\frac{a^2}{n}$ | $\frac{a^3}{n}$ | ... | $\frac{a^{-1}}{n}$ |
| 2 | $\frac{1}{n}$ | $\frac{a^2}{n}$ | $\frac{a^4}{n}$ | $\frac{a^6}{n}$ | ... | $\frac{a^{-2}}{n}$ |
| ⋮ | ⋮ | ⋮ | ⋮ | ⋮ | ... | ... |
| $\frac{n}{2}$ | $\frac{1}{n}$ | $-\frac{1}{n}$ | $\frac{1}{n}$ | $-\frac{1}{n}$ | ... | ... |
| ⋮ | ⋮ | ⋮ | ⋮ | ⋮ | ... | ... |
| $n-2$ | $\frac{1}{n}$ | $\frac{a^{-2}}{n}$ | $\frac{a^{-4}}{n}$ | $\frac{a^{-6}}{n}$ | ... | $\frac{a^2}{n}$ |
| $n-1$ | $\frac{1}{n}$ | $\frac{a^{-1}}{n}$ | $\frac{a^{-2}}{n}$ | $\frac{a^{-3}}{n}$ | ... | $\frac{a}{n}$ |

$a = e^{j\theta_0}$ where $\theta_0 = \frac{2\pi}{n}$

For $n$ odd, row $n/2$ should be omitted.
The reverse transformation is

$C_A^1 =$

| | 0 | 1 | 2 | ... | $\frac{n}{2}$ | ... | $n-2$ | $n-1$ |
|---|---|---|---|---|---|---|---|---|
| $A$ | 1 | 1 | 1 | ... | 1 | ... | 1 | 1 |
| $B$ | 1 | $a^{-1}$ | $a^{-2}$ | ... | $-1$ | ... | $a^2$ | $a$ |
| $C$ | 1 | $a^{-2}$ | $a^{-4}$ | ... | 1 | ... | $a^4$ | $a^2$ |
| $D$ | 1 | $a^{-3}$ | $a^{-6}$ | ... | $-1$ | ... | $a^6$ | $a^3$ |
| : | : | : | : | : | : | : | : | : |
| : | : | : | : | : | : | : | : | : |
| $N$ | 1 | $a$ | $a^2$ | ... | ... | ... | $a^{-2}$ | $a^{-1}$ |

For $n$ odd, column $n/2$ should be omitted.

The correlation between the symmetrical components and the 2-reaction components are as follows:[9,10]

$C_d^1 =$

| | 0 | 1 | 2 | .... | $\frac{n}{2}$ | .... | $n-2$ | $n-1$ |
|---|---|---|---|---|---|---|---|---|
| 0 | 1 | | | | | | | |
| $d$ | | $\epsilon^{-j\theta}$ | | | | | | $\epsilon^{j\theta}$ |
| $q$ | | $-j\epsilon^{-j\theta}$ | | | | | | $j\epsilon^{j\theta}$ |
| $u_1$ | | | 1 | | | | 1 | |
| $v_1$ | | | $-j$ | | | | $j$ | |
| ⋮ | | | | ⋮ | | ⋮ | | |
| $w$ | | | | | 1 | | | |

All the empty spaces should be indicated by 0. For $n$ odd, column $n/2$ and row $w$ should be omitted.

$C_1^d =$

| | 0 | $d$ | $q$ | $u_1$ | $v_1$ | ..... | $w$ |
|---|---|---|---|---|---|---|---|
| 0 | 1 | | | | | | |
| 1 | | $\frac{1}{2}\epsilon^{j\theta}$ | $j\frac{1}{2}\epsilon^{j\theta}$ | | | | |
| 2 | | | | $\frac{1}{2}$ | $j\frac{1}{2}$ | | |
| ⋮ | | | | | | ... | |
| $\frac{n}{2}$ | | | | | | | 1 |
| ⋮ | | | | | | ... | |
| $n-2$ | | | | $\frac{1}{2}$ | $-j\frac{1}{2}$ | | |
| $n-1$ | | $\frac{1}{2}\epsilon^{-j\theta}$ | $-j\frac{1}{2}\epsilon^{-j\theta}$ | | | | |

All the empty spaces should be indicated by 0. For $n$ odd, column $w$ and row $n/2$ should be omitted.

Then we can get $C_A^d$ and $C_d^A$ from the relations:

$$C_A^d = C_A^1 C_1^d$$
$$C_d^A = C_d^1 C_1^A$$

Notice that $C_1^d$ and $C_d^1$ are of very simple form, and, since $C_A^1$ and $C_1^A$ are well known from the method of symmetrical components, $C_A^d$ and $C_d^A$ can be written down very simply without going through the details of matrix algebra.

## Appendix III. Derivation of 2-Reaction Flux Linkages

Substituting equation 2 into equations 3 and 4, we can derive the expressions for $\psi_d$ and $\psi_q$ as follows:
Consider $\psi_d$ first. From equation 3, we have

$$\psi_d = \frac{2}{n}[\psi_A \cos\theta + \psi_B \cos(\theta - \theta_0) + \psi_C \cos \times (\theta - 2\theta_0) + \ldots + \psi_N \cos\theta - (n-1)\theta_0]$$

Let us examine the different components of the phase flux linkages separately. The first component is $I_d \cos\theta$. Hence

$$\psi_{d(1)} = \frac{2}{n} I_d[\cos\theta\cos\theta + \cos(\theta - \theta_0)\cos(\theta - \theta_0) + \cos(\theta - 2\theta_0)\cos(\theta - 2\theta_0) + \ldots] = I_d$$

Similarly, for the second component $-I_q \sin\theta$, we get

$$\psi_{d(2)} = -\frac{2}{n} I_q [\sin\theta\cos\theta + \sin(\theta - \theta_0)\cos(\theta - \theta_0) + \sin(\theta - 2\theta_0)\cos(\theta - 2\theta_0) + \ldots] = 0$$

For the third component, $-x_0 i_A$, we have

$$\psi_{d(3)} = -\frac{2}{n} x_0 [i_A \cos\theta + i_B \cos(\theta - \theta_0) + i_C \cos(\theta - 2\theta_0) + \ldots]$$
$$= -x_0 i_d$$

The fourth component is as follows:

$$\psi_{d(4)} = \frac{2}{n}\left[x_0 - \left(\frac{x_d + x_q}{2}\right)\right]\left(\frac{2}{n}\right)[\{i_A + i_B\cos\theta_0 + i_C\cos 2\theta_0 + \ldots\}\cos\theta + \{i_A\cos\theta_0 + i_B + i_C\cos\theta_0 + \ldots\}\cos(\theta - \theta_0) + \{i_A\cos 2\theta_0 + i_B\cos\theta_0 + i_C + \ldots\}\cos(\theta - 2\theta_0) + \ldots]$$

Now we may combine the terms into the following groups:

$$\left(\frac{2}{n}\right)[i_A\cos\theta + i_A\cos\theta_0\cos(\theta - \theta_0) + i_A\cos 2\theta_0\cos(\theta - 2\theta_0) + \ldots] = i_A\cos\theta$$

$$\left(\frac{2}{n}\right)[i_B\cos(\theta - \theta_0) + i_B\cos\theta_0\cos(\theta - 2\theta_0) + \ldots + i_B\cos\theta_0\cos\theta] = i_B\cos(\theta - \theta_0)$$

So we get

$$\psi_{d(4)} = \frac{2}{n}\left[x_0 - \left(\frac{x_d + x_q}{2}\right)\right][i_A\cos\theta + i_B\cos(\theta - \theta_0) + i_C\cos(\theta - 2\theta_0) + \ldots]$$
$$= x_0 i_d - \left(\frac{x_d + x_q}{2}\right) i_d$$

For the fifth component, we have

$$\psi_{d(5)} = -\frac{2}{n}\left(\frac{x_d - x_q}{2}\right)\left(\frac{2}{n}\right)[\{i_A\cos 2\theta\, i_B\cos(2\theta - \theta_0) + i_C\cos(2\theta - 2\theta_0) + \ldots\}\cos\theta \{i_A\cos(2\theta - \theta_0) + i_B\cos(2\theta - 2\theta_0) + i_C\cos(2\theta - 3\theta_0) + \ldots + \ldots\}\cos(\theta - \theta_0) \{i_A\cos(2\theta - 2\theta_0) + i_B\cos(2\theta - 3\theta_0) + i_C\cos(2\theta - 4\theta_0) + \ldots\}\cos(\theta - 2\theta_0) + \ldots]$$

Grouping the terms together, there is

$$\left(\frac{2}{n}\right)[i_A\cos 2\theta\cos\theta + i_A\cos(2\theta-\theta_0)\cos(\theta-\theta_0) + i_A\cos(2\theta-2\theta_0)\cos(\theta-2\theta_0)+\ldots] = i_A\cos\theta$$

$$\left(\frac{2}{n}\right)[i_B\cos(2\theta-2\theta_0)\cos(\theta-\theta_0) + i_B\cos(2\theta-3\theta_0)\times\cos(\theta-2\theta_0)+\ldots+i_B\cos(2\theta-\theta_0)\cos\theta] = i_B\cos(\theta-\theta_0)$$

So we have

$$\psi_{d(5)} = -\frac{2}{n}\left(\frac{x_d-x_q}{2}\right)[i_A\cos\theta + i_B\cos(\theta-\theta_0) + i_C\cos(\theta-2\theta_0)+\ldots] = -\left(\frac{x_d-x_q}{2}\right)i_d$$

The sum of 5 components gives

$$\psi_d = I_d - x_d i_d$$

For the quadrature flux linkages, we can derive the expression in a similar manner. The different components will be

$$\psi_{q(1)} = -\frac{2}{n}I_d[\cos\theta\sin\theta + \cos(\theta-\theta_0)\sin(\theta-\theta_0)+\ldots] = 0$$

$$\psi_{q(2)} = \frac{2}{n}I_q[\sin^2\theta + \sin^2(\theta-\theta_0)+\ldots] = I_q$$

$$\psi_{q(3)} = \frac{2}{n}x_0[i_A\sin\theta + i_B\sin(\theta-\theta_0)+\ldots] = -x_0 i_q$$

$$\psi_{q(4)} = -\frac{2}{n}\left[x_0-\left(\frac{x_d+x_q}{2}\right)\right][i_A\sin\theta + i_B\sin(\theta-\theta_0)+\ldots] = x_0 i_q - \left(\frac{x_d+x_q}{2}\right)i_q$$

$$\psi_{q(5)} = -\frac{2}{n}\left(\frac{x_d-x_q}{2}\right)[i_A\sin\theta + i_B\sin(\theta-\theta_0)+\ldots] = \left(\frac{x_d-x_q}{2}\right)i_q$$

The sum of the above 5 components will then give

$$\psi_q = I_q - x_q i_q$$

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# Fuels of Tomorrow

FUELS of today and tomorrow were discussed by A. C. Fieldner, retiring president, American Society for Testing Materials, in his presidential address at the annual meeting of the society held in New York, N. Y., June 28–July 2, 1937. Doctor Fieldner first covered fuels of today, including such topics as the search for oil, developments in refining petroleum, displacement of coal by fuel oil, rise of natural gas, and coal production and utilization. After discussing fuels of today and outlining national fuel reserves, he discussed fuels of tomorrow, indicating that gas, oil, and coal are available today in abundance. There is coal enough for hundreds, and possibly thousands of years; but natural gas and oil obtainable by present methods may be exhausted in less than 100 years, and a shortage of our domestic supply may begin within 10 or 20 years.

He indicated that coal will continue to be the principal fuel used for the generation of public utility and major industrial power. Technologic improvements and new hydroelectric power will tend to reduce the consumption of coal; on the other hand, an increasing demand for energy and a decreasing supply of cheap residual oil will increase the amount of coal consumed for power purposes. No material change is expected in either direction in the near future, but in 10 or 15 years the trend will favor increased consumption of coal. Tomorrow's power and central heating plant will burn any kind of coal completely and efficiently.

The convenience and uniformity of automatic heating of homes with gas or oil will continue to attract more users, even at higher costs than those prevailing today. The insulation of houses has been improved greatly, and future homes will permit higher unit cost of fuel without increasing the total heating bill.

Referring to railroad and marine fuels he indicated that further improvements in the over-all efficiency of the steam locomotive and a gradual increase of electrification will retain the use of coal for freight traffic throughout the age of oil and natural gas, and that the convenience and economy of Diesel-engine drive for ships and boats is such that its use will continue even after declining production of petroleum requires the production of Diesel fuel from shale or coal.

In discussing the motor fuel supply, one of the most interesting questions, he pointed to the prediction of Snider and Brooks that by 1945 there is the probability of considerable shortage of domestic petroleum. Doctor Fieldner said that from the very beginning of the automobile industry, recurring threats of shortage of gasoline were met—in the field by finding new pools and improving production technique, and in the refinery by increasing yields and making a more efficient product. "The end has not been reached. We are just beginning to use scientific methods in extracting oil from the sands, and catalytic polymerization and hydrogenation eventually will furnish the means for complete conversion of volatile liquids and heavy petroleum to gasoline."

# Discussions

## Of AIEE Papers—as Recommended for Publication by Technical Committees

ON THIS and the following 2 pages appear all remaining discussions submitted for publication, and approved by the technical committees, on papers presented at the 1937 AIEE winter convention, New York, N. Y., January 25–29. Discussions of papers presented at the sessions on general power applications, vibration and balance, communication and research, power transmission, education, power generation and electrical machinery, instruments and measurements, insulation co-ordination, and lightning protective equipment at the 1937 AIEE summer convention, Milwaukee, Wis., June 21–25, now are being reviewed by the technical committees, and will appear in ELECTRICAL ENGINEERING as they are released for publication.

Members anywhere are encouraged to submit written discussion of any paper published in ELECTRICAL ENGINEERING, which discussion will be reviewed by the proper technical committee and considered for possible publication in a subsequent issue. Discussions of papers scheduled for presentation at any AIEE meeting or convention are closed 2 weeks after presentation.

## Watt-Hour Meter Bearings

**Discussion and authors' closure of a paper by I. F. Kinnard and J. H. Goss published in the January 1937 issue, pages 129–37, and presented for oral discussion at the instruments and measurements session of the winter convention, New York, N. Y., January 28, 1937.**

**F. C. Holtz** (Sangamo Electric Company, Springfield, Ill.): To me, there are few subjects which offer greater possibilities for scientific adventure and speculation than the study of watt-hour meter bearings. No branch of physics or chemistry seems able to escape being involved in this problem in at least one form or another. It offers a challenge to the best we have in modern scientific technique, in the fine structure and architecture of solids and it plays with stresses seldom considered in modern machinery. Any familiarity with the problem reveals that the great mass of knowledge is still to be gained from carefully planned investigation.

One cannot help but be impressed by the long list of references which is only one indication of the great commercial importance attached to the problem and the desire to further improve what for a time seemed incapable of improvement. Beginning with the work of Shotter and others, it was quite evident that practical improvement lay in the direction of materials rather than of form and the present work is without question a valuable and important contribution.

I trust, in commenting on the present paper, it will not be out of order to draw on the experience of others and to relate certain conclusions which we are able to draw from our own observations.

The success of any bearing system must be judged from the results obtained in the field under all possible conditions of installation and use.

Because of the wide variation in these conditions the application of statistical methods are very helpful in determining the success of any particular arrangement and from this point of view we, as manufacturers, are very grateful for the friendly co-operation and assistance which we received from the public utilities in the form of data on the many millions of meters scattered throughout the country. All experimental data should be examined in its relation to the practical aspects of the problem.

The present paper is for the most part a record of laboratory experiment and from that standpoint is extremely interesting and satisfying to the user of meters in pointing out the care and consideration which is given to the problem before a commercial arrangement is arrived at.

Figure 2 is extremely interesting in showing how the friction varies with pivot radius; however, it should be pointed out that it is also a function of the jewel radius. Strictly speaking, it is probably a function of the order of contact between the 2 surfaces and from this point of view it would be interesting to know how this friction varies as the jewel radius approaches that of the pivot. The values indicated by the authors are very close to what might be considered an average throughout the industry. They are somewhat smaller than the values chosen a few years ago due to the lighter weight moving systems, higher expected values of overload, which together with higher torque gives a greater tendency for the pivot to ride on top of the jewel. While other means are provided to prevent it, the deeper and smaller radius cup is the ideal arrangement.

While the curve of figure 3 is extremely interesting, it is to be noted that in watt-hour meter practice meter pivots are seldom worn at the point. This, as is well known, is due to the fact that both driving and damping torques act to force the pivot up the side of the meter jewel until the forces are balanced, leaving the point of contact at some suitable distance from the axis of the pivot. At light load this is near the stationary position, but in this case the speed of rotation is small, hence no great amount of wear is to be expected. In some respects this is fortunate for if wear results at the higher loads the corresponding friction does not appreciably alter the meter registration; yet during periods of light load the pivot returns to put into contact areas which are little affected and which again has little effect on the initial accuracy. I should like at this time to refer to the curves of figure 7 which, in the light of past experience seems to be an anomalous behavior of materials. It is generally agreed that the pivot-and-cup type of bearing is improved by oiling and that its life is correspondingly increased. The work of Stott, Shotter, and others points very clearly to this conclusion and I am sure that it has been thoroughly supported by field observation. It certainly must be true for a great variety of materials, if not all. Why, then, does the oiled cobalt-tungsten pivot wear as rapidly as dry steel in the beginning and then slow down to that of dry cobalt tungsten at 10,000,000 revolutions, and then less with advancing revolutions?

It would be interesting also to know something of the performance of the oiled steel pivot drawn to the same scale for comparative purposes.

Figure 7 is apt to give the impression that a pivot begins to wear the instant it begins rotation. This may be true of some alloys and even steel in the dry state, but it is not necessarily true of an oiled steel pivot. I have tried to form an opinion based on the great mass of evidence supplied by the operating companies. There is ample evidence in support of the contention that wear begins with some unfortunate accident to the bearing system, the nature of which is, as yet, not fully understood. We know, for example, that some pivots will apparently operate for millions of revolutions without showing more than a trace of wear and then without warning increase rapidly at a fairly uniform rate somewhat as shown in figure 7. It is as if Mr. Kinnard's curves did not all start in the same place but chose to distribute themselves out along the axis of revolutions in some quite arbitrary manner. This type of action is hinted at in Shotter's paper, but so far as I know it has not been recorded in the form of a curve. If this were not true, we could readily predict the exact number of revolutions which a meter should make before changing bearings. I believe that I have the support of the meter man in the above statement based on a systematic and careful examination of meter pivots removed at the time of periodic test. It would be extremely interesting to carefully measure the radius of worn areas on a relatively large number (say 1,000) of meter pivots and plot these results in terms of meter revolutions. This will require that the work be followed in a territory where conditions are fairly uniform both as to loads, methods of handling, etc.

The impact tests are extremely interest-

ing in pointing out the manner in which jewels and pivots may be damaged by short circuit conditions. We conducted tests some years ago to determine the relative susceptibility of jewels of various types and orientation to damage by impact. To eliminate certain types of errors and render the results more uniform and dependable, the arrangement provided for applying the impact at the center and thinnest section of the jewel. To do this the jewel was mounted on a relatively massive iron anvil. A small steel ball was placed in the jewel which combination then received the impact from a small hardened steel cylinder dropped through a small tube from varying heights. In this case the impacts were repeated on the same jewel from varying heights until microscopic examination revealed that the jewel had been damaged.

The results show clearly that to obtain consistent results considerable care is necessary in properly mounting the jewel and that the results are influenced by the nature of the back surface of the jewel.

The subject of pivot materials is in itself a most interesting one, and I should like to discuss it according to the 6 qualities laid down by the present authors:

1. *Noncorrosive.* The question of corrosion resistance is, so I am told, tied up with 2 different properties of the metal or alloy. The first assumes that the metals are relatively inert as to forming chemical combinations with the compounds with which they may be in contact. Gold, platinum, osmium, tungsten, and other noble metals belong to this group. They achieve their corrosion resistances through their extreme stability and refusal to readily form compounds.

The second group are those which are relatively active, chemically, and readily form oxide layers over their surfaces which in themselves are chemically inactive. Aluminum and stainless steels belong to this class.

It should be quite obvious that materials of the second class should not be considered acceptable for meter pivots since the abrasive action of the jewel and pivot in contact will remove this oxide covering and expose the under layer to further corrosion. This explains why, under certain conditions a stainless steel pivot will show considerable quantities of red iron oxide after having operated dry in a meter bearing. All such oxides are invariably hard, brittle, and therefore quite abrasive.

2. *Nonabrasive.* A careful examination of the abraded material also raises an interesting question: Are the products of abrasion dependent upon the abrasive qualities of the constituent alloys or do the oxides of such alloys have qualities which are independent of them?

If they depend upon the individual constituents, it would be an easy matter to say which metals should and which should not form a satisfactory combination for a meter pivot. The problem is not so simple for the abrasive qualities of the material removed frequently does not resemble any of its constituents. The former is, nevertheless, a safe guide to follow. Oxides of tungsten and cobalt are each relatively mild abrasives and so far as we know the oxide of the alloy is also. Shotter, in his paper, comments very favorably on tungsten which has been verified by further test, but it requires very careful preparation.

3. *Shock Resistance.* There are some extremely interesting things about the alloys suitable for pivot materials. In addition to the corrosion resistance already referred to, there is the property of hardness.

I am inclined to feel from numerous tests that extreme hardness is essential to abrasion resistance. This follows from a consideration of diamond and sapphire as jewel materials and it is equally true in pivot materials. It may, however, be possible for a pivot material to be so hard as to resist wear, and when used against sapphire, wear the latter.

In most cases the reverse is true, but in some cases such as in alloys containing comparatively large percentages of iridium the pivot will actually cut the jewel, especially when run dry.

Frequently the presence of minute inclusions of foreign matter in the pivot material may damage the jewel. It is extremely necessary, therefore, to watch alloys for the appearance of minute inclusions in any series of experiments to determine a suitable material.

The present paper refers to cobalt-tungsten alloy as being softer than steel. In one sense this is true and in another it is not. Cobalt-tungsten alloy as with other alloys, especially precipitation hardening alloys, comprises a series of hard crystals in a matrix of softer material. For this reason the material is soft from the standpoint of deformation and hard from the standpoint of wear. This property of the structure is shown when determining superficial hardness. A perfectly conical diamond penetrator will frequently leave a triangular shaped depression showing that the hard crystals are moved about as a body in a matrix of softer material.

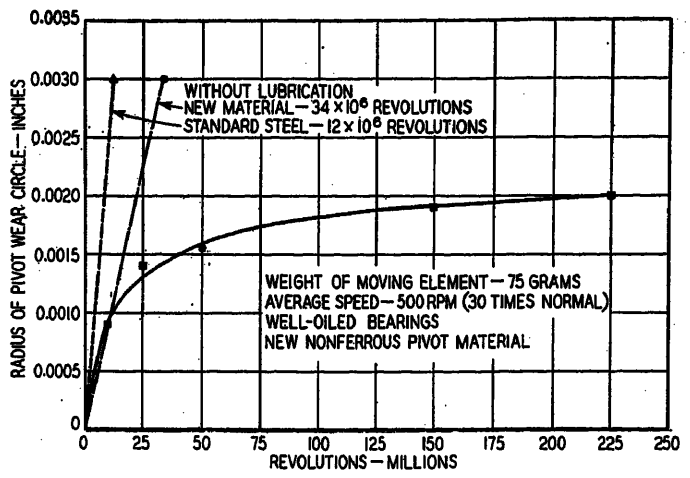
No comment will be made on the last 2 properties; namely, low friction and workability, since this in itself involves a consideration of many materials. I should, however, remark that certain alloys of osmium, rhodium, and platinum show great promise as pivot materials and it is hoped that the cost can be brought within permissible figures.

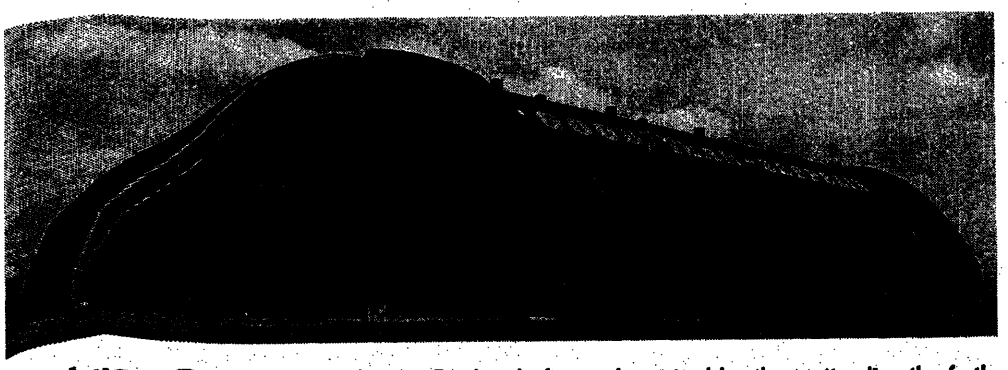
In pointing to the possibility of operating the cobalt-tungsten pivot without oil, no mention is made of the relative friction in each case and the variation in friction over long periods of operation. It would be interesting to know something of this.

4. *Lubrication.* With the rapidly growing tendency toward outdoor meter installations, the matter of lubrication is extremely important and the qualities outlined by the authors is an excellent guide in the selection of a suitable lubricant. In general the mineral oils have a somewhat greater tendency to creep but this can be reduced by suitably applying to the surfaces a mixture known to the watchmaking industry as "epilame." Its essential ingredients are steric acid in toluene, and when applied its thickness is of molecular dimensions.

In addition to chemical tests, certain simple mechanical tests are extremely useful in detecting any undesirable qualities. A small quantity of the oil is placed in a hemispherical cup which is alternately rotated and stopped in the presence of warm

**Figure 7. Accelerated life test wear curves**



The huge Goodyear Zeppelin Air Dock, which may be visited by those attending the forthcoming AIEE Middle Eastern District meeting to be held at Akron, Ohio

air or oxygen. Centrifugal action drives the oil over the surface in a thin layer and then allows it to settle to the bottom. This test will quickly reveal any tendency toward gumming and frequently reveals conditions which cannot be detected by chemical tests. It corresponds to an accelerated service test and is therefore of considerable value.

**I. F. Kinnard and J. H. Goss:** The discussion of the paper, especially by Mr. S. Green, Mr. F. C. Holtz, and Professor M. W. Pullen has brought out much information of interest to users and designers of watt-hour meters. Some of the points raised require further discussion by the authors.

Mr. F. C. Holtz has referred to the effect of the radius of the jewel cup on the value of friction torque between the pivot or ball and the jewel cup. Mr. V. Stott (reference 2 of the bibliography) has shown by a mathematical analysis that a negligibly small error is introduced if the radius of the jewel cup is assumed to be infinite over the small area of contact of a new bearing within the range of radii for pivots, balls, and jewels which are used commercially.

Figure 7, which Mr. Holtz questions, was plotted in error and the authors are pleased to include in this discussion a corrected figure. It will be noted that the oiled cobalt-tungsten bearing follows almost exactly the same wear curve as the dry for the first few million revolutions. A possible explanation for this behavior is that due to the extremely high bearing pressures during this period, little or no lubrication is present under the contact area. As the bearing wears, the pressure drops until the oil film is eventually able to support the load.

There is no question but that many bearings have been operated for long periods without showing appreciable wear. The phenomena of just what initiates wear is difficult to understand. It has been the aim of the authors to present data to permit a logical explanation of the major factors that influence watthour meter bearing life. At this time it appears to be impossible to fully explain every case.

Mr. Holtz suggests it would have been worth while to publish the wear curve for a well oiled steel pivot along with the curve of cobalt-tungsten shown in figure 7. Such a curve was published in a previous article (reference 1 of the bibliography) and for that reason was omitted.

Professor Pullen brings up the point of preforming the radius of the pivot contact area to match the jewel. There has been no change in pivot manufacturing methods to allow the exact matching of the pivot and jewel radius.

The radius of a pivot can be quite accurately ground while somewhat greater variations are found in sapphire jewel cups.

The hardness of boron carbide, figure 5, was plotted in error and should be 19.7 instead of 29.

Figure 10 showing the oxidation of oils should show a total range of acidity of 1.0 per cent instead of 10 per cent. The ordinates should be tenths of a per cent, the decimal points being omitted.

The authors wish to express their appreciation for the favorable discussion of their paper by Doctor H. B. Brooks and by Mr. E. W. Allen.

# First Report of Power System Stability

**Closure of a report of the AIEE subcommittee on interconnection and stability factors published in the February 1937 issue, pages 261–82, and presented for oral discussion at the power transmission session of the winter convention, New York, N. Y., January 26, 1937. Previous discussions and closure appeared in the May 1937 issue, pages 632–4.**

**R. D. Evans:** Raymond Bailey, H. K. Sels, and Nicholas Stahl have called to our attention the fact that table III contains certain discrepancies as applied to the Pennsylvania-New Jersey interconnection. It is believed that these can best be clarified by republishing part of the table. The accompanying tabulation supersedes item I for the Pennsylvania Power & Light Company and the next 5 columns headed "Pennsylvania and New Jersey Interconnection."

Mr. Bailey has also pointed out certain errors in table III as applying to the Philadelphia Electric Company's system. Under item I for the Conowingo-Plymouth Meeting circuit, line *B*-5 should show "H.T." bus at both sending and receiving ends; and line *E*-2 should show:

Phase: High-speed differential induction impedance.

Ground: High-speed differential and high-speed overcurrent.

Under item II for the Plymouth Meeting-Westmoreland circuit, line *B*-5 should also show "H.T." bus at both sending and receiving ends; and under line *B*-2 should show:

Phase: Induction impedance.
Ground: High-speed directional overcurrent.

**Table III. Recent Practices Regarding Stability Studies**

| | Pennsylvania and New Jersey Interconnection | | |
|---|---|---|---|
| | Pennsylvania Power & Light Company<br>Philadelphia Electric Company<br>Public Service Electric and Gas Company | | |
| | Item I<br>Plymouth Mtg.-Siegfried | Item II<br>Plymouth Mtg.-Roseland | Item III<br>Siegfried-Roseland |
| **A. Transmission** | | | |
| 1. Voltage, kilovolts | 220 | 220 | 220 |
| 2. Distance, miles | 48.7 | 75.8 | 83.7 |
| 3. Frequency, cycles | 60 | 60 | 60 |
| 4. Power, kilowatts sent out | 185,000† | 185,000† | 185,000† |
| **B. Circuit arrangement** | | | |
| 1. Number of circuits | 1 | 1 | 1 |
| 2. Intermediate Switching station | None | None | None |
| 3. Load taken off at intermediate points, kilowatts | None | None | None |
| 4. Synchronous condenser, kva at intermediate points | None | None | None |
| 5. Bussing arrangements | | | |
| *a.* Sending end | H.T. | H.T. | H.T. |
| *b.* Receiving end | H.T. | H.T. | H.T. |
| 6. Grounding | | | |
| *a.* Sending end | Solid | Solid | Solid |
| *b.* Receiving end | Solid | Solid | Solid |
| **C. Generator** | | | |
| 1. Kilovolt-amperes | Intersystem tie | Intersystem tie | Intersystem tie |
| 2. Short circuit ratio | | | |
| 3. Transient reactance | | | |
| 4. Inertia constant | | | |
| 5. Damper winding | | | |
| **D. Excitation system** | | | |
| 1. Exciter response | | | |
| **E. Breakers and relays** | | | |
| 1. Breaker speed, cycles | 8–12 | 3.5–8 | 3.5–10 |
| 2. Relaying type* | Phase: Directional Impedance<br>Ground: Hi-speed Directional Overcurrent | (Same as item I) | (Same as item I) |
| 3. Total time, cycles** | Phase: 9–75<br>Ground: 9–35 or 70–90 | Phase: 9–75<br>Ground: 9–35 or 50–100 | Phase: 12–60<br>Ground: 12–30 or 60 100 |
| **F. Lightning protection** | | | |
| 1. Tower construction | Steel | Steel | Steel |
| 2. Ground wires | 2 | 2 | 2 |
| 3. Counterpoises | None | None except gndg. cable at high-res. tower footings | (Same as item II) |
| 4. Insulators | Susp.: 16 5-3/4" Units<br>Deadend: 18—same | Susp.: 16 or 18 5-3/4" units<br>Deadend: 18 or 20—same | Susp.: 14, 16, or 18 5-3/4" units<br>Deadend: 18 or 20—same |
| 5. Lightning arresters | Plymouth Mtg. only | Plymouth Mtg. only | None |

* Note: High-speed directional impedance phase relays installed at Plymouth Meeting end of items I and II.
** Note: In certain cases of sequential tripping, time given applies to first breaker only.
† Note: Based on thermal limitations.

# News

## Of Institute and Related Activities

# Middle Eastern District Meeting and Student Branch Convention

AKRON, OHIO, will be host to a 3-day meeting of the Middle Eastern District of the AIEE, October 13–15, 1937. The meeting headquarters will be in the Mayflower Hotel. The local committees have arranged an attractive technical program which consists of 6 sessions and a student session to be held during the mornings and have planned for the afternoons and evenings interesting inspection trips, entertainment, and a banquet. In addition, a special program has been arranged for the women, who are especially urged to attend the meeting.

Akron is called "The City of Opportunity." It is a prosperous, enterprising industrial community with a population of 255,000, ranking thirty-fifth in the United States as to population, but twelfth in the value of its manufactures. It is the world's largest rubber manufacturing center and the dirigible-airship-manufacturing center of the United States. The committee has taken full cognizance of these industries in the arrangement of inspection trips.

### Technical Program

A special effort has been made by the meetings and papers committee to arrange a technical program of a sufficiently diversified nature to offer general appeal to those in the electrical engineering profession. To accomplish this, parallel sessions will be held each morning, as shown in the program.

On Friday morning the student technical session will parallel the other 2 meetings. This session will be followed by a luncheon meeting in the Mayflower Hotel of Branch counselors and student chairmen. It is hoped that a minimum of conflict will occur on the part of those attending any particular series of sessions.

### Inspection Trips

Those attending the Middle Eastern District meeting will have an opportunity to see a representative cross section of the manufacturing and points of interest in Akron and vicinity. Transportation on all inspection trips by bus will be available at a nominal cost for those who desire it.

In addition to the scheduled inspection trips appearing on the program, a visit to the Goodyear Air Dock and the Goodyear Museum can be arranged for those interested by consulting a member of the registration committee in the hotel lobby.

Trips that are desired should be indicated at the time of registration at the meeting.

**Babcock & Wilcox Company**

The manufacturing operations of the Barberton plant to be seen will include the complete central station and industrial plant, high- and low-pressure steam boilers, pulverized coal equipment, economizers, air heaters, etc. To those interested in power plant equipment this trip offers an unusual opportunity to see the fabrication processes involved in a wide field of manufacture.

**B. F. Goodrich Company**

Those choosing this trip will see those manufacturing processes which characterize Akron as being "The Rubber City." Starting with the crude rubber as it is received from the native plantation, it will be followed through the various stages of cutting, plastication, mixing, milling, tubing, and curing to become a finished product in the form of a tire or tube.

**Nela Park**

An extensive tour has been arranged to be made through Nela Park, Cleveland, for those registered at the District meeting. The laboratory trip is scheduled to begin at 3:00 p.m. and will show the methods of development and manufacture of lamps. Following the tour through the laboratory there will be a discussion on lamp development and lighting research after which an inspection of the General Electric Lighting Institute will be made. Dinner will be given to guests at 6:30 and followed by an evening of popular entertainment.

Because of the many interesting displays of home applications this trip should be of equal interest to the ladies and has been arranged with this in mind.

**Ohio Brass Company**

An inspection of the Barberton plant of the Ohio Brass Company will be made starting from the main office building and will include inspection of the processes, production methods, and routine testing in the manufacture of high-voltage porcelain insulators for both station and line use. The plant inspection will be followed by a demonstration of normal-frequency and impulse tests on various insulator equipment. These tests will be made in the electrical testing laboratory.

**Daniel Guggenheim Airship Institute**

One of the main test stands of the Daniel Guggenheim Airship Institute is the vertical wind tunnel. It provides a uniform open air stream 6½ feet in diameter. Wind velocity can be regulated in small steps from zero to 125 miles per hour. This wind tunnel is driven by a 225-horsepower d-c motor and propeller-type fan, the electrical system being provided with various automatic and hand regulators and safety devices. This wind tunnel was built primarily for lighter-than-air testing, but is now being used also for airplane and various other industrial tests, for example, for testing the wind resistance of buildings and radio towers, the streamlining of trains, ventilating and cooling, etc. Some of the models used in such testing will be demonstrated.

The whirling arm is a unique apparatus, being the only one now in use in the United States for aeronautical testing. It is an arm 32 feet in length, turning at a height of 10 feet above the ground with



**Electrical testing laboratory of the Ohio Brass Company, Barberton, a few miles southwest of Akron. An inspection trip to this plant has been included on the program of the AIEE Middle Eastern District meeting to be held in Akron, October 13-15**

# Program

Eastern Standard Time

In this program, reference to the issue and, in so far as possible, to the page in ELECTRICAL ENGINEERING, is given for all papers.

## Wednesday, October 13

### 9:00 a.m.—Registration

### 9:45 a.m.—Opening of meeting

Address of Welcome: Lee D. Schroy, mayor of Akron

Response: I. Melville Stein, vice-president of Middle Eastern District

### 10:15 a.m.—Selected Subjects

Presiding: I. Melville Stein

A REVIEW OF RADIO INTERFERENCE INVESTIGATION, Frank Sanford and Willard Weise, Cincinnati Gas and Electric Company.
Scheduled for October issue

*NOTES ON RADIO INTERFERENCE, Grover Lapp, Lapp Insulator Company, Inc.

*RADIO DISTURBANCE MEASUREMENTS. W. S. Jennens and C. J. Miller, Jr., Ohio Brass Company.

*IMPROVEMENTS IN MINE VENTILATION, Theodore Troller, Guggenheim Airship Institute.

### 10:15 a.m.—Protective Devices

Presiding: Russell Krammes

*USE OF ELECTRONIC TUBES FOR RELAY PURPOSES, E. E. George, Tennessee Electric Power Company.

*THE ADVANCE IN INDUSTRIAL SWITCHGEAR, R. Paxton and F. E. Fairman, General Electric Company.

*THE DESIGN AND TEST OF A HIGH-SPEED HIGH-INTERRUPTING-CAPACITY RAILWAY CIRCUIT BREAKER, W. F. Skeats and H. E. Strong, General Electric Company.

### 2:00 p.m.—Inspection Trips

1. Babcock & Wilcox Company, Barberton, or
2. B. F. Goodrich Company, Akron

### 7:30 p.m.—Inspection Trip

Daniel Guggenheim Airship Institute

* These papers are scheduled for presentation, but at the time of going to press they have not been accepted for publication.

## Thursday, October 14

### 9:30 a.m.—Electrical Machinery

Presiding: A. M. MacCutcheon

*TRENDS IN THE DESIGN OF POWER TRANSFORMERS, L. H. Hill, Allis-Chalmers Manufacturing Company.

SINGLE-PHASE INDUCTION-MOTOR PERFORMANCE, A. F. Puchstein and T. C. Lloyd, Robbins and Myers, Inc. Scheduled for October issue

*5,000-KW. EXTRACTION TURBINE, W. S. Kramer, Westinghouse Electric & Manufacturing Company.

*ELECTRICAL APPLICATION IN RUBBER MILLS, John Grotzinger, R. S. Ferguson, and W. A. Brown, Goodyear Tire and Rubber Company.

### 9:30 a.m.—Electronics

Presiding: J. R. Martin

LOW-CURRENT IGNITORS, A. H. Toepfer, Westinghouse Electric & Manufacturing Company.
July, pages 810–12

REGULATION OF GRID-CONTROLLED RECTIFIERS, L. A. Kilgore and J. H. Cox, Westinghouse Electric & Manufacturing Company.
September, pages 1134–40

*THE IGNITER-TYPE MERCURY ARC RECTIFIER AS A POWER CONVERSION UNIT, A. Lee Barrett, Pittsburgh Coal Company.

*MERCURY ARC RECTIFIERS IN CHLORINE PRODUCTION, L. J. Rimlinger, Pittsburgh Plate Glass Co.

### 1:30 p.m.—Inspection Trip to Nela Park, Cleveland

### 6:30 p.m.—Dinner at Nela Park

### 8:00 p.m.—Popular Entertainment, Nela Park

## Friday, October 15

### 9:30 a.m.—Iron and Steel

Presiding: Wray Dudley

SOME HIGH LIGHTS IN THE USE OF ELECTRICITY IN STEEL MILLS, E. G. Fox, Freyn Engineering Company. September, pages 1115–23

CARBON BRUSHES FOR STEEL MILL EQUIPMENT, W. C. Kalb, National Carbon Company, Inc.
September, pages 1165–8

TENSION MEASUREMENT AND CONTROL IN COLD STRIP ROLLING, C. M. Hathaway and F. Mohler, General Electric Company.
September, pages 1141–4

### 9:30 a.m.—Power Transmission and Distribution

Presiding: F. W. Funk

*LIGHTNING-PROOF TRANSMISSION LINES, E. Hansson and A. F. Bang, Pennsylvania Water and Power Company.

LIGHTNING STROKES IN FIELD AND LABORATORY—II, P. L. Bellaschi, Westinghouse Electric and Manufacturing Company.
Scheduled for October issue

*PENNSYLVANIA RAILROAD ELECTRIFICATION, H. C. Griffith, Pennsylvania Railroad Company.

*POSSIBILITIES OF DIRECT CURRENT POWER TRANSMISSION USING ELECTRICALLY-CONTROLLED RECTIFIERS AND INVERTERS, O. K. Marti, Allis-Chalmers Mfg. Co.

*CROSS CATENARY TRANSMISSION LINES FOR LIGHTNING AND FOG CONDITIONS, A. O. Austin, Consulting and Manufacturing Engineer.

### 9:30 a.m.—Student Technical Session and Conference

Papers to be presented by students from each of the following schools:

Case School of Applied Science
Ohio University
Johns Hopkins University
West Virginia University
The University of Akron

### 12:00 noon—Luncheon Meeting of Branch Counselors and Student Chairmen

### 2:00 p.m.—Inspection Trip to Ohio Brass Company, Barberton

### 7:00 p.m.—Banquet

Presiding: Doctor W. E. Wickenden, president, Case School of Applied Science.

A message from President W. H. Harrison

Lighter-than-air craft will be discussed by Commander Rosendahl of the United States Naval Air Station, Lakehurst, N. J.

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a top speed up to 200 miles per hour. Airplane or airship models are attached to the end of this arm and their behavior in curved flight can be investigated and the air forces determined by means of suitable instruments. A wind tunnel used in connection with this whirling arm makes it possible to duplicate the effect of atmospheric gusts on aircraft, when the model attached to the arm is made to traverse the open jet of this tunnel. The air forces in this case are recorded by means of diamonds scratching on glass cylinders.

Another test stand, just now in development, is a water tank, in which the free movement of an airship under the influence of gusts is imitated. Water is used to obtain kinematic and dynamic similarity. The airship model in this tank may be seen describing a path similar to that of an airship in flight in gusty weather.

Among the instruments to be demonstrated is a hot-wire anemometer, which is used for the measurement of rapid fluctuations of air velocity in magnitude and direction. This hot-wire anemometer, consisting essentially of thin platinum wires in a Wheatstone bridge, heated electrically and cooled by the moving air, is an important instrument for laboratory and atmospheric investigations.

### WOMEN'S PROGRAM

A special invitation is extended to the women to attend the District meeting with their husbands. Particular attention has been given the program of activities by the ladies committee and everything will be done to make their visit an enjoyable one.

**October 13**

Morning—Registration
Luncheon—Mayflower Hotel
Afternoon—Garden pilgrimage, courtesy of Akron Garden Forum, Mrs. T. A. Chittenden, president
Evening—Informal dinner dance

**October 14**

Morning—Portage Country Club. Golf, games, or bridge
Luncheon—Portage Country Club
Afternoon—Nela Park, Cleveland
Evening—Nela Park, Cleveland

## Future AIEE Meetings

**Middle Eastern District Meeting**
Akron, Ohio, Oct. 13–15, 1937

**Winter Convention**
New York, N. Y., January 24–28, 1938

**North Eastern District Meeting**
Pittsfield, Mass., Spring 1938

**Summer Convention**
Washington, D. C., June 20–24, 1938

**Pacific Coast Convention**
Portland, Ore., date to be determined



**Cuyahoge Valley, Metropolitan Park, and high-level bridge in Akron, Ohio, in which city the forthcoming AIEE Middle Eastern District meeting will be held. The Gorge hydro-electric plant of the Ohio Edison Company may be seen just beyond the bridge, to the right**

**October 15**

Morning—Blimp rides
Luncheon—Y.W.C.A.
Afternoon—Bridge-tea at the home of A. O. Austin, Barberton
Evening—Banquet

### Student Conference

After the student technical session on Friday morning a luncheon conference of the Branch chairmen and counselors will be held in the headquarters hotel.

### Rules on Presenting and Discussing Papers

At the technical sessions, papers may be presented in abstract, 10 minutes being allowed for each paper unless otherwise arranged or the presiding officer meets with the authors preceding the session to arrange the order of presentation and allotment of time for papers and discussion.

Any member is free to discuss any paper when the meeting is opened for general discussion. Usually 5 minutes is allowed to each discusser for the discussion of a single paper or of several papers on the same general subject. When a member signifies his desire to discuss several papers not dealing with the same general subject, he may be allowed a somewhat longer time.

It is preferable that a member who wishes to discuss a paper give his name in advance to the presiding officer of the session at which the paper is to be presented. Each discusser is to step to the front of the room and announce, so that all may hear, his name and professional affiliations. Three typewritten copies of discussion prepared in advance should be left with the presiding officer.

Other discussions to be considered for publication should be typewritten (double spaced) and submitted in triplicate to C. S. Rich, secretary of the technical program committee, AIEE headquarters, 33 West 39th St., New York, N. Y., on or before October 29, 1937. Discussion of unpublished addresses and papers need not be submitted.

### Hotel Rates

Members should make room reservations by writing directly to the hotel of their preference. For convenience the rates of the headquarters hotel, the Mayflower, as well as the rates of other hotels are listed in Table I.

### Advance Registration

Members of the District who will attend the meeting should register in advance by returning the addressed advance-registration card which they will receive by mail. This will be helpful to the registration committee and permit badges to be prepared in advance and reduce the work necessary on the opening day to a minimum.

A minimum registration fee of $2.00 will be charged all nonmembers except Enrolled Students and the immediate families of members.

### Committees

The committees handling the various phases of the work in connection with the meeting are as follows:

**District Meeting Committee:** W. H. Harrison, I. Melville Stein, H. A. Dambly, A. G. Ennis, Paul Frederick, Warren C. Kalb, E E. Kimberly, E. O. Lange, and O. C. Schlemmer.

**General Committee:** Harold L. Brouse, chairman; A. O. Austin, Ralph Higgins, R. A. Hudson, H. C. Paiste, Harold H. Schroeder, V. W. Shear, and J. T. Walther.

**Meetings and Papers Committee:** A. O. Austin, chairman; T. F. Brandt, S. C. Henton, and H. L. Rorden.

**Entertainment and Reception Committee:** R. A. Hudson, chairman; Thomas Dee, R. P. Dunmire, W. C. Fick, Fred Nimmer, R. C. Putnam, A. P. Regal, W. A. Smith, and William H. Tucker.

**Hotels and Registration Committee:** Verne W Shear, chairman; George G. Clark, H. D. Duncan, F. A. Green, and P. C. Smith.

**Transportation and Inspection Committee:** H. C. Paiste, chairman; E. B. Crane, T. J. Newman, and N. W. Wing.

**Student Sessions Committee:** J. T. Walther, chairman; Kenneth Burgan, Carl Delagrange, Robert Miller, and P. D. Remark.

**Attendance and Publicity Committee:** Harold H. Schroeder, chairman; P. S. Bechtol, R. W. Drushel, and Louis McConaghy.

**Finance Committee:** Ralph Higgins, chairman; John Grotzinger, R. R. Krammes, and A. L. Richmond.

**Women's Committee:** Mrs. Ralph Higgins, chairman; Mrs. A. O. Austin, Mrs. J. W. Funk, Mrs. R. A. Hudson, and Mrs. Verne W. Shear.

**Table I Hotel Rates**

| Hotel and Location | Single Without Bath | Single With Bath | Double Without Bath | Double With Bath | Twin |
|---|---|---|---|---|---|
| Mayflower (headquarters), 259 S. Main St. | $ .... | $3.00 to 4.50 | $ .... | $5.00 to 6.50 | $5.50 to 6.50 |
| Portage, 10 N. Main St. | 1.75 | 2.00 to 3.00 | 2.75 | 3.00 to 4.50 | 4.00 to 6.00 |
| Akron, 92 E. Market St. | 1.50 to 1.75 | 2.00 to 2.50 | 2.50 | 3.00 to 3.50 | 3.50 |
| Howe, 11 S. Main St. | .... | 1.75 to 2.75 | .... | 3.00 to 3.25 | 4.00 |
| Anthony Wayne, 314 S. Main St. | 1.50 to 1.75 | 2.50 to 2.75 | 2.50 to 3.00 | 4.00 to 4.50 | .... |

**ASME Fall Meeting.** Papers on power, railroads, fuels, and petroleum are planned for the 1937 fall meeting of The American Society of Mechanical Engineers, which will be held at Erie, Pa., October 4–6. Inspection trips to several industrial plants, including that of the General Electric Company at which railroad equipment and refrigerator bodies are made, have been planned.

## Additional Awards for 1936 Institute Papers

In addition to the national and District prize awards for papers presented before the Institute during 1936 announced in ELECTRICAL ENGINEERING for June 1937, page 756, the awards for Districts 5 and 8 have now been announced. These awards are:

DISTRICT 5

**Prize for Branch paper awarded to Orville A. Becklund for his paper "An Artificial Ear for Sound Measurements," presented at a joint meeting of Minnesota Section and University of Minnesota Branch, April 21, 1937.**

DISTRICT 8

**Prize for best paper awarded to Joseph S. Carroll (A'24, M'37) and John A. Koontz Jr., (A'11, M'20) for their paper "Cable Vibration—Methods of Measurement," presented at the summer convention, Pasadena, Calif., June 22–26, 1936.**

**Prize for initial paper awarded to Otto A. Knopp (A'09, M'34) for his paper "Some Applications of Instrument Transformers," presented at the summer convention, Pasadena, Calif., June 22–26, 1936.**

## ECPD Offers Guides to Engineers

A pamphlet containing suggestions to junior engineers and another presenting a list of university extension facilities throughout the United States have been prepared by Engineers' Council for Professional Development. These pamphlets, together with 5 bibliographical pamphlets described in ELECTRICAL ENGINEERING for August 1937, page 1060, are intended to guide engineers in postcollegiate study.

In "Suggestions to Junior Engineers," a questionnaire is given to aid making a personal appraisal and a reading list to serve as a basis on which the nontechnical culture of the engineer can be continued. The pamphlet giving university extension facilities presents the scope of 54 courses and indicates their availability through class or correspondence study at more than 30 American institutions. The separate pamphlets can be had for 10 cents each, or for 5 cents each in lots of 50 copies, assorted if desired. Requests should be sent to Engineers' Council for Professional Development, 29 West 39th Street, New York, N. Y.

**Chemical Industries to Hold Exposition.** Plans for The Sixteenth Exposition of Chemical Industries, to be held at Grand Central Palace, New York, N. Y., December 6–11, 1937, are progressing rapidly. A feature of the exposition will be the award of a prize of $250 in cash to the person submitting the "best descriptive expression encompassing the purposes and the benefits redounding to the common good from the activities of the chemical industries." Raw materials, finished products, plant equipment, and machinery and apparatus will constitute major sections of the exhibits. Metals and alloys and the newer synthetic plastics and molded products likewise will be featured. Admission will be without charge, by registration or invitation only, and no tickets will be sold.

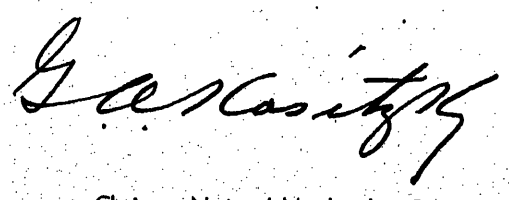
## Membership—

Mr. Institute Member:

Progress commands respect and admiration. Our Institute has gone forward consistently and the progress made in membership growth is just one of the many reasons for the pride we feel in being identified with this organization. There has been a steady gain in members during the past few years, and each year has had a larger gain than the preceding one. This progress was possible only because of the active assistance and support of the members—not only the officers and committeemen, but you and you. We appreciate your help and want to thank you.

Another year began on August 1. There will be new officers, new committees, and, of course, new members.

We are hopeful that the growth in members in this coming year may be greater than last year's increase. With your help it *will* be greater. We are again counting on your support.



Chairman National Membership Committee

## Aluminum Company Plans Expansion

Expenditures which may finally reach $15,000,000 will be necessary to provide added facilities for production of virgin aluminum and for additional fabricating units, electrical installations, housing facilities, and other auxiliary equipment in an expansion program contemplated by the Aluminum Company of America at Alcoa, Tenn. This expansion will require many additional employees with the likelihood that the present force of approximately 5,000 will be doubled when the program is completed. A contract with the Tennessee Valley Authority has been signed whereby the company secures at an early date a large quantity of power to augment the present supply from its own hydroelectric system.

Aluminum Company of America was attracted to this section more than 25 years ago because of the hydroelectric possibilities for an industry which finds cheap power one of the prerequisites for manufacture of its product at a price at which it can compete with other materials. Despite the fact that all the raw materials except power have to be brought into the state, the company found it desirable constantly to expand operations at Alcoa where the annual output now represents about 30 per cent of the virgin aluminum produced in the United States. Fabricating operations at Alcoa have been an important part of the company's manufacturing plants for semifinished and finished aluminum, for many years the largest aluminum sheet and plate mill in the country being located at this point.

To provide power for existing operations, the company has developed 3 large hydroelectric projects on the Little Tennessee River and its tributaries at Calderwood, Cheoah, and Santeetlah. It has several other dam sites for future use, one of which, on the Nantahala River, is already partially developed. Application for the completion of several of these projects is about to be made to governmental authorities.

In addition to the large sums spent in Tennessee and western North Carolina for power projects to serve the Alcoa works, the company has its own hydroelectric plants on the Yadkin River to provide power for an aluminum works at Badin, N. C. Most recent announcement of expansion in that section was the statement within the past month that the company is building a dam at Tuckertown.

**Engineering Society of Detroit Receives Gift.** Total endowment of The Engineering Society of Detroit, successor to the Detroit Engineering Society, has reached $1,000,000 with a second gift of $500,000 from The Horace H. and Mary A. Rackham Fund. The purpose of this gift is to provide a suitable building to be used by the society as a permanent home; income from the first half-million-dollar gift is to be used for operating expenses. The Engineering Society of Detroit is an entirely new organization with 12 affiliated groups and a membership which numbers nearly 3,000.

## Student Training in Air Conditioning

An extensive educational program designed to attract young men into the air-conditioning industry has been begun by the General Electric Company. The plan is modeled after the test courses started by the company in 1888.

The new program, although sponsored by the company itself, will be worked out through its distributors in the field, in the belief that the distributor organization offers wider practical experience and greater possibilities for the employment of the students. It will be open primarily to graduates of colleges, technical schools, and high schools who desire to establish themselves in the industry, but in special instances it may be open to men who have been otherwise employed, provided they demonstrate potential capabilities for the business. Because many phases of air-conditioning work involve engineering problems, the opportunity is generally greatest for those who have had technical training.

Practical manuals, courses, and distributor training activities have been designed by the General Electric air-conditioning department. They will be augmented by various forms of instruction in the field by district managers and factory men. Applications for training should be made to distributors or to the headquarters of the air-conditioning division of the company in Bloomfield, N. J.

## Conference Board Elects Officers

At its 21st annual meeting, the National Industrial Conference Board elected officers for the ensuing year. Elon H. Hooker, president of the Hooker Electrochemical Company, was elected chairman, and John Henry Hammond was elected honorary chairman. Doctor Virgil Jordan continues as president and chief executive of the board.

The following vice-chairmen were elected: Irenée du Pont, director, E. I. du Pont de Nemours and Company; E. Kent Hubbard, president, Manufacturers Association of Connecticut; Hon. Walter J. Kohler, chairman, Kohler Company; and W. Gibson Carey, Jr., president, Yale and Towne Manufacturing Company. Fred I. Kent, director of the Bankers Trust Company, was re-elected treasurer. Members of the executive committee elected for the ensuing year are:

Neal Dow Becker, president, Intertype Corporation, Brooklyn, N. Y.
E. R. Behrend, president, Hammermill Paper Company, Erie, Pa.
Philip E. Bliss, president, The Warner & Swasey Company, Cleveland, Ohio
Walter S. Case, president, Case, Pomeroy & Company, New York, N. Y.
S. Bayard Colgate, president, Colgate-Palmolive-Peet Company, Jersey City, N. J.
Arthur M. Collens, president, Phoenix Mutual Life Insurance Company, Hartford, Conn.
John F. Deasy, vice-president, Pennsylvania Railroad Company, Philadelphia
William C. Dickerman, president, American Locomotive Company, New York, N. Y.
James F. Fogarty, president, The North American Company, New York, N. Y.
David M. Goodrich, chairman, The B. F. Goodrich Company, Akron, Ohio
De Forest Grant, chairman, Federal Seaboard Terra Cotta Company New York, N. Y.
R. J. Hamilton, president, American Radiator Company, New York, N. Y.
John Henry Hammond, Hines, Rearick, Dorr & Hammond, New York, N. Y.
Howard Heinz, president, H. J. Heinz Company, Pittsburgh, Pa.
J. Taber Loree, vice-president, The Delaware and Hudson Railroad Corporation, Albany, N. Y.
Thomas Luke, president, West Virginia Pulp and Paper Company, New York, N. Y.
Auguste G. Pratt, president, The Babcock and Wilcox Company, New York, N. Y.
A. W. Robertson (A'27), chairman, Westinghouse Electric & Manufacturing Company, Pittsburgh, Pa.
David Sarnoff (M'23), president, Radio Corporation of America, New York, N. Y.
Malcolm B. Stone, president, Ludlow Manufacturing Associates, Boston, Mass.
J. A. Sweetser, president, Bigelow-Sanford Carpet Company, New York, N. Y.

Conference board councilors include:

Eugene G. Grace, president of the Bethlehem Steel Company
Cornelius F. Kelley, president of the Anaconda Copper Mining Company
L. F. Loree, president of the Delaware and Hudson Railroad Corporation
Hon. Andrew W. Mellon, Pittsburgh, Pa.
George M. Verity, chairman of the American Rolling Mill Company
Owen D. Young, chairman of the General Electric Company

## Isle Maligne Plant Reaches Designed Capacity

With the completion of the current installation of the twelfth 33,500-kva 112.5-rpm hydroelectric unit, the Isle Maligne Hydroelectric power station at the head of the Saguenay river about 100 miles north of Quebec will have been brought to the ultimate of its designed capacity of some 402,000 kva.

Described as "the largest single installation in water power development ever undertaken" up to that time, by the late W. S. Lee in his paper "Hydroelectric Development of the Saguenay River," (AIEE TRANS., v. 44, 1925, pp. 722–36), the project was authorized in December 1922, and the plant went into operation in 1925 with 8 units installed and space provided for 4 more. Located at the outlet of Lake St. John, the station is authorized to use the storage capacity of that lake between "ordinary low water and ordinary high water." Surveys established the permissible depth variation at 17.5 feet. which corresponded to an area variation from 328 square miles at low water to some 408 square miles at high water, and made available effective storage, of an estimated 187.1 billion cubic feet, adequate to serve effectively for the estimated 30,000-square-mile run-off area. Median operating head is 110 feet.

The magnitude of the project, its far-northerly location and the consequent severe winter weather conditions, and its distance from centers of transportation and civilization, made the project one of especial interest at the time of its construction. As described and discussed in some detail by Mr. Lee, "the design and layout of the construction plant were given as much attention.... as the design of the power house."

## Ford of Canada to Expand Power Plant

A power plant expansion program to cost about $3,500,000 has been undertaken by the Ford Motor Company of Canada, Ltd., at its Windsor plant, according to a recent announcement. The program provides for increased output, lower production cost, and the use of some of the original equipment without enlarging the present plant building.

The original plant consisted of 3 boilers each having a capacity of 100,000 pounds of steam per hour, each at a pressure of 235 pounds per square inch and a temperature of 580 degrees Fahrenheit; space was provided for a fourth boiler. Two turbogenerators were used, with capacities of 10,000 and 5,000 kw, respectively. When the present program is completed, the generating capacity will have been increased to 35,000 kw and the steam generating capacity to 600,000 pounds per hour. The ultimate development contemplated to be undertaken in the future will have a maximum output of 45,000 kw and a steam generating capacity of 800,000 pounds per hour.

The program now under way will include the installation of 3 new boilers and 2 new turbines, one of which will be a superposed unit exhausting into the existing 10,000-kw turbine. After careful study, a turbine throttle pressure of 800 pounds per square inch and temperature of 800 degrees Fahrenheit were selected as being most economical for this installation.

The 800-pound-pressure turbogenerator will be a 5,000-kw unit and will exhaust at 175 to 200 pounds pressure and 500 to 600 degrees Fahrenheit into the existing low-pressure 10,000-kw condensing turbogenerator, and in addition will supply steam for high-pressure process use. The other turbogenerator to be installed will be a 20,000-kw condensing double-bleeding unit. Both bleed points will be automatically controlled so that the turbine will furnish high-pressure process or low-pressure heating steam.

## Electrical Companies to Exhibit at 1939 Fairs

Plans for electrical exhibits at the New York World's Fair and the Golden Gate International Exposition are progressing rapidly, and several large electrical companies already have signed leases for exhibition space in the fair buildings or have contracted for lots on which they will erect their own exhibition structures.

Although no definite plans for individual company exhibits have been made public, the Westinghouse Electric & Manufacturing Company, which has contracted for a floor space of 10,922 square feet in the projected Electrical Production Building (see accompanying illustration) of the New York World's Fair, has announced that its exhibit will include demonstrations of scientific research and electrical applications in air conditioning, transportation, and lighting equipment, radio, television, and X rays. The General Electric Com-



**Photograph of a scale model of the Electrical Production Building to be constructed for the 1939 World's Fair at New York**

pany, expecting to present an amplification of its "House of Magic," a series of dramatic demonstrations of the achievements of electrical research, has signed a contract for a lot 68,339 square feet in area upon which it will build its own exhibition structure.

The Radio Corporation of America likewise has contracted for a lot space of 81,699 square feet. David Sarnoff (M'23) president, in describing the World's Fair plans of RCA said that the exhibit would show " . . . how radio safeguards the passage of ships at sea, and the flight of ships in the air, . . . how photographs are transmitted across the ocean by radio, . . . the most modern equipment for recording sound in motion-picture studios and reproducing it in theaters." Other attractions will include a radio communications center at the fair, so that visitors may send radiograms to any part of the world, an actual demonstration of what goes on behind the scenes in radiobroadcasting, and a public demonstration of television, whatever its status may be at the time of the exposition.

Other companies that have contracted for building space at the New York fair include: Bell Telephone System, 139,400 square feet (see June 1937 issue, page 766); Consolidated Edison Company of New York, Inc., 75,183 square feet; Johns-Manville, 29,317 square feet; American Gas Association, 122,008 square feet; and United States Steel Corporation subsidiaries, 55,166 square feet.

The Electrical and Communications Exhibits Building at the Golden Gate International Exposition will occupy a ground area of 89,400 square feet near the main portal of the exposition grounds. Westinghouse Electric & Manufacturing Company, General Electric Company, and the Bell Telephone System have signed contracts for exhibition space, and have indicated broadly the nature of their exhibits. The Westinghouse display will occupy nearly 5,000 square feet, and is expected to be a comprehensive showing of products for industry and household, mostly operating demonstrations of a scientific and educational character. The General Electric exhibits will be similar to those at the New York fair. The Bell System exhibit, which will occupy a space of approximately 7,000 square feet in the electrical building, will provide demonstrations in which the visitors themselves will participate, and will present new features in communications devices. The demonstration equipment is being designed by Bell Telephone Laboratories, Inc., will be erected by the American Telephone and Telegraph Company, and will be operated by The Pacific Telephone and Telegraph Company.

Several foreign nations have completed negotiations for sending scientific and commercial exhibits to both fairs, and many others have signified their intentions of being represented.

**Swedish Engineers Plan 1,500-Kilometer Line.** Leading Swedish electrical engineers recently met in Stockholm to discuss problems of the electrical industry in that country, among which was a consideration of the possibility of transmitting to southern Sweden the energy produced in the rich waterpower sources of the far North. A line from Krångede, in northern Sweden, to Malmö, in the extreme South, a distance of 1,000 kilometers (621 miles) already is under construction, and a 1,500-kilometer (930-mile) line is being considered. Aluminum is being used in increasing amounts in the construction of these long Swedish lines, and the Stockholm convention of engineers paid a visit to a modern aluminum plant producing 2,000 tons of aluminum per year electrolytically, with a power consumption of 40,000,000 kilowatt-hours of electrical energy.

**Standard for Welding Electrodes.** The first draft of a specification for coated electrodes for structural steel has been issued by the French committee for welding standards. Eleven diameters (0.04 to 0.51 inch) and 4 lengths (6 to 18 inches) are standardized. Four standard colors are given to electrodes according to their mechanical properties. Mechanical properties are determined on all-weld-metal specimens machined from a deposit made in an angle iron 10 inches long. The speed of welding must be such that the corners of the angle iron do not become red. Copies of the draft have been ordered by the American Standards Association for use of its members.

## New Generating Unit to Use 2,400-Pound Steam

According to a recent announcement of the American Gas and Electric Company, a new steam-electric generating unit to operate at the record pressure of 2,400 pounds per square inch and temperature of 940 degrees Fahrenheit will be installed in the Twin Branch station of one of its subsidiaries, the Indiana and Michigan Electric Company, Mishawaka, Ind. The decision to use such high pressure and temperature is the outcome of studies in high temperatures and pressures for generating units made by engineers of the company with the object of reducing plant investment and increasing operating efficiency, with full consideration to the financial soundness of investment.

The new unit will have a rating of 62,500 kw and will consist of a 22,500-kw 2,400-pound-pressure turbogenerator, cross-compounded with a new 40,000-kw 400-pound-pressure turbogenerator. This unit, together with the 2,500-pound-pressure boiler and accessory equipment, will entail an expenditure of some $4,000,000.

## Westinghouse Creates "New Products" Division

Responsibility for developments either new in the art or not previously undertaken by the company has been centralized by the Westinghouse Electric & Manufacturing Company of East Pittsburgh, Pa. in a newly formed "new products" division, according to a recent announcement. Functioning the same as the other operating units of the company, this division will include separate engineering, manufacturing, and sales departments.

The division will concentrate its facilities in developing and broadening the field of applications of products that have not reached the status of commercial apparatus. Then, after the field for each new product has been determined and the product has passed through the initial plant stage, the product will be taken over by one of the regular divisions. It is stated also that the new division will be responsible for training a staff that will be "adequate for the further promotion of the product."

**Technological Trends Studied by Government.** New inventions necessitate constant revision of national policies, according to a report of the National Resources Committee on "Technological Trends and National Policy," recently released by Chairman Harold L. Ickes, Secretary of the Interior. The first report on the science resources of the United States deals with new inventions and their social implications and calls attention to the need for planning to meet the new situations caused by technological advance. Prepared by a large group of scientists and engineers, the report "presents a survey of most of the fields of technology and applied science. . . . " The National Resources Committee urges that a series of continu-

ous studies be undertaken by existing planning boards and by appropriate agencies developed by the Federal Government, with the definite function of investigating and reporting on the progress and trends of science and invention, and the possible social and economic effects that may follow them. The report recommends that to study the technical aspects of the question the science committee of the Natural Resources Committee make an investigation of the adequacy of reporting on inventions and discoveries and advise on the feasibility of more balanced coverage, of selecting those more socially significant, and of assembling such data in some central location. Copies of the report are available from the Superintendent of Documents, Washington, D. C.

**More Boulder Dam Generators.** Contracts for the supply of 2 additional turbogenerator units to increase the generating capacity of the Boulder Dam plant to half of its full projected value of 1,835,000 horsepower recently were awarded. The new turbines, vertical-shaft units rated at 115,000 horsepower each, are to be constructed by the Allis-Chalmers Manufacturing Company. Contracts for the generating equipment were awarded to the Westinghouse Electric & Manufacturing Company. Already serving the city of Los Angeles and other municipalities in southern California are 4 3-phase 60-cycle units, each rated at 82,500 kva, with an output voltage of 16.5 kv. Of these, 2 were manufactured by the General Electric Company and 2 by the Westinghouse Electric & Manufacturing Company; in addition, the General Electric Company now is constructing 2 similar units, which will be completed in 1938. The units just contracted for will be ready for operation in 1939 and 1940.

**New York Building Code Now Permits Welding.** A new building code for the city of New York, N. Y., to become effective January 1, 1938, permits the use of welding in place of riveting in steel construction work. Previously, welding was prohibited because the existing code was formulated before modern welding methods were evolved. This action is congruous with New York's recent noise-abatement campaign; moreover, welded steelwork is advantageous in several other ways, being lighter, stiffer, creating more compact joints, and effecting an appreciable saving in the amount of steel required.

**Power Exposition to Be Held.** The Chicago (Ill.) Exposition of Power and Mechanical Engineering, to be held at the New International Amphitheatre, October 4–9, 1937, is expected to be one of the largest events of its kind ever held in the Midwest area, according to plans of its sponsors. Advance reports of machines and materials to be exhibited are said to be comprehensive and of interest to both executives and operators in the power and mechanical-engineering fields.

**Standard Symbols for Welding.** Realizing that welding cannot take its place as an engineering tool unless suitable means for conveying explicit information from designer to workman are provided, the American Welding Society has derived and published a set of standard welding symbols covering both fusion and resistance welding. The symbols, which are ideographic, have been made as simple as possible, and are based upon a principle of having the most common form of any weld require a minimum of numerical data. In effect the system amounts to a shorthand system with which a large amount of information may be transmitted in a few simple lines and figures. Complete information may be obtained from the American Welding Society, 33 West 39th Street, New York, N. Y.

# Current Items From American Engineering Council

## Who's Who in Engineering

Engineers and engineering organizations have a new directory and biographical dictionary in the fourth edition of "Who's Who in Engineering," which has just been published by the Lewis Historical Publishing Company, Inc., 8th Avenue and 14th Street, New York, N. Y. It is well done and is a most excellent reference volume. In addition to the biographical dictionary this issue carries a comprehensive list of engineering organizations in the United States and brief descriptions of each of several functional instrumentalities of engineering societies.

## Coal Price Fixing Is Here

Twenty-three district boards of code members managed by the National Bituminous Coal Commission in the Investment Building at 15th and K Streets, N. W., Washington, D. C., came into existence on June 21, 1937. All are authorized by the Guffey or Bituminous Coal Act of 1937, entitled "An act to regulate interstate commerce in bituminous coal and for other purposes." The principle objectives are the establishment of marketing rules and regulations, fixing minimum and maximum prices, and the prevention of unfair competition in the bituminous-coal industry.

The Bituminous Coal Act of 1937 also created a Consumers' Counsel to provide protection for all consumers of bituminous coals in the United States. The counsel has established headquarters in the Tower Building at 14th and K streets, N. W., Washington, D. C. "It shall be the duty of the Consumers' Counsel to appear in the interest of consuming public in any proceedings before the Commission, to offer testimony, examine witnesses or parties to the proceedings," and to have the Commission certify to information or conduct investigations of conditions believed to be responsible for unfair consumer prices.

American Engineering Council has been asked to assist Consumers' Counsel and the Commission with the location of engineers and engineer executives experienced in the several phases of the bituminous-coal industry and it has been invited to co-operate in bringing the objectives of these regulatory bodies to the attention of all engineers connected with or interested in bituminous-coal production, distribution, and consumption. Both agencies are seeking engineering advice and assistance with efforts being made to improve the soft-coal situation in the public welfare.

Engineering societies are urged to acquaint individual engineers and committees with the fact that the coal agencies "are now attempting to help establish fair minimum and maximum prices and are sponsoring the promulgation of rules and regulations regarding the production, marketing, and use of bituminous coal which may have far reaching effects on all fuel users as well as all fuel producers, dealers, etc." Results of such efforts are likely to change power and other industrial costs for which certain engineers may be directly or indirectly responsible.

Copies of the "Bituminous Coal Act of 1937, the Bituminous Coal Code, Taxes on the Sale or Other Disposal of Bituminous Coal, and Rules of Practice and Procedure before the National Bituminous Coal Commission" may be obtained directly from the agencies named, from the National Coal Association in the Southern Building, or from the Government Printing Office in Washington, D. C. The Counsel and the Commission invite correspondence and co-operation calculated to improve the present bituminous coal situation.

Most of the activities of these soft-coal agencies involve problems of more concern to trade associations than professional societies, but questions of potential importance to engineers employed in industry as well as those in consulting and private practice are having serious consideration. It is, therefore, suggested that engineers who are concerned with any phase of the bituminous-coal industry or the use of soft coal in other industries be urged to keep themselves advised regarding what is being done by these government regulatory bodies with soft-coal prices and the control of production, distribution, and consumption.

Consumers' counsel is John C. Carson of Michigan, former secretary to the late Senator Couzens. His principal assistants

are Ellery P. Gordon and W. L. Chandler. The commission is: Chairman, Charles F. Hosford, Jr., of Pennsylvania; Pleas E. Greenlee of Indiana, Thomas S. Hammond of Kentucky, John C. Lewis of Iowa, Walter H. Maloney of Missouri, C. E. Smith of West Virginia, and Percy Tetton of Ohio. Although the National Bituminous Coal Commission and the Consumers' Counsel were created jointly by the Bituminous Coal Act of 1937, they function as independent agencies of the Department of Interior under the administrative control of Secretary Ickes.

# Letters to the Editor

CONTRIBUTIONS to these columns are invited from Institute members and subscribers. They should be concise and may deal with technical papers, articles published in previous issues, or other subjects of some general interest and professional importance. ELECTRICAL ENGINEERING will endeavor to publish as many letters as possible, but of necessity reserves the right to publish them in whole or in part, or reject them entirely.

ALL letters submitted for consideration should be the original typewritten copy, double spaced. Any illustrations submitted should be in duplicate, one copy, to be an inked drawing but without lettering, and other to be lettered. Captions should be furnished for all illustrations.

STATEMENTS in these letters are expressly understood to be made by the writers; publication here in no wise constitutes endorsement or recognition by the American Institute of Electrical Engineers.

## AIEE Publications

*To the Editor:*

The recent discussion at the summer convention in Milwaukee, Wis., regarding Institute publications prompts me to send the following comments.

At the outset I want to express my keen appreciation of the excellent work that has been done by the publication committee and of the able manner in which the editorial work of ELECTRICAL ENGINEERING has been conducted. As a regular contributor to Institute publications I have had full co-operation. The work has been efficiently conducted and speedily and accurately executed. Nor is my experience unique in this respect. I believe that a survey will show that other contributors have a similar reaction to Institute publications.

I am also mindful of the excellent services rendered to the Institute by the technical program committee. They have given us excellent technical programs at all Institute conventions. They have introduced technical conferences at which ideas are exchanged freely by authorities in the field. Through their efficient and capable secretary they have given contributors prompt and courteous service which is beyond criticism.

It is not in the administrative aspects of Institute publications that the fault lies, it is rather in the quality of the articles that are submitted for publication.

If one were to classify the Institute membership according to their interests he would find the following classes:

*a.* The highly-specialized analytically-inclined members. This group comprises a rather small minority of the Institute membership. It is technically strong and is responsible for the majority of the papers published in ELECTRICAL ENGINEERING and the TRANSACTIONS.

*b.* The practicing engineers whose work is of a technical nature and who like to keep up with the progress of the art but who are not sufficiently specialized or analytically inclined to read and understand the majority of the published work. This group constitutes, by far, the largest minority (if not a majority) of the Institute membership.

*c.* The student and cadet engineers who have no practical background but who will form the future backbone of the Institute. They constitute a sizeable minority of the membership.

A few would question the fact that Institute publications should be so designed as to meet the needs and requirements of all the membership. The problem is how to modify the publications so as to accomplish this result.

I wish to submit a plan which would seem to solve this problem and which follows closely the general plan presented by the publication committee and has for its object the endorsement of the policies submitted by that committee. The plan consists of making the TRANSACTIONS and ELECTRICAL ENGINEERING 2 entirely distinct publications.

The TRANSACTIONS would comprise exclusively highly technical and highly specialized papers which contain new contributions to the art. Such papers would be submitted to the various technical committees of the Institute and would be earmarked by these committees as worthy of presentation at Institute conventions and of publication in the TRANSACTIONS. The TRANSACTIONS would thus become a publication which satisfies the needs of group *a* of the membership.

The journal ELECTRICAL ENGINEERING, since it is received by all the members of the Institute, would comprise articles of interest to the membership at large (groups *a*, *b*, and *c*). Papers published in ELECTRICAL ENGINEERING would also be submitted to the various technical committees but would be earmarked by these committees for publication in the journal. Such articles need not contain new contributions. The following types of articles might properly be published in ELECTRICAL ENGINEERING:

*a.* Expository articles, written in text-book form and readily understood by practicing electrical engineers and engineering students, on important recent developments in electrical engineering. The paper by Travis on per-unit quantities and Prentice's paper on fundamental concepts of synchronous machine reactances, form excellent illustrations of this class.

*b.* Articles on economic and social problems of the engineer. Hellmund's paper in the April 1937 issue of ELECTRICAL ENGINEERING and Spooner's paper in the December 1934 issue are typical of this class. I might also here include the excellent addresses of Doctor Bush and Doctor Flanders which were delivered at the Milwaukee convention.

*c.* Articles on recent developments in the basic sciences such as physics and chemistry written from the point of view of possible application in the practice of electrical engineering. The services of the committee on basic sciences (formerly the electrophysics committee) may be pressed for obtaining such papers.

*d.* Educational articles. Several articles on education have appeared in Institute publications. These articles have always aroused interest not only among educators but also among practicing engineers.

*e.* Descriptive articles of recent engineering projects. Such articles are of interest to utility and power engineers.

*f.* Articles on the professional aspects of engineering including engineering ethics, licensing of engineers, etc.

*g.* News of the Institute, its activities and its members. This section in ELECTRICAL ENGINEERING is read by practically all members.

*h.* Short abstracts, prepared by the authors, of all technical papers presented at Institute conventions and published only in the TRANSACTIONS.

*i.* Student papers which are awarded prizes or/and honorable mention.

*j.* Letters to the editor.

Having at last arrived at the letter *j* my imagination ceases to function so I shall close with the hope that the readers of this letter will take enough interest in this vital matter to communicate to you their reaction to this proposal.

Very truly yours,

MICHEL G. MALTI (M'34)
Assistant Professor of Electrical Engineering, Cornell University, Ithaca, N. Y.

## Most Economical Voltages For Incandescent Lamps

*To the Editor:*

Until recently the writer has seen nothing written explaining how to determine the most economical voltages at which to operate incandescent lamps. When purchasing Mazda lamps the consumer has the 110-115-, and 120-volt lamps from which to select. If the socket voltage happens to be, say 115 volts, it most certainly does not follow that the most economical lamp to buy will be the 115-volt lamp. This fact, and a method to determine which voltage lamp the purchaser should buy, the writer will attempt to explain in this article.

It is well known that if the operating voltage of a lamp is raised, the life of the lamp will be materially shortened, and the lumens output will be increased accordingly. If the operating voltage is reduced, the opposite effect will take place, that is, the life will be lengthened and the lumens output diminished. If the socket voltage is very low, the cost of lamp renewals will be almost eliminated, but the cost of electric power per lumen will be high. On the contrary, if the socket voltage is high, the lumens output will be increased, but the total cost per lumen-hour will be prohibitive because of the cost of lamp renewals. At some voltage in between these extremes (for any given lamp with a specified cost for power) lies the point at which the user can get the most lumen-hours for his money.

In the Bureau of Standards Research Paper No. 502, characteristic equations are

given for tungsten-filament vacuum and gas-filled lamps. They are of the form

$$y_n = A_n x^2 B_n + C$$

The equations express the relation of voltage to lumens output, to current, to watts input, and to the efficiency. In these equations the variable $x$ is the logarithm of the ratio of any voltage to that voltage at which a lamp operates when it emits light at an assumed "normal" efficiency. The variable $y_n$ is the logarithm of the ratios of currents, lumen outputs, or watts at these voltages. $A$, $B$, and $C$ are constants.

These equations have proved to be quite accurate, but are cumbersome to use. Professor Parry Moon ("The Scientific Basis of Illuminating Engineering," McGraw-Hill Book Company, Inc.) has reduced these equations to a simpler form, for use where great accuracy is not required. However, by calculation, the errors do not exceed 5 per cent, even though the voltage varies from 80 per cent to 130 per cent normal. These equations, in part, are as follows:

$$F/F_0 = (V/V_0)^{B_2} \text{ luminous flux} \qquad (1)$$

$$P/P_0 = (V/V_0)^{B_3} \text{ power} \qquad (2)$$

$$L/L_0 = (V/V_0)^{-B_5} \text{ life} \qquad (3)$$

where $V_0$ is the rated voltage of the lamp and $F_0$, $P_0$, and $L_0$ are the values at rated voltage. The constants are obtained from table I.

With the ratio of socket voltage to lamp voltage as the independent variable, Professor Moon has set up another equation giving the cost per lumen-hour. Differentiating, a minimum voltage ratio is found, which is the most economical operating point. The proof will not be given here, but the general equation arrived at giving the voltage ratio for most economical operation is

$$\left(\frac{V}{V_0}\right)_m = \left[\frac{bP_0}{c}\frac{B_2 - B_3}{B_5 - B_2}\right]^{\frac{1}{B_5 - B_3}}$$

where
$c$ equals cost of one lamp plus installation charge (cents)
$b$ equals cost of power in cents per kilowatt-hour
$V$ equals actual operating voltage
$V_0$ equals rated voltage of lamp
$P_0$ equals rated power of lamp
Constants are taken from table I.

For each division of lamps in table I the writer has reduced equation 4 so that curves may be plotted, making it easier to determine the most economical voltage. These curves are shown in figure 1. As an example, consider a residence where $b$ equals 5 cents per kilowatt-hour, $P_0$ equals 60 watts, and $c$ equals 15 cents.

$$\frac{bP_0}{c} = \frac{5 \times 60}{15} = 20$$

From figure 1 the corresponding value of $V/V_0$ equals 1.126. If the circuit is operating at $V$ = 115 volts, the lamp rating for most economical operation should not be 115 volts, but

$$V_0 = \frac{V}{1.126} = 102 \text{ volts (approximately)}$$

As the cost of power becomes lower, $V_0$ and $V$ become more nearly equal. As a general rule, it is more economical to operate lamps above rather than below their rated voltage. It is of interest to note from the curves that when $bP_0/c$ = 4.5 or less, then $V/V_0$ becomes less than unity, and in that case, lamps should be operated below their rated voltage.

**Table I**

| Symbol | Gas-Filled Lamps | | |
|---|---|---|---|
| | 40-50 Watts | 60-150 Watts | 200 Watts and up |
| $B_2$ | 3.685 | 3.613 | 3.384 |
| $B_3$ | 1.523 | 1.523 | 1.543 |
| $B_5$ | 13.5 | 13.5 | 13.1 |

After determining from figure 1 what voltage lamp to buy, one can compute the savings to be made by using equations 1, 2, and 3. If it is desired to make a comparison on the basis of cost per 1,000 lumen-hour hours, the additional formula may be used,

$$\text{Cost per 1,000 lumen-hours} = \frac{Ct + c}{Lt/1{,}000} \qquad (5)$$

where
$C$ equals cost of power in cents per hour
$t$ equals life of lamp in hours
$L$ equals average lumens output of lamp

A very interesting example met with in actual practice, involving all of the foregoing formulas, is as follows: A certain firm was using 200-watt lamps for general illumination, which was considered sufficient. The cost of electricity was approximately 2½ cents per kilowatt-hour. The average operating voltage was close to 113 volts. Lamps rated 120 volts were bought at a 20 per cent discount, and the labor cost for installation was estimated at 8 cents per lamp.

$$\frac{bP_0}{c} = \frac{2.5 \times 200}{48 + 8} = 8.93$$

From figure 1, $V/V_0$ equals 1.053. Therefore, the lamp rating for most economical operation is

$$V_0 = \frac{113}{1.053} = 107 \text{ volts (approximately)}$$

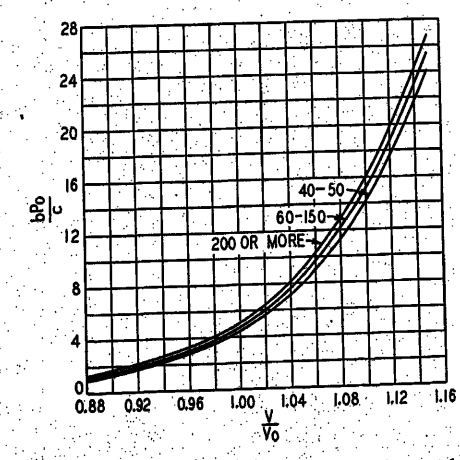



**Figure 1. Curves for determining most economical voltage**

Numbers on curves are ratings of lamps in watts

so 110-volt lamps should be used. But it has been stated that the illumination was considered sufficient, and using 200-watt lamps of this voltage rating would increase the illumination, the number of burn outs, and the power.

A comparison may now be made with 150-watt lamps. Using equations 1, 2, and 3 for the 200-watt 120-volt lamp, and obtaining the value of $F_0$ from the manufacturer's table,

Lumens output at 113 volts
Luminous flux = $F$ =

$$F_0\left(\frac{V}{V_0}\right)^{B_2} = 3{,}400\left(\frac{113}{120}\right)^{3.384} =$$

2,770 lumens.

Life of lamp = $L$ =

$$L_0\left(\frac{V}{V_0}\right)^{-B_5} = 1{,}000\left(\frac{113}{120}\right)^{-13.1} =$$

2,190 hours.

Power = $P$ =

$$P_0\left(\frac{V}{V_0}\right)^{1.543} = 200\left(\frac{113}{120}\right)^{1.543} =$$

182.5 watts.

Similarly, for the 150-watt 110-volt lamp on a 113-volt circuit, the following values are obtained:
$F$ equals 2,660 lumens
$L$ equals 698 hours
$P$ equals 156.2 watts
Using equation 5 for the 200-watt 120-volt lamp,

Cost per 1,000 lumen-hours =

$$\frac{2.5 \times \frac{182.5}{1{,}000} \times 2{,}190 + 56}{2{,}770 \times 2{,}190 \div 1{,}000} = 0.174 \text{ cents.}$$

For the 150-watt 110-volt lamp,
Cost per 1,000 lumen-hours =

$$\frac{2.5 \times \frac{156.2}{1{,}000} \times 698 + 40}{2{,}660 \times 698 \div 1{,}000} = 0.168 \text{ cents}$$

Now since the 150-watt lamp in this case has a lumen output almost equal to that of the 200-watt lamp, and the cost per lumen-hour is less for the 150-watt lamp, then the latter is the one to use.

However, the most interesting part is that there was another electric rate which the firm wanted to get on. The cost for power on this more favorable rate would amount to about 2 cents per kilowatt-hour, while the firm was paying around 2½ cents per kilowatt-hour on the rate which it was on. In the availability clause of this better rate was this requirement, "the lighting load shall not exceed 10 per cent of the total connected load." This requirement made the firm ineligible for the better rate, although their percentage of lighting load did not exceed 10 per cent by a great margin. However, it so happened that changing over to the 150-watt 110-volt lamps made it possible to get more lumens per kilowatt-hour, practically the same amount of illumination, and at the same time, to reduce the lighting load so as to get on this more favorable rate and net a savings of almost $2,000 a year.

Very truly yours,
CAMPBELL McCORD
Engineer, The Knoxville News-Sentinal, Knoxville, Tenn.

# Personal Items

S. P. MacFadden (A'19, M'30) vice-president of the Puget Sound Power & Light Company, Seattle, Wash., has assumed new duties as executive vice-president of the company. Mr. MacFadden was born June 17, 1894, at Laredo, Texas and received the degree of bachelor of science in electrical engineering at the Texas Agricultural and Mechanical College in 1916. Following his graduation, he entered the student engineering course of the Westinghouse Electric & Manufacturing Company, East Pittsburgh, Pa., and upon completion of the course in 1917 became affiliated with the Eastern Texas Electric Company, Beaumont. In the same year, however, he received a commission as lieutenant in the Coast Artillery Corps of the United States Army, and served with the American Expeditionary Force in France until 1919. At the end of the World War, Mr. MacFadden returned to the employ of the Eastern Texas Electric Company, but remained there only briefly before being designated assistant to the district manager of the southwestern district of Stone and Webster, Inc., with offices at Houston, in 1920. From 1924 until 1930 he was associated with several companies, including the Eastern Texas Electric Company, Port Arthur; Western Public Service Company, Scottsbluff, Nebr.; and Stone and Webster Service Corporation, Boston, Mass. Mr. MacFadden has been vice-president of the Pugent Sound Power & Light Company since 1930.

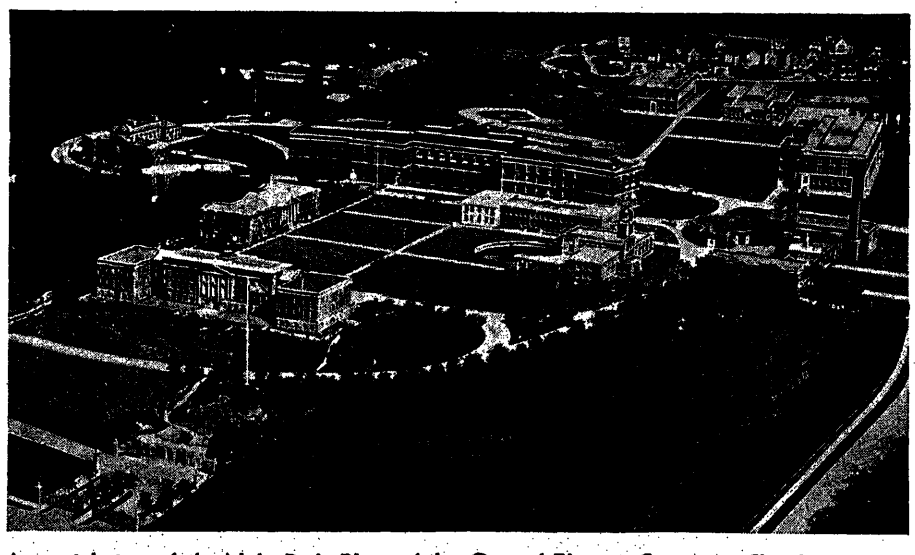
F. B. Corey (A'93, F'12, member for life) plant engineer, Pittsburgh Valve and Fittings Division, The Pitcairn Company, Barberton, Ohio, has retired from active service. Mr. Corey was born September 28, 1869, at Homer, N. Y., and was graduated from Cornell University with the degree of mechanical engineer in 1892, following which he entered the employ of the Elektron Manufacturing Company as a sales engineer in the Boston, Mass., offices. After several other brief affiliations he became a designing engineer in the railway engineer department of the General Electric Company in 1900. Mr. Corey remained with that company until 1911 before becoming engineer of inspection and tests for the Union Switch and Signaling Company Swissvale, Pa. In 1914 he established his own consulting-engineering offices in Pittsburgh, Pa., but in 1916 was appointed efficiency engineer for the Pittsburgh Valve and Fittings Company, Barberton. He was employed by that company in various capacities for more than 20 years before his retirement.

B. T. Anderson (A'35) who has been director of the bureau of railway signaling economics of the Union Switch & Signal Company, New York, N. Y., has been appointed general sales manager of the company. Mr. Anderson, a native (1884) of Alexis, Ill., received the degree of bachelor of science in electrical engineering at the University of Illinois in 1907, and upon graduation entered an apprenticeship course in railway signaling in the Union Switch and Signaling Company, Swissvale, Pa. In 1910 he became a draftsman for the Atchison, Topeka, and Santa Fe Railway Company, Topeka, Kans., but later was made construction foreman and assistant signal engineer and remained with that company until 1914. In that year he was appointed assistant signal engineer with the Delaware, Lackawanna, and Western Railway Company, Hoboken, N. J., where he remained until 1923. For 4 years (1923–27) Mr. Anderson was superintendent of signals for the Chesapeake and Ohio Railway Company, with offices at Richmond, Va., and during that period became active in the work of the American Railway Association. Since 1927 he has been affiliated with the Union Switch and Signaling Company as assistant to the vice-president, assistant to the president, publicity representative, and director of the bureau of railway signaling economics.

M. M. Kenneally (M'29) for the last 7 years manager of the power utilities department of the Ohio Brass Co., Mansfield, has been appointed sales manager of the Porcelain Insulator Corporation, Lima, N. Y. Mr. Kenneally was born March 16, 1894, at Oelwein, Iowa, and received the degrees of bachelor of science in electrical engineering (1915) and electrical engineer (1920) at Iowa State College. Following brief associations with several public utility companies, he was appointed electrical engineer on operation and construction for the Iowa Public Service Company, at Humboldt, in 1924. In 1926 Mr. Kenneally became assistant to the electrical engineer of the United Gas Improvement Company, Philadelphia, Pa., in which capacity he assisted in designing and supervising the construction of transmission equipment for that system. In the following year he became affiliated with the Ohio Brass Co. in its high-voltage laboratory, and after a few months' training there, was transferred to the New York, N. Y., offices of the company. In 1928 he was named district sales manager in the New York area, and in 1930 was returned to the Mansfield offices as manager of the power utilities department, in charge of sales, advertising, and engineering.

H. F. Boe (M'30) eastern district manager, Westinghouse Electric & Manufacturing Company, New York, N. Y., has assumed additional duties as commercial manager of the company. Mr. Boe, a native (1884) of Mansfield, Ohio, attended Carnegie Institute of Technology, and has been associated with the Westinghouse company since 1900, continuously except for one year (1916–17) as chief engineer and manager of the Vaile Kimes Company, Dayton, Ohio. Until 1916 Mr. Boe's work was in general engineering and sales in the East Pittsburgh offices of the Westinghouse company; in 1918 he was transferred to the Rochester, N. Y., offices as a sales engineer, and in 1922 he went to Buffalo, N. Y., as district industrial division manager. Later he was made manager of that office, and in 1935 was transferred to New York, N. Y., where in 1936 he became eastern district manager.

H. W. Tenney (M'36) section engineer in the materials and process engineering department of the Westinghouse Electric & Manufacturing Company, East Pittsburgh, Pa., has been appointed engineering manager of the recently created new products division of the company. Mr. Tenney, a native (1899) of Leominster, Mass., received the degrees of bachelor of science in electrical engineering (1920) and electrical engineer (1922) at Worcester Polytechnic Institute, and has been associated with the



**An aerial view of the Nela Park Plant of the General Electric Company, Cleveland, Ohio which may be visited by those attending the Middle Eastern District meeting, Akron, Ohio, October 13-15**

Westinghouse company continuously since his graduation in 1920. He entered the employ of the company as a laboratory assistant, but later became successively oscillograph specialist, foreman in charge of the engineering laboratory, assistant section engineer in the materials and process engineering section, and section engineer.

S. L. NICHOLSON (A'00, F'13, member for life) assistant to vice-president, Westinghouse Electric & Manufacturing Company, New York, N. Y., has relinquished his duties in that organization, and is retiring from active business. Mr. Nicholson was born November 10, 1870, at Germantown, Pa., and received his formal education in private schools in Philadelphia. After having held several engineering positions in Philadelphia and New York, he was engaged by the Westinghouse company as a sales engineer in 1898. In 1909 Mr. Nicholson was made sales manager, and in 1917 became assistant to the vice-president. He has been active in the affairs of the National Electrical Manufacturers Association and the American Standards Association.

VANNEVAR BUSH (A'15, F'24 Lamme Medalist '35, director) vice-president and dean of engineering, Massachusetts Institute of Technology, Cambridge, has been appointed a member of a special committee of the National Research Council to make a comprehensive survey of the applications of radio, sound recording and reproduction, motion pictures, photography, and other scientific achievements in the field of education.

C. L. COLLENS (A'07) president of the Reliance Electric and Engineering Company of Cleveland, Ohio, has been elected to membership on the board of directors of the American Standards Association, on nomination of the National Electrical Manufacturers Association. Mr. Collens is a past member of the ASA board (1929–32) and a past-president of NEMA in various activities of which he long has been active.

F. B. JEWETT (A'03, F'12, Edison Medalist '28, past-president) vice-president American Telephone and Telegraph Company, New York, N. Y., has been appointed a member of a special committee of the National Research Council to make a comprehensive survey of how radio, sound recording and reproduction, motion pictures, photography, and other scientific achievements may be applied to learning.

W. R. VAN BOKKELEN (A'12, M'26) has been appointed chief of the division of electricity for the 1939 Golden Gate International Exposition at San Francisco, Calif. Mr. Van Bokkelen was electrical engineer and chief engineer of the Coast Counties Gas and Electric Company, San Francisco, for 18 years; has been in consulting practice for the past few years.

G. V. HARRAP (A'34) assistant engineer in the power station of the Hull (England) Corporation Electricity Department, has been awarded a premium by the Institution of Electrical Engineers (Great Britain) for his paper "Taxation of Electricity Undertakings," recently presented before a session of the Institution.

O. A. BECKLUND (Enrolled Student) has received the AIEE Great Lakes District prize for branch paper for his paper "An Artificial Ear for Sound Measurements." Mr. Becklund is a native (1915) of St. Paul, Minn., and received the degree of bachelor of engineering in June 1937, at the University of Minnesota.

R. E. LYLE (A'32) who has been an electrical engineer in the engineering experiment station of Washington State College, Pullman, recently joined the engineering division of the Westinghouse Electric & Manufacturing Company, Seattle.

FRANK WALSH (A'26, M'30) district manager, Puget Sound Power and Light Company, Bellingham, Wash., has been elected a vice-president of the Northwest Electric Light and Power Association for the state of Washington.

P. J. AMBROSE (A'36) who has been a radio-engineering instructor at Indiana Technical College, Fort Wayne, now is employed in the power distribution department of the Consumers Power Company, Jackson, Mich.

E. A. RICKER (A'36) formerly a demonstrator on the faculty of applied science of the University of Toronto (Ont., Canada), now is a draftsman for the Canadian Westinghouse Company, Hamilton, Ont.

W. H. MCGRATH (A'02, M'20) has retired from active duty as executive vice-president of the Puget Sound Power & Light Company, Seattle, Wash. He will continue as a director of the company.

F. L. WEST (A'37) assistant engineer, Niagara, Lockport, and Ontario Power Company, Buffalo, N. Y., has been transferred to the Avon, N. Y., offices of that company in the capacity of superintendent.

H. E. PEARSON (A'26, M'32) formerly district power maintainer for the Board of Transportation of the City of New York, N. Y., now is employed by the Roller-Smith Company, Bethlehem, Pa.

## Obituary

JOHN WHITE HOWELL (A'87, M'88, F'12, Edison Medalist '24, member for life, past manager) retired chief engineer of the lamp works of the General Electric Company, died July 28, 1937. Mr. Howell was born at New Brunswick, N. J., December 22, 1857. In 1881, he finished a special course in electrical engineering at Stevens Institute of Technology, and received the honorary degree of electrical engineer in 1899. He became identified with the Edison Lamp Company as an electrician in 1881, and became technical adviser to the manager of works in 1890; in 1912, when the company became a part of the General Electric Company, he was engineer and assistant manager of the lamp works. He retired in 1931 as chief engineer. He was recognized as one of the most distinguished of electrical pioneers in the production of incandescent lamps. Among his important achievements were the development of a successful portable voltmeter, a Wheatstone bridge type of potential indicator, and the comparative indicator. He determined for the first time the relation between the life and candle power of an incandescent lamp (1886); introduced a carbonaceous clamp that decreased clamping and filament costs and increased the quality of the lamp (1887); and later made changes to effect an increase in the speed of exhausting the envelope. He improved the Thomson-Houston method of treating carbon filaments, and devised a machine that made great advances in the treating process. He assisted in the design of the first stem-making machine and in the derivation of metalized filaments. Mr. Howell was a manager of the Institute, 1888–90, and a member of The American Society of Mechanical Engineers, Franklin Institute, and other technical societies. He was a member of the Edison Medal Committee from 1926 to 1931.

CHARLES BROSSMAN (M'28) consulting engineer, Indianapolis, Ind., died June 30, 1937. Mr. Brossmann was born January 17, 1877, at Philadelphia, Pa., and received his formal technical education at the Philadelphia Manual Training High School. In 1896 he became a draftsman and designer for the Baldwin Locomotive Works at Philadelphia, were he remained until 1898, when he served in the Spanish-American War. In 1900, he was engaged by the Indianapolis Water Company for some special design work, and in 1904 he established the consulting-engineering company of Brossman and King, with offices at Indianapolis. Mr. Brossman maintained his consulting practice continuously for more than 32 years, and was active in the affairs of the Indiana Engineering Society. He was a member of The American Society of Mechanical Engineers, American Society of Civil Engineers, and American Water Works Association.

FRANK BENJAMIN RAE (A'84, M'20, member for life) retired consulting engineer, Berkeley, Calif., and a charter member of the Institute, died July 28, 1937. Mr. Rae was born July 25, 1854, at Elmira, N. Y., and was self-educated. From 1870 until 1881 he was engaged in the telegraph business, first as messenger and operator, and later as manager of the Atlantic and Pacific Telegraph Company and the Western Union Telegraph Company. In 1881, he resigned the position of electrician at San Francisco for the Western Union company and became engineer for the Brush Electric Light Company, San Francisco,

and manager of the San Jose (Calif.) Brush Electric Company. In 1883 he became engineer for the Commercial Telegram Company, an organization devoted to dispatching stock quotations, at New York, N. Y. From 1885 to 1887 he was a consulting engineer in New York, as a member of the firm of Mailloux and Rae. In 1887 Mr. Rae was consulting engineer for the Barker Syndicate in China, and from 1887 until 1892 was engineer for the Detroit (Mich.) Electrical Works, engaged on the Rae Electric Railway System. Since 1892 he had been a consulting electrical engineer in various cities throughout the United States. In 1923 he became electrical engineer for the city of Berkeley, Calif., but resigned and retired from active service in 1930. Mr. Rae was the holder of about 100 patents on various electrical devices and systems.

WILLIAM GODFREY HEPTINSTALL (A'26) manager of Waikato Carbonisation, Ltd., Rotowaro, New Zealand, died October 1, 1936, according to word just received at Institute headquarters. Mr. Heptinstall was born July 2, 1883, at Yorkshire, England, and attended London (England) University. Following a period of service with the Royal (British) Naval Volunteer Reserve he went to Canada, where he took charge of the operation of a small municipal gas and electric plant for the town of Minnedosa, Man. In 1920 he became plant superintendent of the Lignite Utilization Board, Bienfait, Sask., and remained there for almost 10 years before going to New Zealand to become manager of Waikato Carbonisation, Ltd.

ROBERT KING (A'35) electrical engineer in the port department, City of Oakland, Calif., died recently. Mr. King was born March 4, 1885, in Alaska, and received his technical education by serving an apprenticeship in an electrical shop. In 1901 he established an electrical-contracting business, which he maintained until 1925, when he started a wholesale electrical-supply business. From 1927 until 1929 he served as a consulting engineer during the construction of several public schools in or near Oakland. He was appointed electrical engineer in the port department of that city in 1929.

# Membership

## Addresses Wanted

A list of members whose mail has been returned by the postal authorities is given below, with the addresses as they now appear on the Institute record. Any member knowing of corrections to these addresses will kindly communicate them at once to the office of the secretary at 33 West 39th St., New York, N. Y.

Charlton, H. C., 4827 Wilson Avenue, Montreal, Que., Canada.
Evans, Maldwyn F., Canadian Comstock Company, Ltd., Toronto, Ont., Canada.
Gregory, G. A., 1217 Jefferson Street, Olympia, Wash.
Hardy, John E., 1741 Pennsylvania Avenue, Denver, Colo.
Jones, K. B., Trumbull Electric Manufacturing Company, Inc., Ludlow, Ky.
Roberts, Fred A., 2010 West Michigan Street, Indianapolis, Ind.
Schaefer, Philip E., 5154 St. Paul Avenue, Chicago, Ill.
Sikofsky, George L., 1206 East New York Avenue, Brooklyn, N. Y.

8 Addresses Wanted

## Applications for Election

Applications have been received at headquarters from the following candidates for election to membership in the Institute. If the applicant has applied for direct admission to a grade higher than Associate, the grade follows immediately after the name. Any member objecting to the election of any of these candidates should so inform the national secretary before September 30, 1937 or November 30, 1937, if the applicant resides outside of the United States or Canada.

Barbee, J. E., Humble Pipe Line Company, Houston, Texas.
Barnett, H. E., Cincinnati Suburban Bell Telephone Company, Cincinnati, Ohio.
Beck, R. W. (Member), 121 City Light Bldg., Seattle, Wash.
Birdsong, T. S., Alabama Power Co., Birmingham, Ala.
Casselman, C. H., Buffalo Niagara Electric Corp., Tonawanda, N. Y.
Conklin, W. A., Commonwealth and Southern Corporation, Jackson, Mich.
Curtis, C. E. (Member), University of Texas, Austin, Texas.
Daugherty, W. W., Bethlehem Steel Corporation, Cornwall, Pa.
Davis, R. L., General Electric Company, New York, N. Y.
De Arman, C. R., The Bristol Company, Waterbury, Conn.
DeVaughn, W., Forty Wall Street Corp., New York, N. Y.
Ellis, H. W. G., Ferranti Electric, Limited, Toronto, Ont., Canada.
Hall, E. S., Kansas Gas and Electric Company, Newton.
Harris, C. A., Southwestern Bell Telephone Co., St. Louis, Mo.
Hay, J. V., Southern Bell Telephone and Telegraph Company, New Orleans, La.
Johnson, L. C., Washington Water Power Company, Spokane.
Kight, M. B., Bureau of Reclamation, Denver, Colo.
Knight, N. (Member), Bell Telephone Co. of Canada, Toronto 2, Ont., Can.
Masso, A., Hertner Electric Company, Cleveland, Ohio.
MacGregor, D. M., Phoenix Engineering Corp., New York, N. Y.
Nannini, F., 445 Sierra Street, Reno, Nev.
Neuhardt, F. H., General Electric Company, New York, N. Y.
Pahl, J. G., K-P-F Electric Company, San Francisco, Calif.
Parri, I. W., Perfex Controls Co., Milwaukee, Wis.
Rose, A. M., American Telephone and Telegraph Company, Cleveland, Ohio.
Rothschild, H., Cline Electrical Mfg. Co., Chicago, Ill.
Sigman, F. I., McCarthy Brothers and Ford, Buffalo, N. Y.
Siegel, R., 393 Belmont Ave., Newark, N. J.
Smith, L. L., Pacific Tel. & Tel. Co., Portland, Ore.
Taylor, J. J., Ohio Brass Co., Barberton, Ohio.
Titus, C. F. (Member) Florida Power and Light Company, Daytona Beach.
Turner, J. T., Jr., National Light & Power Co. Ltd., Moose Jaw, Saskatchewan, Canada.
Walker, R. J., General Motors Corporation, Detroit, Mich.
Wilson, S. E., National Geophysical Company, Jennings, La.

34 Domestic

Foreign

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Reid, J. H. (Member), Trinidad Electric Company, Ltd., Port-of-Spain, Trinidad, B. W. I.
Schuepp, R. H. (Member), Volkart Brothers, Lahore, India.
Souza, B. R., Compania Cubana de Electricidad Havana, Cuba.
Thirivengadam, M., Guntur Power & Light Ltd., Tenali, Madras, S. India.

9 Foreign

# Engineering Literature

## New Books in the Societies Library

Among the new books received at the Engineering Societies Library, New York, recently are the following which have been selected because of their possible interest to the electrical engineer. Unless otherwise specified, books listed have been presented gratis by the publishers. The Institute assumes no responsibility for statements made in the following outlines, information for which is taken from the preface of the book in question.

ALIGNING PHILCO RECEIVERS. By J. F. Rider. New York, John F. Ryder, 1440 Broadway, 1937. 136 pages, diagrams, 8x5 inches, cloth, $1.00. A practical manual for the repairman, containing diagrams and tables for every model of Philco receiver from the earliest to those for 1937.

FUNDAMENTALS of ENGINEERING ELECTRONICS. By W. G. Dow. New York, John Wiley, 1937. 604 pages, illustrated, 10x6 inches, cloth, $5.00. Emphasizes chiefly internal operating principles. A large part of the text is devoted to a study of the use of various geometrics and materials in electronic devices, and a relatively small part to circuit studies. The point of view is that of the engineer.

SOUND. By A. T. Jones. New York, D. Van Nostrand Company, 1937. 450 pages, illustrated, 9x6 inches, cloth, $3.75. An elementary book on sound. Sound production and transmission, free and forced vibrations, musical scales and instruments, speech and hearing are considered with their modern technical applications.


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H. M. Hobard — C. H. Willis
D. C. Jackson, Jr. — R. J. Wiseman
K. S. Wyatt

**Transportation**

G. I. Wright, Chm., Westinghouse Electric & Mfg. Co., East Pittsburgh, Pa.

R. Beeuwkes — A. J. Klatte
C. M. Davis — H. N. Latey
E. G. Davis — J. J. Linebaugh
J. V. B. Duer — P. A. McGee
D. D. Ewing — John Murphy
E. B. Fitzgerald — A. J. Nichol
J. E. Gardner — J. A. Noertker
Selby Haar — F. B. Powers
W. S. H. Hamilton — Dwight L. Smith
C. R. Jones — L. J. Turley
L. C. Josephs — W. M. Vandersluis
Sidney Withington

## Institute Representatives

(Where names are missing, appointments have not yet been made for 1937–38)

**Alfred Noble Prize Committee, ASCE**

H. S. Osborne

**Am. Assoc. for the Adv. of Science, Council**

C. C. Knipmeyer — R. E. Nyswander

**American Committee on Marking of Obstructions to Air Navigation**

G. E. Dean — H. L. Huber

**American Engineering Council, Assembly**

C. O. Bickelhaupt — William McClellan
F. J. Chesterman — C. E. Stephens
W. H. Harrison — H. H. Henline, *Alternate*

**American Marine Standards Committee**

**American Standards Assoc., Standards Council**

A. M. MacCutcheon — V. M. Montsinger
E. L. Moreland

*Alternates*

R. E. Hellmund — H. S. Osborne — E. B. Paxton

**American Stds. Assoc., Bd. of Directors**

H. P. Charlesworth

**American Year Book, Advisory Board**

H. H. Henline

**Charles A. Coffin Fellowship and Research Fund Committee**

W. H. Harrison

**Committee of Apparatus Makers and Users, NRC**

**Committee on Heat Transmission, NRC**

**Committee on Low Voltage Hazards, ASSE-Engg. Section, National Safety Council**

**Electrical Standards Committee, ASA**

A. M. MacCutcheon — E. L. Moreland
H. S. Osborne

*Alternates*

H. E. Farrer — R. E. Hellmund — E. B. Paxton

**Engineering Foundation Board**

F. M. Farmer — W. I. Slichter

**Engineering Societies Monographs Committee**

F. M. Farmer — W. I. Slichter

**Engineers' Council for Professional Development**

Charles F. Scott — L. W. W. Morrow

**Hoover Medal Board of Award**

H. H. Barnes, Jr. — Gano Dunn — Wm. McClellan

(*Continued on page 1220*)

## Geographical District Executive Committees

| District | Chairman (Vice-President, AIEE) | Secretary (District Secretary) | Chairman, District Committee on Student Activities |
|---|---|---|---|
| No. 1—North Eastern | A. C. Stevens, General Electric Co., Schenectady, N. Y. | R. G. Lorraine, General Electric Co., Schenectady, N. Y. | F. N. Tompkins, Brown University, Providence, R. I. |
| No. 2—Middle Eastern | I. Melville Stein, Leeds & Northrup Co., 4901 Stenton Ave., Philadelphia, Pa. | H. A. Dambly, Philadelphia Electric Co., 900 Sansom St., Philadelphia, Pa. | A. G. Ennis, George Washington University, Washington, D. C. |
| No. 3—New York City | O. B. Blackwell, 463 West St., New York, N. Y. | J. F. Fairman, Consolidated Edison Co. of New York, Inc., 4 Irving Pl., New York, N. Y. | H. N. Walker, N w York University, University Heights, New York, N. Y. |
| No. 4—Southern | Edwin D. Wood, Louisville Gas & Electric Co., 311 W. Chestnut St., Louisville, Ky. | Stanley Warth, Southern Bell Tel. & Tel. Co., 521 W. Chestnut St., Louisville, Ky. | S. W. Anderson, Virginia Military Institute, Lexington, Va. |
| No. 5—Great Lakes | C. F. Harding, Purdue University, Lafayette, Ind. | A. G. Dewars, Northern States Power Co., 15 S. 5th St., Minneapolis, Minn. | S. S. Attwood, University of Michigan, Ann Arbor, Mich. |
| No. 6—North Central | L. N. McClellan, U.S. Bureau of Reclamation, 440 Customhouse, Denver, Colo. | W. F. McPhail, U. S. Bureau of Reclamation, Customhouse, Denver, Colo. | L. A. Bingham, University of Nebraska, Lincoln, Neb. |
| No. 7—South West | L. T. Blaisdell, General Electric Co., 1801 N. Lamar St., Dallas, Tex. | L. C. Starbird, 820 Telephone Building, Dallas, Tex. | Chester Russell, University of New Mexico, Albuquerque, N. M. |
| No. 8—Pacific | J. P. Jollyman, Pacific Gas & Electric Co., 245 Market St., San Francisco, Calif. | A. M. Bohnert, Ohio Brass Co., 1006 Matson Bldg., San Francisco, Calif. | E. F. Peterson, University of Santa Clara, Santa Clara, Calif. |
| No. 9—North West | C. E. Rogers, Pacific Tel. & Tel. Co., 1203 Telephone Bldg., Seattle, Wash. | Sidney E. Caldwell, Pacific Power & Light Co., Public Service Bldg., Portland Ore. | J. A. Thaler, Montana State College, Bozeman, Mont. |
| No. 10—Canada | M. J. McHenry, Canadian General Electric Co. Ltd., 212 King St. W., Toronto, Ont. | J. M. Thomson, Ferranti Electric Ltd., Mount Dennis, Toronto, Ont. | |

Note: Each District executive committee includes also the chairmen and secretaries of all Sections within the District, and the District vice-chairmen of the national Membership Committee.

INSTITUTE REPRESENTATIVES—Continued

**John Fritz Medal Board of Award**

A. W. Berresford — A. M. MacCutcheon — J. B. Whitehead

**Library Board, United Engineering Trustees, Inc.**

W. S. Barstow — H. H. Henline
W. A. Del Mar — W. I. Slichter

**National Bureau of Engineering Registration, Advisory Board**

W. I. Slichter

**Nat'l Fire Protection Assoc., Electrical Committee**

F. V. Magalhaes, *Alternate*

**National Fire Waste Council**

**Nat'l Research Council, Division of Engineering & Industrial Research**

V. Bush — Everett S. Lee — J. B. Whitehead
H. H. Henline, *ex-officio*

**Radio Advisory Committee, Bureau of Standards**

**Research Procedure Com., Engg. Foundation**

L. W. Chubb

**Thomas Alva Edison Foundation**

H. H. Barnes, Jr. — Charles F. Scott
L. W. W. Morrow — Clayton H. Sharp

**United Engineering Trustees, Inc.**

H. P. Charlesworth — G. L. Knight
H. R. Woodrow

**U.S. National Committee of the International Commission on Illumination**

Robin Beach — A. E. Kennelly — Clayton H. Sharp

**U.S. Nationa Committee of the International Electrotechnical Commission**

A. M. MacCutcheon — E. L. Moreland
H. S. Osborne

*Alternates*

H. E. Farrer — R. E. Hellmund — E. B. Paxton

**Commission of Washington Award**

H. B. Gear — G. G. Post

## Student Branches of the Institute

| Name and Location | District | Counselor (Member of Faculty) |
|---|---|---|
| Akron, Univ. of, Akron, Ohio | 2 | J. T. Walther |
| Alabama Polytechnic Inst., Auburn, Ala | 4 | W. W. Hill |
| Alabama, Univ. of, University, Ala | 4 | Fred R. Maxwell, Jr. |
| Arizona, Univ. of, Tucson, Ariz | 8 | J. C. Clark |
| Arkansas, Univ. of, Fayetteville, Ark | 7 | W. B. Stelzner |
| Armour Inst. of Tech., Chicago, Ill | 5 | E. H. Freeman |
| British Columbia, Univ. of, Vancouver, B. C., Can. | 10 | W. B. Coulthard |
| Brooklyn, Poly. Inst. of, Brooklyn, N. Y | 3 | C. C. Whipple |
| Brown Univ., Providence, R. I | 1 | F. N. Tompkins |
| Bucknell Univ., Lewisburg, Pa | 2 | G. A. Irland |
| Calif. Inst. of Tech., Pasadena, Calif | 8 | F. C. Lindvall |
| Calif., Univ. of, Berkeley, Calif | 8 | Abe Tilles |
| Carnegie Inst. of Tech., Pittsburgh, Pa | 2 | G. R. Patterson |
| Case School of Applied Science, Cleveland, Ohio | 2 | A. C. Seletzky |
| Catholic Univ. of America, Washington, D. C | 2 | T. J. MacKavanagh |
| Cincinnati, Univ. of, Cincinnati, Ohio | 2 | L. R. Culver |
| Clarkson College of Technology, Potsdam, N. Y | 1 | A. R. Powers |
| Clemson Agri. Col., Clemson S. C. | 4 | S. R. Rhodes |
| Colorado State Col. of A. & M. Arts, Fort Collins, Colo. | 6 | H. G. Jordan |
| Colorado, Univ. of, Boulder, Colo | 6 | H. B. Palmer |
| Columbia University, New York, N. Y | 3 | G. T. Harness |
| Cooper Union, New York, N. Y | 3 | F. H. Tallman |
| Cornell Univ., Ithaca, N. Y | 1 | E. M. Strong |
| Denver, Univ. of, Denver, Colo | 6 | R. E. Nyswander |
| Detroit, Univ. of, Detroit, Mich | 5 | H. O. Warner |
| Drexel Inst. of Tech., Philadelphia, Pa | 2 | E. O. Lange |
| Duke Univ., Durham, N. C | 4 | W. J. Seeley |
| Florida, Univ. of, Gainesville, Fla | 4 | E. F. Smith |
| George Washington Univ., Washington, D. C | 2 | A. G. Ennis |
| Georgia School of Tech., Atlanta, Ga | 4 | T. W. Fitzgerald |
| Harvard Univ., Cambridge, Mass | 1 | J. D. Cobine |
| Idaho, Univ. of, Moscow, Idaho | 9 | J. H. Johnson |
| Illinois, Univ. of, Urbana, Ill | 5 | E. A. Reid |
| Iowa State Col., Ames, Iowa | 5 | B. S. Willis |
| Iowa, Univ. of, Iowa City, Iowa | 5 | G. F. Corcoran |
| Johns Hopkins Univ., Baltimore, Md | 2 | J. H. Lampe |
| Kansas State Col., Manhattan, Kansas | 7 | R. G. Kloeffler |
| Kansas, Univ. of, Lawrence, Kansas | 7 | E. W. Hamlin |
| Kentucky, Univ. of, Lexington, Ky | 4 | E. A. Bureau |
| Lafayette Col., Easton, Pa | 2 | F. W. Smith |
| Lehigh Univ., Bethlehem, Pa | 2 | Wm. H. Formhals |
| Lewis Inst., Chicago, Ill | 5 | F. A. Rogers |
| Louisiana State Univ., Baton Rouge, La | 4 | M. B. Voorhies |
| Louisville, Univ. of, Louisville, Ky | 4 | |
| Maine, Univ. of, Orono, Me | 1 | W. H. Bliss |
| Marquette Univ., Milwaukee, Wis | 5 | E. W. Kane |
| Maryland, University of, College Park, Md | 2 | L. J. Hodgins |
| Mass. Inst. of Tech., Cambridge, Mass | 1 | Gordon S. Brown |
| Michigan Col. of Min. & Tech., Houghton, Mich | 5 | G. W. Swenson |
| Michigan State Col., E. Lansing, Mich | 5 | L. S. Foltz |
| Michigan, Univ. of, Ann Arbor, Mich | 5 | S. S. Attwood |
| Milwaukee Sch. of Engg., Milwaukee, Wis | 5 | |
| Minnesota, Univ. of, Minneapolis, Minn | 5 | J. H. Kuhlmann |
| Mississippi State Col., State College, Miss | 4 | L. H. Fox |
| Missouri Sch. of Mines and Met., Rolla, Mo | 7 | I. H. Lovett |
| Missouri, Univ. of, Columbia, Mo | 7 | C. M. Wallis |
| Montana State Col., Bozeman, Mont | 9 | J. A. Thaler |
| Nebraska, Univ. of, Lincoln, Neb | 6 | L. A. Bingham |
| Nevada, Univ. of, Reno, Nev | 8 | S. G. Palmer |
| Newark Col. of Engg., Newark, N. J | 3 | C. H. Stephan |
| New Hampshire, Univ. of, Durham, N. H | 1 | L. W. Hitchcock |
| New Mexico, Univ. of, Albuquerque, N. Mex | 7 | Chester Russell, Jr. |
| New York, Col. of the City of, New York, N. Y | 3 | Harry Baum |
| New York Univ., New York, N. Y | 3 | H. N. Walker |
| North Carolina State Col., Raleigh, N. C | 4 | R. S. Fouraker |
| North Carolina, Univ. of, Chapel Hill, N. C | 4 | |
| North Dakota Agri. Col., Fargo, N. D | 6 | H. S. Rush |
| North Dakota, Univ. of, Grand Forks, N. D | 6 | H. F. Rice |
| Northeastern Univ., Boston, Mass | 1 | R. G. Porter |
| Northwestern Univ., Evanston, Ill | 5 | |
| Notre Dame, Univ. of, Notre Dame, Ind | 5 | J. A. Caparo |
| Ohio Northern Univ., Ada, Ohio | 2 | B. F. Wyandt |
| Ohio State Univ., Columbus, Ohio | 2 | E. E. Kimberly |
| Ohio Univ., Athens, Ohio | 2 | W. M. Young |
| Oklahoma A. & M. Col., Stillwater, Okla | 7 | Albrecht Naeter |
| Oklahoma, Univ. of, Norman, Okla | 7 | C. T. Almquist |
| Oregon State Col., Corvallis, Ore | 9 | A. L. Albert |
| Pennsylvania State Col., State College, Pa | 2 | L. A. Doggett |
| Pennsylvania, Univ. of, Philadelphia, Pa | 2 | C. D. Fawcett |
| Pittsburgh, Univ. of, Pittsburgh, Pa | 2 | H. E. Dyche |
| Porto Rico, Univ. of, Mayaguez, P. R | 3 | G. F. Anton |
| Pratt Institute, Brooklyn, N. Y | 3 | C. C. Carr |
| Princeton Univ., Princeton, N. J | 2 | A. E. Vivell |
| Purdue Univ., Lafayette, Ind | 5 | J. H. Bowman |
| Rensselaer Poly. Inst., Troy, N. Y | 1 | L. C. Holmes |
| Rhode Island State Col., Kingston, R. I | 1 | W. B. Hall |
| Rice Institute, Houston, Texas | 7 | J. S. Waters |
| Rose Poly. Inst., Terre Haute, Ind | 5 | C. C. Knipmeyer |
| Rutgers Univ., New Brunswick, N. J | 3 | P. S. Creager |
| Santa Clara, Univ. of, Santa Clara, Calif | 8 | E. F. Peterson |
| South Carolina, Univ. of, Columbia, S. C | 4 | T. F. Ball |
| South Dakota State Col., Brookings, So. Dak | 6 | W. H. Gamble |
| So. Dak. State Sch. of Mines, Rapid City, So. Dak | 6 | J. O. Kammerman |
| Southern California, Univ. of, Los Angeles, Calif | 8 | W. G. Angermann |
| Southern Methodist Univ., Dallas, Texas | 7 | E. H. Flath |
| Stanford Univ., Stanford University, Calif | 8 | H. H. Skilling |
| Stevens Inst. of Tech., Hoboken, N. J | 3 | H. C. Roters |
| Swarthmore Col., Swarthmore, Pa | 2 | J. D. McCrumm |
| Syracuse Univ., Syracuse, N. Y | 1 | C. W. Henderson |
| Tennessee, Univ. of, Knoxville, Tenn | 4 | J. G. Tarboux |
| Texas A. & M. Col., College Station, Texas | 7 | N. F. Rode |
| Texas Technological Col., Lubbock, Texas | 7 | W. F. Helwig |
| Texas, Univ. of, Austin, Texas | 7 | J. W. Ramsey |
| Tufts Col., Tufts College, Mass | 1 | E. A. Walker |
| Tulane University, New Orleans, La | 4 | C. W. Ricker |
| Union Col., Schenectady, N. Y | 1 | |
| Utah, Univ. of, Salt Lake City, Utah | 9 | A. L. Taylor |
| Vermont, Univ. of, Burlington, Vt | 1 | E. R. McKee |
| Villanova Col., Villanova, Pa | 2 | H. S. Bueche |
| Virginia Military Inst., Lexington, Va | 4 | S. W. Anderson |
| Virginia Poly. Inst., Blacksburg, Va | 4 | Claudius Lee |
| Virginia, Univ. of, University, Va | 4 | J. S. Miller |
| Washington, State Col. of, Pullman, Wash | 9 | O. E. Osburn |
| Washington, Univ. of, Seattle, Wash | 9 | R. E. Lindblom |
| Washington Univ., St. Louis, Mo | 7 | R. S. Glasgow |
| West Virginia Univ., Morgantown, W. Va | 2 | A. H. Forman |
| Wisconsin, Univ. of, Madison, Wis | 5 | G. F. Tracy |
| Worcester Poly. Inst., Worcester, Mass | 1 | C. D. Knight |
| Wyoming, Univ. of, Laramie, Wyo | 6 | G. H. Sechrist |
| Yale Univ., New Haven, Conn | 1 | A. G. Conrad |

Total . . . . . 120

# Local Sections of the Institute

| Name | District | Chairman | Secretary | Secretary's Address |
|---|---|---|---|---|
| Akron | 2 | A. O. Austin | T. F. Brandt | Ohio Brass Co., Barberton, Ohio |
| Alabama | 4 | L. M. Smith | F. R. Maxwell, Jr, | University of Alabama, University, Ala. |
| Atlanta | 4 | H. N. Pye | J. M. Flanigen | Georgia Power Co., Atlanta, Ga. |
| Baltimore | 2 | L. S. Billau | H. A. Frey | Locke Insulator Corp., Baltimore, Md. |
| Boston | 1 | H. A. McCrea | J. M. Murray | 66 Sidney St., Cambridge, Mass. |
| Central Indiana | 5 | L. G. Anderson | John M. Webb | 740 So. Alabama St., Indianapolis, Ind. |
| Chicago | 5 | N. C. Pearcy | A. J. Krupy | Commonwealth Edison Co., 72 West Adams St., Chicago, Ill. |
| Cincinnati | 2 | L. R. Culver | R. F. Schierland | The Cincinnati Gas & Elec. Co., Cincinnati, Ohio |
| Cleveland | 2 | F. E. Harrell | H. J. Dible | Ohio Bell Telephone Co., 750 Huron Rd., Cleveland, Ohio |
| Columbus | 2 | C. D. Price | W. L. Everitt | Ohio State University, Columbus, Ohio |
| Connecticut | 1 | J. A. French | H. W. Sundius | Southern New England Tel. Co., New Haven, Conn. |
| Dallas | 7 | O. S. Hockaday | E. B. Robertson | P. O. Box 745, Dallas, Texas |
| Denver | 6 | N. R. Love | R. H. Owen | 1625 California St., Denver, Colo. |
| Detroit-Ann Arbor | 5 | D. H. Baker | R. E. Greene | Detroit Edison Co., 2000 Second Ave., Detroit, Mich. |
| East Tennessee | 4 | E. E. George | V. J. Cissna | In care T V A, Old Post Office Bldg., Chattanooga, Tenn. |
| Erie | 2 | L. S. Cooper | W. D. Bearce | 4121 Sassafras St., Erie, Pa. |
| Florida | 4 | A. P. Michaels | Joseph Weil | University of Florida, Gainesville, Fla. |
| Fort Wayne | 5 | C. S. Allen | N. L. Winter | General Electric Co., 1635 Broadway, Fort Wayne, Ind. |
| Houston | 7 | V. O. Clements | Seth Evans | Hughes Tool Co., Houston, Texas |
| Iowa | 5 | O. A. Brown | G. Charlesworth | Iowa Railway Commission, Des Moines, Iowa |
| Ithaca | 1 | L. A. Burckmyer, Jr | W. W. Cotner | Cornell University, Ithaca, N. Y. |
| Kansas City | 7 | M. M. Boggess | L. L. Davis | Kansas City Public Service Co., 728 Delaware St., Kansas City, Mo. |
| Lehigh Valley | 2 | E. F. DeTurk | J. E. Treweek | Pennsylvania Pwr. & Lt. Co., Hazleton, Pa. |
| Los Angeles | 8 | W. F. Grimes | M. A. Sawyer | Southern Calif. Tel. Co., Box 5300 Met. Sta., Los Angeles, Calif. |
| Louisville | 4 | Stanley Warth | F. W. Russell | 119 No. Third St., Louisville, Ky. |
| Lynn | 1 | R. M. Pfalzgraff | C. F. Savage | General Electric Co., West Lynn, Mass. |
| Madison | 5 | E. D. Ayres | W. A. Kuehlthau | 441 West Johnson St., Madison, Wis. |
| Memphis | 4 | J. H. Tole | M. J. Mallery | Power Equipment Co., 1352 Madison Ave., Memphis, Tenn. |
| Mexico | 3 | F. P. Teuscher | E. M. Gonzalez | Apartado 8-Bis, Mexico, D. F., Mexico |
| Milwaukee | 5 | L. H. Hill | R. R. Ranson | Cutler Hammer, Inc., Milwaukee, Wis. |
| Minnesota | 5 | A. Nelson | I. B. Garthus | Northern States Power Co., Minneapolis, Minn. |
| Montana | 9 | R. S. Stokan | J. A. Thaler | Montana State College, Bozeman, Mont. |
| Nebraska | 6 | F. W. Norris | Ray Blain | Signal Corps, U. S. Army, Omaha, Neb. |
| New Orleans | 4 | F. G. Frost | F. E. Johnson | 317 Baronne St., New Orleans, La. |
| New York | 3 | A. F. Dixon | J. F. Fairman | Consolidated Edison Co. of N. Y., Inc., 4 Irving Pl., New York, N. Y. |
| Niagara Frontier | 1 | R. M. Darrin | N. E. Brown | Buffalo General Elec. Co., 429 Electric Bldg., Buffalo, N. Y. |
| North Carolina | 4 | W. J. Seeley | Otto Meier, Jr | Duke University, Dept. of Elec. Engg., Durham, N. C. |
| Oklahoma City | 7 | E. H. Dinwiddie | J. L. Jones | 1006 Telephone Bldg., 405 No. Broadway, Oklahoma City, Okla. |
| Philadelphia | 2 | J. B. Harris, Jr | H. S. Phelps | Philadelphia Elec. Co., 2301 Market St., Philadelphia, Pa. |
| Pittsburgh | 2 | Paul Frederick | W. A. Furst | Westinghouse Elec. & Mfg. Co., E. Pittsburgh, Pa. |
| Pittsfield | 1 | A. Boyajian | J. L. Cantwell | General Electric Co., Pittsfield, Mass. |
| Portland | 9 | C. C. Boozier | C. B. Carpenter | Pacific Tel. & Tel. Co., Portland, Ore. |
| Providence | 1 | E. Carlson, Jr | O. E. Sawyer | 59 Lawrence St., Cranston, R. I. |
| Rochester | 1 | B. M. Werly | C. L. Smith | Rochester Gas & Elec. Co., 89 East Ave., Rochester, N. Y. |
| St. Louis | 7 | B. T. McCormick | L. L. Crump | James R. Kearney Corp., 4236 Clayton Ave., St. Louis, Mo. |
| San Antonio | 7 | M. H. Lovelady | Louis Thein | St. Mary's University, San Antonio, Texas |
| San Francisco | 8 | R. O. Brosemer | C. A. Andrews | Westinghouse E. & M. Co., 1 Montgomery St., San Francisco, Calif. |
| Saskatchewan | 10 | F. E. Estlin | James Smith | Canada Wire & Cable Co. Ltd., P. O. Box 426, Regina, Sask. |
| Schenectady | 1 | S. A. Holme | E. M. Hunter | General Electric Co., Schenectady, N. Y. |
| Seattle | 9 | C. H. Hoge | R. E. Lindblom | University of Washington, 203 Engg. Hall, Seattle, Wash. |
| Sharon | 2 | H. S. Smith | F. L. Snyder | Westinghouse E. & M. Co., Sharon, Pa. |
| Spokane | 9 | M. F. Hatch | Neal Baden | East 303 Glass Ave., Spokane, Wash. |
| Springfield | 1 | F. R. Longley | R. E. Curtis | Western Massachusetts Companies, Springfield, Mass. |
| Syracuse | 1 | W. H. Lawrence | E. J. Gibbons | 206 Elizabeth St., Syracuse, N. Y. |
| Toledo | 2 | W. M. Campbell | H. R. Daykin | 3701 Larchmont Parkway, Toledo, Ohio |
| Toronto | 10 | R. E. Jones | O. W. Titus | Canada Wire & Cable Co. Ltd., Box 340, Toronto, Ont. |
| Urbana | 5 | C. A. Keener | J. T. Tykociner | University of Illinois, Elec. Engg. Dept., Urbana, Ill. |
| Utah | 9 | C. A. Wolfrom | A. C. Kelm | Utah Power & Light Co., Salt Lake City, Utah |
| Vancouver | 10 | C. Arnott | J. H. Steede | B. C. Electric Railway Co. Ltd., 425 Carrall St., Vancouver, B. C |
| Virginia | 4 | W. F. Nimmo | J. S. Miller | University of Virginia, University, Va. |
| Washington | 2 | J. F. Meyer | N. B. Ames | George Washington University, Washington, D. C. |
| Worcester | 1 | V. Siegfried | W. W. Locke | Worcester Polytechnic Institute, Elec. Engg. Dept., Worcester, Mass. |

Total 62

# Industrial Notes

**Pittsburgh Flood Prevention Project.**—The first major flood prevention project to reach the construction stage in the Pittsburgh district will protect the Turtle Creek Valley in which lies the huge works of the Westinghouse Elec. & Mfg. Co. and other major industries. In the future when high water from the Monongahela river threatens the valley, two huge gates will be lowered, forming a barrier against rising waters and the normal flow of Turtle Creek will be continued by means of powerful pumps. The project announced by Westinghouse vice-president Ralph Kelly, will cost $500,000. Installation of the gates will be made just below the main Westinghouse works. One of the steel gates, 80 feet long by 30 feet high will form a dam in Turtle Creek; the other, 40 feet long and 20 feet high will close the street. When not in use the gates will be held approximately 20 feet above the street level to accommodate traffic. The three pumps, of the vertical type, were designed by the Westinghouse condenser engineering department at South Philadelphia, and will have a combined capacity of 5000 to 7500 cubic feet per second. Each will be 11 feet 11 inches in diameter and will be driven at 112 rpm by 5000 hp electric motors. Each of the motors will be 23 feet in diameter.

**Progress in Building Construction.**—With the July record, once again construction has established a new high level for the recovery. According to figures of F. W. Dodge Corp., the July total for all classes of construction amounted to $321,602,700 in the 37 eastern states, topping the previous high figure of the recovery reported in June of this year in the amount of $317,842,100 and representing an increase of 8 per cent over the total of $294,734,500 reported in July 1936. Of the July 1937 volume, $81,046,000 was for residential building, $138,063,500 for non-residential building, and $102,493,200 for civil engineering projects, i.e., public works and public utilities.

**New Coil Winding Company.**—Electrical Windings, Inc., 16 No. May St., Chicago, has been organized to specialize in the design and manufacture of all types of transformers, solenoids, chokes, magnets, etc. The new company is set up to design coils and mountings for any specific purpose, or to work from manufacturers' specifications. Orland Murphy, president, was formerly associated with Utah Radio Products and Standard Transformer Corp. and was recently chief engineer for Robertson-Davis.

**Empire Sheet Appointment.**—Joseph B. Montgomery, Jr. became associated with Empire Sheet & Tin Plate Company's organization August 1st and assumed charge of sales. At a meeting of the Board of Directors held on Monday, August 9, he was elected vice-president in charge of sales, according to an announcement made by J. M. Hill, president. Mr. Montgomery was previously employed in the sales organization of the Bethlehem Steel Corp., in the sheet and strip sales department.

**American Rolling Mill Appointment.**—Marvin Marsh, special Armco sales representative in the Kansas City territory, has been named manager of the company's newly created district office at 7100 Roberts St., Kansas City, Mo., according to W. W. Sebald, vice-president in charge of commercial activities of The American Rolling Mill, Middletown, O.

**Absorbs E-M Capacitor Division.**—The Cornell-Dubilier Electric Corp., South Plainfield, N. J., has taken over the condenser manufacturing equipment and sales staff of the Electric Machinery Mfg. Co., Co., Inc., Minneapolis. According to Octave Blake, president of Cornell-Dubilier, the additional equipment supplements the modern machinery already housed in the company's 11 buildings covering more than 33 acres.

# Trade Literature

**Transformers.**—Bulletin 2259, 4 pp. Describes industrial substation service transformers. Allis-Chalmers Mfg. Co., Milwaukee, Wis.

**Motors.**—Bulletin GEA 1195B, 4 pp. Describes large synchronous motors for driving metal-rolling mills. General Electric Co., Schenectady, N. Y.

**Switchgear.**—Bulletin 1187, 8 pp. Describes indoor type cubicle switchgear, listing outstanding advantages, applications, and details of construction as well as complete dimensions. Allis-Chalmers Mfg. Co., Milwaukee, Wis.

**Aircraft Wires and Cables.**—Bulletin A-832, 28 pp. Describes mechanical control cords and aircraft strand, galvanized wire and fittings; also electrical cables for use in airplane construction. John A. Roebling's Sons Co., Trenton, N. J.

**Switchboards.**—Bulletin GEA 2617, 8 pp. Describes safety enclosed, air circuit breaker switchboards, with trip-free air circuit breakers rated at 250 volts d-c, 600 volts a-c; up to 10,000 amperes, manually or electrically operated. General Electric Co., Schenectady, N. Y.

**Lift Magnet Controller.**—Bulletin, 4 pp. Describes a new automatic-discharge type controller enabling high speed lifting magnet operation, as well as quick release of the load. The Electric Controller & Mfg. Co., Cleveland, O.

**Silent Gears.**—Bulletin, 8 pp. Describes Celeron (laminated plastic) silent gears. Recommended practises for machinery, gear tooth data and tables on horsepower rating per inch of face are included. Continental-Diamond Fibre Co., Newark, Del.

**Arc Welder.**—Bulletin GEA 2447C, 10 pp. Describes new Mutator arc welder (electronic rectifier) specially designed to provide direct current at the low values required for welding of light-gauge metal. General Electric Co., Schenectady, N. Y.

**Booster Regulators.**—Catalog, Sec. 47–230, 8 pp. Describes application, operation, construction and ratings of the four step feeder-voltage booster-regulator, designed for use on rural lines or distribution circuits where the load changes over a wide range. Westinghouse Elec. & Mfg. Co., E. Pittsburgh, Pa.

**Cable Testing Equipment.**—Catalog E-54 (3), 8 pp. Describes apparatus for power factor measurements by the phase defect compensation method for high voltage production tests of power cables. Leeds & Northrup Co., 4962 Stenton Ave., Philadelphia, Pa.

**Porcelain in Wiring.**—Bulletin, "The Fact Manual of Standard Electrical Porcelain," second edition, rearranged and revised to illustrate the 1937 National Electric Code Revisions. Includes wall chart depicting proper use of porcelain knobs, tubes and cleats, as well as the newly developed all porcelain outlet, switch and receptacle boxes. Standard Electrical Porcelain Manufacturers, 201 No. Wells St., Chicago, Ill.

**Diesel Generating Sets.**—Bulletin 3600-A2, 16 pp. Describes the construction and application of model 36-A Diesel generating sets in industrial plants, either as independent units carrying the entire load or for parallel or auxiliary operation in conjunction with other electrical service. Alternating-current sets are offered in ratings from 5.3 to 100 kva and direct current sets from 5 to 80 kw. Fairbanks, Morse & Co., 900 So. Wabash Ave., Chicago, Ill.

**Condensers.**—Catalog, 32 pp. Lists a large and diversified line of condensers, together with essential resistors, in a manner which permits of finding any required condenser in minimum time. Condensers are grouped first under their general type classification, and then under working voltage, and finally by capacity. Eight pages of exact duplicate replacement condensers are included, covering practically all standard set requirements. Aerovox Corp., 70 Washington St., Brooklyn, N. Y.

**Distribution System.**—Catalog, 40 pp. Describes Universal type "Trol-E-Duct," a mobile electrical distribution system designed for general lighting and light duty power applications. This innovation consists essentially of section lengths of formed steel duct enclosing copper bus bars partially wrapped in insulating material. Movable current-carrying trolleys and stationary twistout plugs to which lights, tools and appliances can be wired are inserted in a narrow continuous slot extending along one side of the duct. The new system supplements Industrial "Trol-E-Duct," for heavy duty power applications. Bull Dog Electric Products Co., 7610 Jos. Campau Ave., Detroit, Mich.

# Electrical Engineering

Registered U. S. Patent Office

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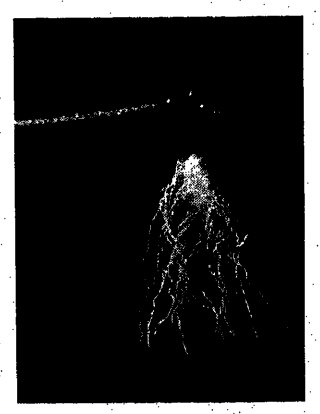
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## The Cover

**A 14-foot discharge at the high-voltage laboratory of the Ohio Brass Company, Barberton, which may be visited by those attending the forthcoming AIEE District meeting at Akron**



# High Lights

**Spinning Atoms and Electrons.** In the construction of the physical world, mass and charge fulfill the rôle of raw materials, and laws of angular momentum furnish the principles of the architecture thereof, according to a noted authority who recently discussed the subject at a meeting of the Institute's New York Section (*pages 1228–35*).

**Out-of-Step Protection.** Relay requirements for the protection of machines operating out of step may be determined by geometric treatment, which reveals that the common method of assuming a system to be pure reactance leads to errors in low-frequency systems that have low reactance (*pages 1261–7*).

**Radio Interference.** Radiobroadcast listeners today demand reception free from interfering noises, while the variety of devices that may produce noise increases continually; co-operation between manufacturers and service men, radiobroadcast interests, and public utilities may bring interference under control (*pages 1248–52*).

**Alternator Currents.** By the application of symmetrical components, armature and field currents of an alternator under unsymmetrical short-circuit conditions may be obtained that agree well with oscillograms; the method aids in the determination of the effect of resistance in armature and field circuits (*pages 1268–76*).

**Lightning.** Laboratory tests with the lightning-stroke generator and field observations have given information on the lightning-stroke channel; the results suggest a pressure in the "core" some 40 to 60 times atmospheric pressure and a corresponding gas temperature in the range of 11,000 to 17,000 degrees Kelvin (*pages 1253–60*).

**Protective Multiple Earthing.** Investigation in England shows that the present methods of earthing (or grounding) rural electric circuits are not wholly adequate for all circuits; recommendations for improving the situation have been made (*pages 1245–7*).

**Letters to the Editor.** Subjects discussed in the "Letters" columns of this issue include: AIEE Student Branch activities; Institute programs and publications; characteristics of human nature; electric-range units, and solution of impedances in multiple (*pages 1326–9*).

**Specialization in Education.** "Get the humanities and foundations of science, but don't get technology," say industrial leaders when asked what type of education they want in the engineers they hire (*pages 1238–40*).

**Engineering Profession.** The method of engineers rather than their occupation is the characteristic of the engineering profession that distinguishes it from other learned professions, according to a well-known past-president of the Institute (*pages 1235–8*).

**Adding With the Slide Rule.** By combining the ability of the slide rule to perform addition with its more usual functions as a multiplying device and a set of tables, the usefulness of this familiar device may be greatly extended (*pages 1243–4*).

**Engineers and Economics.** A noted engineer and educator, past-president of the Institute, has suggested some ways in which engineers may secure greater influence in guiding economic affairs that have an impact on engineering (*pages 1225–7*).

**Induction Motor Performance.** A method of predicting the performance of single-phase induction motors from design data has been developed which is said to be shorter and more direct than some other methods in common use (*pages 1277–84*).

**Pacific Coast Convention.** Activities at the Institute's 1937 Pacific Coast Convention held recently at Spokane, Wash., are reported in the news section of this issue; a total of 266 members and guests registered (*pages 1320–2*).

**New Photometric Unit.** A new unit of candlepower has been adopted by the International Committee on Weights and Measures which it is hoped will be put into use in 1940 (*pages 1323–4*).

**New Committee Chairmen.** Beginning with this issue, newly appointed chairmen of AIEE committees are being introduced to the membership through the "Personals" columns (*pages 1330–1*).

**D-C Machine Tests.** Recently developed methods of measuring the stray load loss of d-c machines with consistent results permit more accurate determination of the losses and efficiency (*pages 1285–9*).

**Physics in Engineering Education.** According to one authority, effective instruction in physics determines the quality and tempo of engineering teaching (*pages 1241–3*).

**Government Reorganization.** Comments on this subject were included in the current "News Letter" of American Engineering Council (*pages 1325–6*).

# DISCUSSIONS

Appearing in this issue are discussions of the following papers:

## Insulation


Oxidation in Insulating Oil—Whitehead and Mauritz 1304

Properties of Saturants for Paper-Insulated Cables—Sommerman 1302

Tests on Oil-Impregnated Paper—II—Race . . 1298

The Dielectric Strength of Noninflammable Synthetic Insulating Oils—Clark 1299


## Electrical Machinery


Approximating Potier Reactance—Beckwith . . 1318

Characteristic Constants of Single-Phase Induction Motors—Morrill 1312

End-Winding Inductance of a Synchronous Machine—Caldwell 1312

Reactance of End Connections—Douglas . . . 1315


## General Power Applications


A-C Motor Protection—Kuhn . . . . . 1306

Coincidental Electric Drives—Miller . . . . 1307

Impulse Operation of Magnetic Contactors—Stansbury 1307


## Insulation Co-ordination


Application of Spill Gaps and Selection of Insulation Levels—Melvin and Pierce 1290

Application of Arresters and the Selection of Insulation Levels—Foote and North 1293

Basic Impulse Insulation Levels—EEI NEMA Joint Committee 1298

Insulation Co-ordination—Sporn and Gross . . 1296

Insulation Strength of Transformers—AIEE Subcommittee 1297


## Power Transmission


New Oil-Filled Cable Lines in Chicago—Halperin and Shanklin 1307

System Recovery Voltage Determination by Analytical and A-C Calculating Board Methods—Evans and Monteith 1308


## Vibration and Balance


Dynamic Balancing of Small Gyroscope Rotors—Esval and Frische 1305–6

Vibration Isolation of Machinery—Hansel. . . 1306

Vibration-Measuring Instruments—Greentree 1305–6



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# Engineers and Economics—II

By DUGALD C. JACKSON
PAST-PRESIDENT AIEE

**What is the appropriate attitude for engineers to take toward economic problems, as individuals and through the AIEE? In response to a request from the Institute's publication committee, a noted engineer and educator here gives his answer to that question.**

AT THE 1937 AIEE summer convention held in Milwaukee, Wis., an informal session was held to discuss, among other subjects, what the Institute might do to aid the thinking of members regarding the engineer and his relation to economics, over which session I was asked to preside. The circumstances lead me to take that session as an example and as text for this article. The session was attended by perhaps 35 of the younger members of the Institute, including those who were in and out. The discussion was lively. It mostly related to what the Institute and its individual members can do to aid in economic controls. Extreme diversity was exhibited in the views individually expressed with full sincerity, which is common in such forums when economic and social problems are discussed. Also several aspects of any problem were likely to be entangled together in confusion by any speaker, which also is usual in such forums. When I speak of "such forums," I mean groups of able and sincere men who have lived through widely different social and economic experiences and who therefore have diverse (and often contradictory) intellectual outlooks which have arisen from their diverse experiences.

In their primary vocations, engineers have a distinguished habit of studying all the facts of a problem in hand, analyzing the problem into its component elements, filling in incomplete premises by judgment founded on experience with previous problems, then solving the problem by logical reasoning from the premises, but always remembering that the synthesis is only an approximation to exact truth because some of the analyzed premises were incomplete as to facts and were filled in through the application of judgment.

Here we have the age-old, sound process of guiding our thinking by our learning. The Chinese philosopher Confucius, nearly 2,500 years ago, admonished his disciples that thinking without learning is dangerous. We engineers habitually avoid the danger in connection with our technical problems by learning all we can relating to analysis and synthesis of each problem and guiding our thinking thereby. Under these conditions, different engineers of broadly competent experiences readily agree upon the relative merits of different solutions for an engineering problem. Sentiment and prejudice have little place for expression in such situations, and wishful thinking without a factual foundation no place whatever. Examples in which associations of engineers have become of recognized influence as voluntary advisers in engineering matters relating to municipal affairs, such as the situation in Milwaukee which was referred to in the session at the AIEE Milwaukee Convention, are instances where the facts have been sedulously studied for each problem and recommendations made after careful analysis to assure that the facts are understood, followed by synthesis of the results into a clear solution. Recommendations based on such a foundation are always persuasive and are likely to be convincing to any unprejudiced mind.

It is difficult, however, to secure facts for such a solution in social affairs which play so large a part in political economy. I use the phrase political economy as a synonym for economics, in the sense of that branch of learning which comprises the physical and financial, i.e., the material, aspects of social organization, as distinguished from the moral and sentimental aspects of human relations which are peculiarly comprised within the fields of religion and philosophy. We thus have for political economy (of which phrase, the word economics is a synonym) a field which is modified by the state of science and invention and by the modes of living which change from generation to generation as a consequence of experience guided by changes of science and invention. It is a big field which includes concretely the various problems discussed at the informal session in Milwaukee, besides many other important problems.

Economists are likely to leave us considerably in the dark regarding the economic aspects of our problems. Moreover much of economic writing is not directly applicable to engineering affairs. Engineering is a branch of learning and practice which bridges the gulf between the physical sciences and political economy. Therefore, it is natural that only a part of the structure of political economy should at present directly affect our engineering affairs, just as only a part of the structure of science directly affects engineering at present. We, therefore, must help ourselves toward understanding the impact of political economy on our engineering affairs, while enlisting

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This is the second in a series of articles on this subject prepared especially for ELECTRICAL ENGINEERING; the first, by Morris E. Leeds (A'01, F'26) was published in the February 1937 issue, pages 206–07.

DUGALD C. JACKSON is professor emeritus of electrical engineering, Massachusetts Institute of Technology, Cambridge. He received the degree of civil engineer from Pennsylvania State College in 1885 and the honorary degree of doctor of science from Columbia University in 1932. From 1887 to 1891 Doctor Jackson was engaged in the design and construction of electric light and power plants and distribution systems, and in electric railway work. In 1891 he became professor of electrical engineering at the University of Wisconsin, and in 1907 professor and head of the department of electrical engineering at Massachusetts Institute of Technology, which position he held until his retirement in 1935. He was engaged in consulting engineering from 1891 to 1930, and was particularly active in the fields of railway electrification and public utility affairs. In addition to his term as president of the AIEE (1910–11), Doctor Jackson has served on many AIEE committees over a period of more than 20 years, including chairmanship of the following: standards, 1920–21; traction and transportation, 1914–16; education, 1909–10; Edison Medal 1930–32–33; institute policy, 1928–30. He is a member of many other technical societies in this and other countries, and among other honors he has received the Lamme Medal of the Society for the Promotion of Engineering Education, of which society he was president 1905–06. He is the author of 5 books and numerous articles and papers.

the aid of economists in our effort to gain that understanding. This may be carried out in a way that is analogous to the manner in which we have come to understand the impact of science on engineering. As engineers, we continue our intimacy of thought regarding science, and we mutually discuss our problems in the light of science. Our situation calls for a like mental attitude toward political economy.

Those economists who call themselves sociologists are sincerely endeavoring to assemble a factual basis which ultimately may be helpful to our understanding of the relations of engineering to the betterment of life, but the basis is yet so meager that the forward visions of the sociologists are mostly hope, guided by sentiment. As highly as we all regard those 2 qualities (hope and sentiment), we must dismiss the combination from consideration as an adequate foundation for engineering works. Hope guided by science or experience, accompanied by great industry, has led to many great inventions in our field; but this combination of hope guided by science or experience commands infinitely greater reliance than hope guided by sentiment.

The sociologists have produced writings from which we can glean an understanding of the reason why certain types of organizations in the field of engineering are objects of so much popular suspicion and even resentment. For example, the recently published book entitled "American City, a Rank and File History," by Charles R. Walker, with its sordid but unhappily true tale of illegalities and tricky practices exercised or condoned by those least to be justified by standing and education, discloses some of the grounds. However, we must make our interpretations for ourselves rather than accept, second-hand, the interpretations of disciples.

Of this last point, I may be permitted to elaborate an illustration. Karl Marx, of widespread note, author of "Das Kapital" and other widely quoted writings, was a genius in investigating and expounding the philosophy of history, but when dealing with man's daily interests his writings are sometimes contradictory and, it seems to me, are frequently inaccurate. His numerous disciples have interpreted his writings into a structure of the utmost unsoundness, so that such truth as exists in Marx's own philosophy can be grasped only by reading his own productions and considering the groundwork from which his philosophy springs.

There is thus at large much loose talking and much wishful thinking about affairs in the realm of economics which affect us as engineers. Considerable American legislation and some business activities follow the dictates of wishful thinking. We engineers are not altogether without blame. In this realm of economics, which is not a specific part of our own field, we (ourselves) are likely to do thinking and talking without first securing a competent degree of learning regarding the realm and its various features. We go contrary to our usual practice in our engineering specialties. We sometimes take our opinions second-hand, without such critical examination as will assure us that the opinions are founded upon a broad base of facts, and we reach mental decisions without adequate facts for a basis. Leisure is not available for engineers actively employed in their absorbing vocational specialties to follow this collateral path with will and concentration. The results are not in keeping with our repute in the realm of scientific matters. We become imbued with ideas which are only partially supportable. We may come to believe that these ideas are sound "principle," which leads to such reluctance toward modifications that our colleagues with other views may cry "prejudice."

Here again, I may be permitted to illustrate. For some 25 years I lectured on the organization and administration of public service companies as part of my duties as head of the department of electrical engineering at Massachusetts Institute of Technology. This imposed the necessity of discussing corporation forms of organization for such companies. Year by year the students in the group were 15 to 20 graduates of MIT and other engineering schools, and were fairly mature. All had preceded their engineering school undergraduate career by one of the usual forms of preparation for college admission. They were drawn from all parts of the country and many walks of life. They came from the homes of mechanics, industrial managers, bankers, merchants, merchants' clerks, farmers, and so on.

The corporate form of organization (i.e., a corporation) for doing business, established in conformity with specific laws of our several states, is so widely used as an instrumentality of legitimate businesses (large and small) in so wide a range of business activities that obviously it has been accepted by experienced and honest business men as a fair and useful instrument in our social setting. Indeed some who have studied and reflected on the matter believe the corporate form in business to be one of the most serviceable evolutions which have occurred for advancing general welfare. It makes practicable the carrying on of large enterprises which otherwise could not be carried on with equal advantage to the public. It is serviceable in large and small businesses. It operates under legal limitations which can prevent abuses. I confess to being one of those who believe in the desirability of corporations; but I am ready to recognize abuses which arise from the application of defective laws. These abuses can be eradicated on public demand arising for modification of the applicable laws.

In opening the discussion of corporate forms to this group of graduate students I usually asked a few questions to bring out the knowledge which they already possessed respecting corporations and the opinions of the individuals in regard to the corporation as an instrumentality for carrying on business. Year after year without exception a considerable proportion expressed opinions adverse to corporations and often inferred that they were instrumentalities for legalized extortion from customers or other unfair practices. "One sided," do you readers mentally exclaim? But read farther! Now and then there would be in this category of corporation detractors the son of a merchant or of a merchant's employee, proud of the business in which his father was engaged and proud of his father's pride in it, but unknowing that this business, worthy of honest pride, was carried on as a corporation. One sided? I agree; but more—it is an illustration (perhaps somewhat extreme, though true)

of our frequent manner when dealing with economic matters of thinking (and talking) without associating the thoughts with proper learning, contrary to Confucius' ancient but excellent admonition and equally contrary to our own habit when dealing with technical affairs.

To show that observation of such an attitude is not an isolated experience of my own, I will quote from a test by the distinguished psychologist E. L. Thorndike. Professor Thorndike in 1934 made a test of the extent of information and quality of reasoning on business and economic issues exhibited by a group of 76 unemployed persons (44 men and 32 women). He says that the group was "much above the average for the United States" in general intelligence and education. Over half this group alleged that no trade can possibly benefit both parties to the trade. Except that such unsound thinking is injurious to our national society, we might view it with the same humorous tolerance as we view the schoolboy's reputed definition of the word "husbandry" to mean "male dominance." Unfortunately the tragedy lying in the wake of economic errors strips them of all humor.

Some of the responses to certain of his test questions appeared to Thorndike "to be symptomatic of a tendency to regard owners of business concerns and traders as being paid too highly for the services which they and their property render." He worked out such things into what he calls a "prejudice score" for the individuals of his group, a high score meaning high prejudice. He sums up by saying that the abler minds in the group have slightly lower prejudice scores, but the differences can be accounted for by the fact that they make fewer errors of all sorts; that the younger individuals show higher prejudices than the older ones and the women show less than the men; also that ability in an academic examination in economics involves but slight decrease in the prejudice. This prejudice (regarding business affairs) is of a peculiar character "being immune to intelligence of the individual and almost immune to academic knowledge of economics." Of course, Thorndike's group was not composed of engineers; but, are we engineers immune from the same typical prejudices? The informal session at Milwaukee showed that in economic affairs we manifestly arrive at diverse conclusions (which we individually stick to as though they represent abstract, right "principle"), all drawn from alleged similar premises. Is not this definite evidence that in economic affairs people (even engineers) are likely to do their thinking without first accumulating adequate learning? Also, may it not demonstrate that emphatic reliance on our individual inferences leads us to forget that the inferences of no single purely human being ever approximated to "abstract principle," and therefore such inferences should be open to criticism and argument without acrimony?

The circumstances being as thus outlined, what can we do to rescue ourselves from so false a situation and thereby secure more influence in guiding economic affairs which have an impact on engineering? Obviously we must improve our thinking, which we may accomplish in several ways, including among others the following procedure:

First: Members of our Sections can promote informal discussion sessions directed toward economic affairs, in which all points of view regarding the particular affairs are sought out and the adequacy of the foundation for each view is frankly discussed, while rancor is suppressed. By such discussions, the causes of divergence of views may often be exposed and correct views mutually reached. Some who enter such discussions may profit by reading the little book by John Morley (the distinguished British Liberal) entitled "On Compromise," which was published many years ago. The Engineers' Council for Professional Development (which is a mutual instrument of 7 great national societies in the engineering field) has as one of its objectives the aim to give aid to the younger engineers in arranging their continuing self-education. Through its headquarters at 33 West 39th Street in New York City advice may be secured regarding the co-operation of sections of other engineering societies in discussion sessions and collateral educational activities. It is important for the welfare of such discussion sessions that the general topic for consideration shall be clearly announced in advance and that the chairman shall hold each speaker to limits within range of the topic. Aside from this, and the rule that each speaker shall assume the sincerity of all other speakers, no discussion rules are needed.

Second: Sections may invite influential men of the community who are men of experience in business affairs to make addresses in exposition of their own views on questions about which differences have arisen in the informal sessions, if such sessions have been held. To gain any effectiveness from this, any guest invited to give the address on a controversial subject should understand that on some other date an equally distinguished man known to have opposing views will be (or has been) heard. Such bilateral exposition in controversial fields by experienced and honest men of diverse views is the only means of gaining real learning in controversial matters where lectures are relied on. For real learning, however, the discussion sessions are preferable. Professional lecturers dealing with this realm should be viewed with caution because they often are either over-dogmatic or superficial in their expressions.

Third: An informal session at each national convention, of character similar to the Milwaukee discussion session and programmed in advance, would bring together views from all parts of the country if there is as much interest in economic questions among the members under 50 years of age as was alleged in Milwaukee. Catch-as-catch-can rules for debate are appropriate for such sessions provided each speaker will respect the sincerity of every other one, and the presiding officer possesses a fund of common sense in restraining the speakers from straying too far from the objective topic which was programmed. After several such occasions we might find (at least in some of our problems) such unity of views founded on adequate grounds that our mutual influence in the nation would become large in relation to economic affairs affecting our particular branch of engineering. At present we have no such joint influence because we do not agree with each other. We have not as yet mutually accumulated the learning sufficient to support and guide that soundness and unity of thinking in economic affairs which is essential for securing an influence in them that is comparable with our influence in specific technical affairs.

# Spinning Atoms and Spinning Electrons

## An address* describing how it is known that atoms, electrons and other fundamental particles are continually spinning

By K. K. DARROW
ASSOCIATE AIEE

NO DOUBT you are all accustomed to thinking of atoms as objects—very small objects, of course—which are endowed with *weight*. I can say that with perfect safety to an audience of engineers and physicists; but indeed it can be said with safety to any audience—I mean, of course, any audience literate enough to attach any meaning at all to such a word as "atom." It may be that philosophers of the past have imagined weightless atoms—I am not historian enough to deny that, nor to affirm it; but if such have ever been invented, they have remained quite outside the currents of modern thought. For us, weight is a property which we attribute to the atom. Since this is, after all, a professional audience, I will now change over to that other word which many people have such difficulty in distinguishing from "weight": I will say that *mass is a property which we attribute to the atom.* In a way, that is a negative statement. It means that we do not hope to explain mass in terms of something more fundamental; it means that we accept mass as being itself so fundamental that even the elementary particles have it. When I say "elementary particles," I am still referring in part to the atoms, though it is a somewhat careless usage to do so; but I am referring also to electrons both positive and negative, to protons, to alpha-particles, to nuclei—to all the particles, in effect, of which the atoms are built up. Also I ought to include the corpuscles of light, but this lecture will be quite long enough if I leave them almost unmentioned. All of these particles, then, are endowed with mass; each of them has a characteristic mass of its own, which we do not attempt to explain, but which we do try to measure as closely as we can.

There is another property, familiar to you though not to everyone, which we accept as equally fundamental and equally unexplainable with mass: it is *electric charge.* We attribute it also to the elementary particles, though not, it is true, to all of them. We assign it to the electrons, of course, and to protons and alpha-particles and all of the hundreds of nuclei which distinguish the elements and the isotopes thereof from each other. When I say that we "assign" it, I do not for a moment mean that we are doing something arbitrary or untestable. We *know* that these elementary particles are charged, and indeed we have measured their charges. Atoms do normally appear to us uncharged, but we know that that is because the elementary particles of which they in their turn are made up are some of them positive, some of them negative, and the balance normally happening to be perfect. Some particles, the neutrons and the corpuscles of light, seem permanently chargeless; but perhaps some day we shall find it expedient to regard them as groups of smaller particles having charges which balance one another. Apart from these 2 cases, we may say with assurance that whenever we penetrate as far into the fine structure of substance as we are able to go, we find the elementary particles invested with mass and with charge.

And now I arrive at the subject of this talk, the *third* property of the elementary particles: the property which is called "angular momentum," or "spin" for short. Now of course I am speaking as to an audience of physicists, for if this were an audience of laymen it would certainly be frightened by such a term as "angular momentum." This is a misfortune, and perhaps a defect of general education; for angular momentum is about as important as mass or charge, not only on the scale of the elementary particles but also on the scale of the visible world. Think what it would mean if there were no such thing as the conservation of angular momentum! The earth might cease from turning, it might cease from providing us with the regular alternation of day and night, and with our standard of the flow of time; it might even cease from traversing its regular orbit, and fly off into space or fall into the sun. Well, I do not wish to scare you with any such dire imaginings—I only want to remark on the fact that the human race has been acquainted for a very long time indeed with angular momentum as something which is unvarying, imperturbable, incessant; for of all the unvarying and imperturbable and incessant things in the world, the rotation of the earth is the most obvious and the most striking. So striking it is, that you might reasonably expect that all the philosophers and all the physicists of the past would have conferred the property of spin on all the atoms which they have invented. Well, they did not; the notions of the spinning atom, the spinning electron, the spinning nucleus are among the newest in physics. I think that some of the reasons for the delay will be evident later on in this talk, but it remains partly mysterious, at least to me. Looking back on the situation with the well-known advantages of hindsight, I do feel a good deal of surprise that the spinning atom did not make an earlier

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entry upon the scientific stage. Perhaps some of you will remember hearing the words "vortex atom" and "vortex theory" which used to be so prominent in physics, and will take the spinning atom of today for a lineal descendant of those vortices of old. If this were correct, we could trace back the ancestry of the spinning atom for about 300 years; but I think that it is not correct. The vortices of which Descartes and Malebranche were dreaming 3 centuries ago were more like whirlpools of streaming particles, and the vortices which were imagined by Helmholtz and Lord Kelvin some 50 years ago were also whirlpools, but they were whirls in an idealized continuous frictionless fluid. Let us pause for a moment to notice how the attitude of physicists has altered in these 50 years! Kelvin and Helmholtz began with the idea of an ethereal fluid pervading the whole of space, and valiantly tried to represent the atoms as whirlpools in that fluid; but we have long since discarded that ether, and our spinning atoms and other elementary particles are small delimited rotating bodies voyaging in a void.

It is not therefore the vortex which I will introduce to you as the ancestor of the spinning atom, but rather the "Amperian whirl" as it still is sometimes called. You remember, of course, how Ampère in 1820 made a very great achievement which for the purposes of this talk I will divide into three. First, he discovered the fact that an electric current flowing in a circuit is equivalent to a magnet. Next, he worked out the mathematical laws whereby, given a current and the circuit in which that current is flowing, we may calculate the strength or the moment of the equivalent magnet. I will write down the formula for the case of a current $i$, flowing in a plane loop of area $A$: the magnetic moment of the equivalent magnet, $\mu$, is given thus:

$$\mu = iA/c$$

Here $c$ is a factor of transformation which we are now obliged to employ because we habitually use, in atomic physics especially, a unit-system different from Ampère's. The third part of the great achievement was this: Ampère founded what remains to this day the theory of magnetism, by presuming that *the individual atoms of any magnetizable substance are themselves little magnets*, and that *the atoms are magnets because they have little whirls of current in them.*

This notion—the notion that atoms are magnets, and that they are magnets because they have internal circulating currents—is the true forerunner of our present conception of the spinning atom. It is, however, only a very primitive form of the modern conception, and there is much to be added to it. First of all and above all, there is the question of angular momentum. Is angular momentum an attribute of these whirling intra-atomic currents, or is it not? You may think that the answer to this question is self-evidently "yes!" But remember that for many generations of our forefathers electricity was an *imponderable* fluid. Weber, however, did consider the affirmative answer, and Maxwell even attempted to ask the question of Nature by experiment—vainly, as it turned out. Not till the electron was discovered did the mass of electricity become a prominent part of experience. A moment ago I divided Ampère's achievement into three parts; similarly I wish now to divide the discovery of the electron into three. Those who isolated and identified and measured the electron were proving three things: first, that negative electricity consists of corpuscles of a definite charge, $e$; second, that these corpuscles have a mass, $m$; and following from these two, the principle which I have called the third part of the discovery, namely, that an electron revolving in an orbit has an angular momentum.

I will designate angular momentum in general by the letter $p$, and now I will show you a formula for the ratio of $\mu$ to $p$ in an atom in which an electron is running around in an orbit and constituting an Amperian whirl. The formula, like this other one, for $\mu$, is valid for an orbit of any shape, but to get it quickly I will simplify by postulating a circular orbit. The radius of the circle being $r$, the area $A$ is $\pi r^2$; the current around it is equal to the electron-charge $e$, multiplied by the number of times per second that the electron runs around the orbit; if I denote the velocity of the electron by $v$, this number is $v/2\pi r$; hence the product $iA/c$ is equal to $evr/2c$. Now the angular momentum $p$ of the electron, as you all know, is $mvr$; and hence for the ratio I derive:

$$\mu/p = e/2mc$$

which is one of the most important formulas in the whole of atomic physics. You notice that it does not involve in any way the size or shape of the orbit or the frequency with which the electron travels around it. It is the same for any or all of the revolving electrons of any atom of any kind.

Now let us see how this formula may be tested. Imagine a rod of some highly magnetizable metal, iron for instance, and imagine it to be unmagnetized at the start. This means, that at the start the little atomic magnets are pointing at random in all directions; that is to say, the vectors which represent their magnetic moments are pointing every way, and so are the vectors which represent their angular momenta, the latter being parallel to the former. Since these atomic vectors of angular momentum are pointing every way at random, they add up to zero, and the rod as a whole possesses no resultant angular momentum; it is just standing still. Now let the rod be surrounded with a solenoid, and by means of a current in the solenoid let it be magnetized to saturation. Now all the arrows representing magnetic moments are pointing parallel to the axis of the rod. But so are all the arrows representing atomic angular momenta! Their resultant is no longer zero—suddenly there has arisen a *resultant angular momentum*, belonging to the totality of all the atomic magnets, and quite large enough to be detected, instead of being tiny like the angular momentum of an individual atom. Unless our theory is fundamentally wrong somewhere, we should be able to observe this resultant angular momentum.

The experiment is done by hanging the rod vertically from a fine suspension, and sending the magnetizing current through the solenoid. At the instant of the magnetization, the rod turns sharply on its axis, twisting the suspending fiber. Thus it manifests the angular momentum

of which I have just been speaking—though I ought to say that what we observe is of the nature of a recoil, or back-kick: when the totality of the little atomic magnets suddenly acquires its resultant angular momentum, the substance of the rod as a whole acquires an equal and opposite amount (so as to keep constant the total amount of angular momentum in the universe) and it is the latter which we detect. The experiment is quite a delicate one, but its technique has been developed to a remarkable degree since it was first attempted twenty years ago by Einstein and de Haas. What we measure is the ratio of the magnetization of the rod-as-a-whole to the angular momentum of the rod-as-a-whole; and this is just the same as the ratio of $\mu$ to $p$ for the elementary atomic magnets. There are not many properties of matter of which we can say that the value measured on a large piece of matter is the same as the value for the individual atom; but there are a few, and this is one of them.

Now in giving you the result, let me first emphasize the general principle that here we have evidence of the spinning of elementary particles, and of the interrelation between spinning and magnetism. Next, I give you the numerical result itself. For iron and nearly all of the other ferromagnetic materials, we find:

$$\mu/p = e/mc$$

or *twice* the theoretical value which I quoted a moment ago.

This cannot be explained by assuming any peculiarity of size or shape or frequency of the electron-orbits in the atoms, for as I just said the theoretical formula is independent of all these things. We are obliged to make some more drastic assumption. If I had unlimited time before me, I might sketch the history of our assumption; but as I don't, I will come straight to the present situation. We assume first, that in the iron atoms in the rod the electron-orbits are so oriented with respect to each other that their magnetic moments kill one another off completely. We then assume that every electron has a magnetic moment and an angular momentum of its own, intrinsic to it and inherent in it, and altogether independent of whether or not the electron is revolving in an orbit. Just as the earth has a rotation of its own in addition to its elliptical course around the sun, so we imagine that the electron has a rotation of its own; this rotation has an angular momentum, and with it there is connected a magnetic moment. (You will remember doubtless that the earth also has a magnetic moment, but this is one of the analogies which it is better not to force too far.) When we magnetize the iron rod, it is the *electrons* which we are turning; the vectors which we cause to point all in the same direction are the magnetic moments and the angular momenta which are inherent in the electrons, and the value of their ratio is the value which is characteristic of the "spinning electron," as we call it. Therefore, amplifying the notation a little, I write:

$$\mu/p = g(e/2mc) \begin{cases} g = 1 \text{ for electron-orbits} \\ g = 2 \text{ for spinning electron} \end{cases}$$

and now I leave the spinning electron for a few minutes, in order to turn again to the theory of electrons revolving in their orbits.

You all realized, of course, that when I converted the Amperian whirl of current into an electron running around an orbit, I was adopting the atom-model known by the names of Rutherford and Bohr; for these were the original thinkers who impelled all the rest of us, following in their footsteps, to think of the atom as a positively charged nucleus around which electrons are revolving like planets around the sun. This is an atom-model in which magnetism is inherent—*a Rutherford-Bohr atom is intrinsically a magnet.* Anyone who did not know the history of the model might well assume that it was designed expressly to account for magnetism, and any such person might also quite reasonably assume that all the physicists of the early nineteenth century thought of it simultaneously as soon as the electron was discovered. Well, it was *not* designed expressly to account for magnetism, and most of the physicists of the early nineteenth did *not* think of it—or if they did, they thought of it only to reject it. At that time, the atom-model with the orbital electrons seemed to be disqualified by a very potent reason; for according to the classical electromagnetic theory, an electron revolving in an orbit ought to radiate all of its energy in a very short time and fall into the nucleus. Bohr was the man who overrode this objection. He overrode it, not in order to construct a theory of magnetism in defiance of it, but in order to construct a theory of spectra in defiance of it. This theory has been extraordinarily successful. Our theory of magnetism is hardly more than a by-product of that theory of spectra; and this, in an odd sort of way, enhances its credit. A theory devised expressly for a certain purpose is always less impressive than one which follows incidentally from a successful theory devised for quite another purpose; and the contemporary theory of magnetism is a wonderful example of this latter and more impressive type.

The main element of Bohr's theory of spectra—if one can speak of one element as the main one, which is really not quite proper—is an assumption about the angular momentum of the electron in its orbit or, let me say, the angular momentum $p$ of the electron-orbit. It was assumed that the electron may revolve, without radiating its energy, in any orbit of which the angular momentum is an integer multiple of $h/2\pi$, —$h$ now standing, of course, for the famous quantum-constant of Planck which is the emblem of modern physics. I write this down as follows:

$$p = (1,2,3,4,\ldots)(h/2\pi)$$

Bohr was thinking at first about the hydrogen atom; but hydrogen is an inconvenient example to use in talking about magnetism, and iron is a very complicated case indeed, so I will talk entirely about the sodium atom.

The sodium atom has a nucleus with a charge of $+11e$, and 11 electrons circulating in orbits around it. This certainly sounds formidably complex, but it happens—and I shall later remind you of this fact—that the orbits and also the spins of 10 of the electrons are so oriented with respect to one another that their angular momenta and their magnetic moments completely neutralize each other.

I shall therefore ask you to imagine these 10 inner electrons as a sort of cloud. The eleventh electron of the sodium atom—known technically as the "valence" electron—cruises around this system; sometimes it is traveling in an orbit completely outside the cloud, sometimes in an orbit which cuts across the cloud, but never in an orbit which is entirely or even mainly inside the cloud. The 10 inner electrons which constitute the cloud neutralize a part of the force with which the nucleus acts upon the valence-electron; but they make—I repeat—not the slightest contribution to the angular momentum or to the magnetic moment of the atom.

I have given above, the permitted values of the angular momentum of this orbit of the valence-electron. Now I point out that to each of these permitted values of $p$ corresponds a permitted value of the magnetic moment $\mu$, which I obtain by multiplying the former with $e/2mc$:

$$\mu = (1,2,3,4, \ldots)(eh/4\pi mc)$$

However, only one (at most) of these values can be appropriate to the normal state of the sodium atom; all the rest must correspond to abnormal, unusual, or "excited" states. We are going to be interested primarily in the normal state, so we must identify the right one. In the early days of the Bohr theory, the right one was supposed to be the first which I have written down. However, the theory has been greatly remodeled and bettered since those days, with the aid of what is known as "quantum mechanics"; and it now seems quite certain that these lists of the permitted values of $p$ and $\mu$ for electron-orbits are both incomplete. I must add to each of them the value *zero*, so that the 2 lists become

$$p = (0, 1, 2, 3, 4, \ldots)h/2\pi$$
$$\mu = (0, 1, 2, 3, 4, \ldots)eh/4\pi mc$$

Moreover, it is precisely this new value *zero* which belongs to the normal state of the sodium atom. So the theory, in this stage, quite definitely prescribes that the sodium atom in its normal state should have no magnetic moment and no angular momentum. But now let us look at the data.

It would do no good in this connection to make measurements on solid or liquid sodium, for in those "condensed phases" the atoms are crowded so closely together as to be badly distorted. We can, however, experiment on free atoms of sodium, in their normal state, in the way illustrated by figure 1. In the upper portion, $A$ represents an "oven" consisting of a small box heated electrically and containing some liquid sodium which is steadily being vaporized. There is a hole in the wall of the box through which free sodium atoms are steadily shooting in all directions, with the distribution-in-speed which we know from the theory of thermal agitation; and beyond, there is a sequence of diaphragms with slits in them which delimit a straight and narrow beam of these fast-moving atoms. Disregarding what the theory has just said, let us suppose that each of these atoms is a magnet—a bar magnet, with a north pole and a south pole. As they emerge from the oven, these atoms must surely be oriented at random in all directions.

Continuing to look at the upper part of figure 1, we have 2 large magnet-poles, and the beam travels between them, having no trouble with molecules of air as it shoots along, for the whole of this apparatus is enclosed in a highly evacuated tube. It may seem natural to visualize these magnet-poles as the 2 broad flat extremeties of a horseshoe magnet, with a uniform magnetic field pervading all the space between them. Such an arrangement, however, would make the experiment futile. Nothing would happen to any of the atoms, for in the uniform field the north pole of each atomic magnet would be pressed downward just as hard as and no harder than the south pole is drawn upward, and the net force would be zero. The beam would go on unbroadened and undeflected, and make a small spot on the screen $S$, the spot being just opposite the slits in the diaphragms. Something else must be tried; and what we do—or rather, what Gerlach and Stern did in Hamburg some 14 years ago—is, to shape one of the magnet-poles in the form of a wedge and hollow out the other, so that the field between the two shall no longer be uniform. The lower part of figure 1 represents the cross section of such a pair of pole-pieces. The field-strength is now much greater near the wedge than near the opposite pole-piece, and there is a vertical gradient of field-strength which may be made fairly constant over most of the inter-

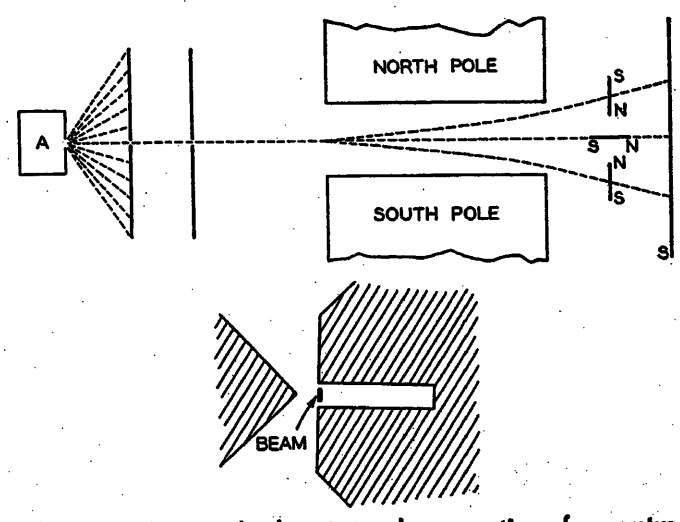



**Figure 1. Longitudinal section and cross section of apparatus for the Gerlach-Stern experiment**

space. Rabi at Columbia achieves the same result more efficiently by peculiar arrangements of current-carrying wires instead of iron magnets.

Now consider (thinking classically!) a few of the atomic magnets as they shoot across this nonuniform field. Think of one which originally is oriented vertically, with north pole down and south pole up—the south pole will be in a stronger part of the field than its mate; it will be drawn upward harder than the north pole is pushed downward; the atom will sweep in a parabolic arc upward. Think of another which originally is oriented vertically with north pole up and south pole down—it will be swept in a parabolic arc downward. Think of another which originally has its axis pointing horizontally—it will shoot in a straight line across the field, as though the pole-pieces were not

there.[1] Now think of all those which are oblique to the vertical; they will describe parabolic arcs of intermediate curvatures, upward or downward as the case may be. One infers that the beam must be spread out into a continuous fan, making a continuous vertical band upon the photographic plate.

Moreover, from the upper edge or from the lower edge of this continuous band, it should be possible to determine the magnetic moment $\mu$ of the atoms. For let us consider one of the vertically oriented atoms, and call its pole-strength $M$ and the length of its magnet $r$. The upward force on the north pole is $MH$, $-H$ standing for the field strength at the point where the north pole is. The downward force on the south pole is $M(H + dH/dz \cdot r)$. The net force is $Mr \cdot dH/dz$, which is $\mu(dH/dz)$, because $Mr$ is the magnetic moment $\mu$ of the magnet by definition. The acceleration of the little atom is equal to this force divided by $m_a$, the mass of the sodium atom. The deflection is equal to half the acceleration by the square of the time during which the atom is exposed to the force. This time is equal to the distance $D$ which the atoms traverse across the field, divided by $v$ the speed which they have when they come out of the furnace. So finally, we have:

$$\text{Deflection} = \frac{1}{2}\,\frac{\mu(dH/dz)}{m_a}\,(D/v)^2$$

We ascertain the deflection by looking at the end of the band on the photographic plate, and we can ascertain all the other things in the equation excepting $\mu$, $-v$ is the hardest to estimate accurately—and so we can solve the equation for $\mu$.

When the experiment is done there appears, however, a very remarkable thing. Instead of there being a long band upon the plate, there are just 2 spots. Instead of the beam having been broadened out into a continuous fan, it has evidently been split into 2 separate pencils. It looks as though the field had acted first of all upon the magnets, by setting them all vertical—half of them with north pole up, and half with north pole down. Not this phenomenon alone, but many others in nature show us that this is just what happens. You may perhaps feel for the moment that it is intelligible, after all; the compass-needle turns to the north—why should not the little atomic magnets, as soon as they enter the field, turn their south poles toward the north pole of the magnet which attracts them? Well this would not account for the magnets which constitute the beam which bends away from the wedge-shaped north pole, instead of toward it; and indeed it does not even account for the beam which bends toward the wedge-shaped pole. Classically the field should have no orienting effect whatsoever upon the atoms, and yet it evidently does.[1] This is one of the phenomena of the atomic world which we cannot properly visualize in terms of the behavior of objects large enough to be tangible and visible. All that I can do is to assert it, and to say that it justifies us in using this formula to calculate $\mu$. When we use it, the value which we find for the magnetic moment of the sodium atom in its normal state is

$$eh/4\pi mc$$

which happens to be one of the values in the sequence which I just wrote down.

I repeat that according to the theory in its present stage the electron-orbits in the normal sodium atom have a net magnetic moment of zero. This value $eh/4\pi mc$ is, therefore, the magnetic moment due to the spin of the valence-electron—it is the magnetic moment of the spinning electron. I write it in the appropriate place, and then with the aid of the $g$-value derived from the gyromagnetic effect I write down the value of angular momentum which we assign to the spinning electron:

$$p = {}^1/_2(h/2\pi)$$

To this roster of 3 statements about the spinning electron I now make a final addition. The Gerlach-Stern experiment on sodium shows that a beam of sodium atoms—which for this purpose is the equivalent of a beam of spinning electrons—is divided into two by a magnetic field. I write down "2" to indicate this number of separated beams; but I will call it by preference the "number of orientations in the field," because that is the fundamental point. The spinning electron always sets itself in one or the other of 2 orientations, with respect to whatever field it happens to be traversing. We call them the "parallel" and the "antiparallel" orientations, though according to quantum mechanics these terms are a little too strong. Here then is the list of the properties of the electron-spin: $g$ equal to 2—angular momentum equal to ${}^1/_2(h/2\pi)$magnetic moment equal to $eh/4\pi mc$—2 permitted orientations in any field.

It has doubtless struck you as rather odd that I began by talking about the angular momenta and the magnetic moments of electron-orbits, and then carefully picked out a couple of special cases in which these neutralized each other altogether and there was nothing left over except what I ascribed to the electron-spin. Is there no point at all, then, in talking about the electron-orbits? Oh, very much so! Indeed there are cases in which the electron-spins neutralize each other altogether, and we have nothing left over except what is attributed to the orbits. To do this I may choose an atom like magnesium, which has a nuclear charge of $+12e$, a cloud of 10 inner electrons which neutralize one another completely as to angular momentum and magnetic moment (just as in sodium), and 2 valence electrons instead of one. In some of the states of the magnesium atom—not in all of its states, but in *some* of them—the spins of the 2 valence electrons are oriented opposite to each other in the atom, and cancel each other out. When the atom is in a state of this kind, then nothing is left over except the angular momenta and the magnetic moments of the orbits of the 2 valence-electrons; and then, all the statements of the orbital theory (page 1230) are applicable—$g$ is equal to unity, the angular momentum takes one of the values $nh/2\pi$ and the magnetic moment takes one of the values $n(eh/4\pi mc)$. Moreover, there is another theorem derived from quan-

1. When thinking classically, we must not expect the atomic magnets to turn their axes toward the field-direction as they shoot across the field; the gyroscopic quality of these magnets, due to their angular momentum, inhibits this.

tum mechanics which turns out to be valid: The number of orientations of such an atom in a field, the number of separated beams which appear in the Gerlach-Stern experiments, is chosen from among the members of this sequence: 1, 3, 5, 7. . . . (It is a most interesting historical fact, that Gerlach and Stern were moved to undertake their difficult experiment by the wish to test this remarkable assertion of quantal theory.) You notice that the number 2 does not appear in the sequence; were it not for the electron-spin, we never could obtain it; it is distinctive of the spinning electron.

I must, however, admit that all these cases of which I have been speaking are special, and comparatively rare. Both the cases in which the spins neutralize each other perfectly, and the cases in which the orbital moments neutralize each other perfectly—both types are unusual. Still more unusual, and yet occurring here and there, is the most special of all cases—that in which *all* of the moments and *all* the momenta, both those of the spins and those of the orbits, balance one another perfectly so that the sums are zero. An atom in such a state is completely devoid both of magnetism and of spin; such atoms are those of helium, of neon, of argon and the other noble gases, when in their normal states. Usually, however, we find ourselves confronted with some example of the general case, in which neither the spins nor the orbits are completely neutralized. The atom has an angular momentum which is a sort of composite or resultant of the angular momenta of the spins and the orbits, and it has a magnetic moment which also is a sort of composite or resultant.

If I were to embark on the description of the general case this lecture might go on interminably, and at its end you would probably not remember anything except what you had already known at its beginning. The laws of the composition of spins and orbits are so foreign to our customary ways of thinking, and the formulas which express them are so curiously built, that to work once only through them is not sufficient: One has to memorize the derivations and the results alike, and go over them incessantly until they are imprinted on the brain. I think you will agree to this readily enough, when I remind you that this theory is none other than the general theory of spectra; for even quite outside the ranks of physicists, the theory of spectra is beginning to be notorious for its complexity. I shall not venture even to give the formulas, much less their derivations; it must suffice to fill out the 2 lists of $p$-values and $\mu$-values on which I have already begun, and the list of $n$-values or numbers-of-permitted-orientations.

The spinning atom is a congeries of electrons, all of them always possessing spin, most of them usually possessing orbital motions; and these motions are compounded with each other in such ways, that:

First, the angular momentum of the spinning atom has one of the values,

$$p = (0, {}^1/_2, 1, {}^3/_2, 2, {}^5/_2, 3 \ldots)h/2\pi$$

Second, the number of beams in the Gerlach-Stern experiment, or the number of permitted orientations of the atom in the field, has one of the values,

$$n = 1, 2, 3, 4, \ldots$$

Third—and now comes a surprise, for you will probably expect me to say of the magnetic moment that it is $eh/4\pi mc$ multiplied either by an interger or a half-integer; but this is not so. The actual state of affairs is described by a formula which is called the $g$-formula, because it gives $g$ in terms of the moments, both spin and orbit, of the individual electrons. It was discovered by Landé and interpreted in terms of the spinning electron by Goudsmit. The $g$-formula gives unity, as of course it must, in the special cases where the electron-spins cancel each other and only the orbital moments are left over, and it gives 2 in the special cases where the orbital moments are neutralized with only the spins left over. In the other cases it may give any one of a large variety of values: mostly one gets simple-looking fractions such as ${}^9/_8$ and ${}^4/_3$ and ${}^5/_6$. The magnetic moments are then computed by multiplying the appropriate $g$-values times $e/2mc$, into the existing values of angular momentum.[2]

I now turn to that component of the atom of which the spin remains to be discussed—to the *nucleus*.

As I have already intimated, the values of $p$ and $n$ and $\mu$ for the electron-family of any atom are mostly ascertained by analyzing their spectra and utilizing the great general theory of spectra. Such magnetic experiments as I used for my examples are relatively few, and feasible for relatively few substances. The reason for making this remark at this late moment is, that by analyzing spectra we may also learn something about the spins of nuclei; for nuclei also are invested with these properties of angular momentum and of magnetic moment. I take in particular the case of the *proton*—that lightest of all nuclei, the nucleus of the lightest known kind of atom which is ordinary hydrogen, so called to distinguish it from "heavy" hydrogen. Analysis of the spectrum of hydrogen shows us that the proton is capable of taking 2 permitted orientations in a field; thus, our first piece of information about the proton-spin is conveyed by writing $n = 2$.

Now that we have this piece of information, we deduce that as the spinning electron has an $n$-value of 2 and an angular momentum of ${}^1/_2(h/2\pi)$, so the proton with its $n$-value of 2 must have an angular momentum of ${}^1/_2(h/2\pi)$. Continuing along this line of thought, we are further tempted to infer that the proton should have a $g$-value of 2 and a magnetic moment of $(eh/4\pi mc)$. But what shall we suppose about $m$? Formerly it represented the mass of the electron; now we are dealing with a different sort of particle, having a mass which (as many other kinds of experiments show us) is about 1,835 times as great as the electron-mass. I denote this mass by $M$. It seems natural, then, to expect for the magnetic moment of the proton the value $eh/4\pi Mc$, or about ${}^1/_{1,835}$ of that of the spinning electron.

This is a formidably small magnetic moment to hope to measure, nay even to detect! Yet Stern and his pupils undertook to measure it, and they succeeded. Of course,

2. Should any reader intend to proceed from this article to a thorough study of atomic theory, he should be warned in advance that according to the latest form of quantal theory, the $p$-values and the $\mu$-values here given are the values of the projections of these vectors upon the field-direction, the magnitudes of the vectors themselves being somewhat greater: I have given details as to this in "Contemporary Advances in Physics, XXIX, ..." *Bell System Technical Journal*, volume 14, 1935, page 293.

modifications had to be made in the technique which worked so well for sodium. Hydrogen being a gas at room-temperature, no heated oven was required; nevertheless they used an "oven," but it was refrigerated instead of being heated—a sort of super-ice-box; this was in order to obtain slow-moving atoms, for the slower the atoms traverse the field, the more accurately the experiment can be made. I just said "atoms"; but as most people know, the particles of gaseous hydrogen are not atoms, but diatomic molecules—systems composed of 2 protons and 2 electrons apiece. This is a circumstance which in many desirable tests of modern theoretical physics is a great inconvenience, for usually our simplest theoretical affirmations refer to hydrogen atoms and we should like to be able to experiment on them directly. Here, however, it turns out to be a great convenience, indeed perhaps the only thing that makes the experiment possible. For if we had an isolated hydrogen atom, the magnetic moment of its electron would so far exceed that of its proton that the latter would be indetectable. (Perhaps it is not superfluous to mention that bare protons could not be used in the experiment either, as the magnetic field would exert so large a force upon their moving charges that the forces upon their magnetic poles would be insignificant by comparison.)

But if in a single hydrogen atom the magnetic moment of the electron swamps that of the proton, how shall this fate be avoided for a system composed of 2 electrons and 2 protons? Here enters in, and in a very important and significant way, that law of the permitted orientations. Just as a spinning particle of angular momentum $^1/_2(h/2\pi)$ can take only 2 permitted orientations in a field, so it can take only 2 with respect to another particle of its kind—the parallel and the antiparallel. It chances—or rather it does not chance, it follows from the underlying laws of nature—that in the hydrogen molecule the 2 electrons are oriented antiparallel to each other. Their magnetic moments cancel each other, and do not trouble the experimenter.

May not, however, the same thing happen in respect to the 2 protons, so rendering the experiment hopeless? It turns out that for these the spins are antiparallel in some molecules but parallel in others. Molecules of the former type, which is called para-hydrogen, are indeed useless for the experiment; but molecules of the latter type, which is called ortho-hydrogen, are available, and in them the magnetic moments of the 2 protons collaborate so that the magnetic moment of the molecule-as-a-whole is twice as great as that of the single proton, a welcome assistance! In ordinary gaseous hydrogen at room temperature, about $^3/_4$ of the molecules are ortho-hydrogen.

When the experiment was at last achieved by the school of Stern, it was found that the foregoing inference as to the $\mu$-value of the proton is roughly but not exactly correct! The latest information is, that the magnetic moment of the proton is close to $2^1/_2$ times $eh/4\pi Mc$. Measurements with another method by Rabi and his school have confirmed these results; and we are definitively debarred from believing that for the proton and the electron, the magnetic moments stand in the inverse ratio of the masses. Perhaps this signifies that the proton is itself a composite particle, a notion for which there is some support from other sources.

I mention briefly the characteristics of a few other nuclei. After the proton, the next simplest is the deuteron or nucleus of the heavy-hydrogen atom. It is composed of a proton and a neutron, the latter being a neutral particle of about the same mass as the proton. We can observe free neutrons wandering about in space, but we cannot determine their spins nor their magnetic moments. The deuteron, however, has 3 permitted orientations (this we discern from the spectrum of heavy hydrogen) and consequently an angular momentum of $(h/2\pi)$. It is inferred that the neutron has $^1/_2(h/2\pi)$ for its angular momentum, and that in the deuteron these 2 constituent particles—proton and neutron—are oriented with their equal spins parallel to one another. The magnetic moment of the deuteron is less than that of the proton, and accordingly the neutron must have its magnetic moment oppositely directed to that of its companion in the system, even though their angular momenta be similarly directed—a strange complication!

After the deuteron, the next simplest among the nuclei (except 2 which are much too rare for investigation) is the alpha-particle or helium nucleus. It is composed of 2 neutrons and 2 protons. We find that its angular momentum and its magnetic moment are zero, a clear indication that the 4 spins of its components are cancelling each other 2 by 2, and the 4 magnetic moments likewise. Next comes a nucleus composed of 3 protons and 3 neutrons, belonging to the element lithium. It is found that in angular momentum as in magnetic moment it is practically a duplicate of the deuteron, its 6 components having disposed themselves into a nearly normal deuteron attached to a nearly normal alpha-particle. I might proceed some distance farther along the list of the known nuclei after this fashion, were there space; but it is best to close this section with a general rule: *nuclei with an even number of constituent particles* (protons and neutrons) *have even spins, nuclei with an odd number of particles have odd spins.* "Even" and "odd" in this formulation mean that the angular momentum is an even or an odd integer multiple of $^1/_2(h/2\pi)$, respectively. One sees that if any 2 spins of magnitude $^1/_2(h/2\pi)$ are allowed to choose only between parallel and antiparallel orientations, the rule follows inevitably; reversely, from the rule (which is based on experience with some 50 or 60 kinds of atom), we derive extra strength for that theorem about orientations.

Now to come to the conclusion and the climax. Although this property of angular momentum, of being allowed to take only a limited number of permitted orientations—although this strange and wonderful property of angular momentum was introduced in this lecture as though it pertained only to atoms subjected to applied external fields, yet it manifests itself far more broadly. Indeed, it manifests itself universally, and the stability and the character of the world are due to it. I have already mentioned in half-a-dozen places how it manifests itself within the molecule and within the atom: how in the atom, it is responsible for those laws of composition

which determine the angular momentum and the magnetic moment of the electron-family—how in the hydrogen molecule, it establishes a difference between ortho-hydrogen and para-hydrogen—how in the nucleus it fixes the angular momenta and the magnetic moments of composite nuclei as sharply as those of their constituents the proton and the neutron. Perhaps these seem to be remote and unimportant qualities; but what has just been said of them may be said with equal truth and equal force of *all* the chemical and physical properties of all the elements, mass alone excepted (and even mass not fully excepted). If this feature of angular momentum did not prevail, there could not be the fixity of properties which characterizes each element by itself and the variety of properties which characterizes the totality of the elements. Gold would not be gold, lead would not be lead, oxygen would not be oxygen, helium would not be helium; for though it is commonly said that each element is distinguished by its nuclear charge and the number of electrons in its electron-family, this is not adequate. It is the law governing angular momentum which imprints upon these electron-families the characters which we recognize as the properties distinctive of the elements. It seems strange indeed that character should depend upon motion, and fixity upon the laws of whirling things; but however strange it may seem, there is no doubt about it. In the construction of houses the builder requires raw material in the form of brick and stone and wood and steel; but he requires also principles of architecture, whereby the raw materials may be parceled off and integrated into the general design. In the construction of the physical world, mass and charge fulfill the rôle of raw materials, and the laws of angular momentum furnish the principles of the architecture thereof.

# The Engineering Profession

## Not what the engineer does, but how he does it differentiates engineering from the other learned professions

By GANO DUNN
PAST-PRESIDENT AIEE

THE ADVENT of the scientific method and the rapid spread of its use in connection with practical things, which began not much more than 150 years ago, called forth the ministrations of many specialists in the application of science to social purposes. There always had been military engineers who made roads, bridges, catapults, and petards; but in the sense we are now considering it, they did not constitute a profession.

To distinguish the new men from these time honored military engineers, they were called civil engineers. In those days civil engineers busied themselves in the whole field of then known science instead of in the narrower field which civil engineering now embraces. James Watt, for instance, was a civil engineer. These civil engineers, as distinguished from military engineers, began to constitute a new class in the community; this class has grown in geometrical ratios as to its numbers and as to the varieties of its occupation, until it has spread its activities into every material department of life. The very foundations of society would be shattered if the class should today cease to exist.

Specialization in this great and growing class has created over 50 branches of engineering sufficiently distinct to be recognized in library catalogs. Because of this growth in scope and subdivision into widely different specialties. occupations in the various engineering branches have become so differentiated that the extremes bear almost no resemblance to each other. Even the grand divisions of the engineering profession represented by the national societies of civil, mining, mechanical, electrical, and chemical engineers, give little more than a hint as to occupation. An electrical engineer may spend his days on the macrocosmic problems of corona in the long-distance transmission of vast amounts of power, or he may wrestle with the microcosmic subtleties of the multiplex modulation of carrier waves. As an indication not only of this diversity of occupation but of the rapidity with which change of subject matter has taken place, I will give a few examples.

It is within my time that power transmission did not

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Essential substance of the commencement address delivered at the 70th graduation exercises of the Massachusetts Institute of Technology, Boston, June 8, 1937.

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exist. The electrical engineer of that day, in one group was concerned with the intricacies of direct-current commutation or with the then still unsuccessful endeavor to produce an electric motor that would run on alternating current, which was at that time a novelty limited to the field of electric illumination. In another group he was estimating the economic barrier represented by the cost of 2-wire metallic circuits for telephones, and cogitating whether the priority which telephones shared with the telegraph in the exclusive use of circuits of a single wire with increasingly noisy ground returns was worth the expensive legal fight its preservation was forcing upon him. In another field the coherer was unconscious of the vacuum tube that was to follow.

Mechanical engineers in their sphere burned midnight oil developing a reciprocating steam engine that would run at a speed high enough for the direct driving of electric generators, in order to make possible the elimination of the grave disadvantages of the ubiquitous leather belt. The successful internal combustion engine and a useful steam turbine had not been born.

I could go on, but trust that I have indicated that the progress of the engineering art in the past already has demonstrated the folly of attempting to forecast in the electrical field alone what will occupy the electrical engineer of 150 years hence.

It is possible that I already have gone far enough to have suggested what it actually is that constitutes the practice of the engineering profession and sets it apart from the other learned professions. The answer is: it is not what the engineer does, but how he does it! Not what the engineer's occupation is, but the intellectual processes by which he attacks that occupation.

In other words the method of engineers rather than their occupation is the characteristic of the engineering profession. Method is the common denominator of all engineers. While the *subject matter* of engineering unquestionably will continue to change in the future, not so with the *method* of engineering. It is certain that the engineer of the future will be using the present method 150 years hence, even if no prescience is capable of forecasting to what occupations that method will be applied.

What is this remarkable method that has changed the nature of the world? As is well known, it is the method of science—that process of reasoning based upon observed data and working hypothesis which, by inductive and deductive procedure and experiment, arrives at new knowledge.

It must be pointed out that, except where their qualities are combined, the engineer and the scientist are not the same person, however much they use the same method. Their objectives are different. Many attempts have been made to define engineering, and engineers do not agree on any one definition; but a definition I worked out some years ago seems to stand the test of criticism and of perspective. It is as follows: Engineering is the art of the economic application of science to social purposes.

Being an art, engineering thrives on repetition. It develops skill and it develops style. The second and third power plants that an engineer builds are likely to be better than the first, although there may not have been introduced a single new principle. The scientist, however, shuts his mind as far as possible to all human prejudice and influence of feeling, save only for the divine fire of that imagination which creates the working hypothesis; and he learns how to discern truth and new knowledge in a study of the order of nature.

The engineer, by the same intellectual processes as the scientist, applies that new knowledge to social service. The essential difference between the scientist and the engineer lies in the economic involvement of the engineer's work. In this hot crucible of the economic test all that an engineer does must be tried. To repeat an old saying, an engineer is a man who can do with one dollar what any fool can do with two; and it is in his economic involvement that the engineer can rise to some of his greatest powers.

Economics is a social, not a physical, science. It embraces problems of the human spirit and the behavior of man as man; and because the engineer's art deals with dollars and economic relations, he is bound into the great business structure of society in a way that the scientist is not. Being bound into this structure, he must be a man among men. He must be able to make his views prevail. He must be able to persuade and to contend. He must be able to give blows and to take them. These activities do not devolve upon the scientist in his laboratory. To the engineer, they are everyday life.

If an engineer's training neglects the great human mirrors of history and languages, particularly his own language; if his mind and heart are not sensible to the great social forces of his day and of his community; if he but feebly develops the subtle qualities of character that make for personality, his career as an engineer is limited, no matter how much science he may know.

If the key to the scientist is thought, the key to the engineer is action. Value and utility are the engineer's criteria, rather than truth, which is the criterion of science.

For these reasons, as the engineering profession has developed, the center of education for engineers has been shifting more toward the humanities. This is one reason for the greater part engineers constantly are playing today in the great rôles of life. But while the humanities are of profound and increasingly recognized importance in the arch of an engineer's education, its keystone always will be science.

Not all men with an engineering education take up the practice of engineering. It is significant how many are drawn off into the field of organization and other fields, where the engineering method of approach to problems and the engineering point of view introduce fermenting leaven into many of the processes of traditional business procedure. Partly for this and for other reasons, engineering has become the cornerstone of industry. In the precipitations of relationships brought about by big business and mass production, the function of management has fallen very largely to the engineer.

In the field of management, involving the play of the human spirit at its best and at its worst, where, particularly in labor relations, generosity, loyalty, and independ-

ence are manifest as well as passion, ignorance, and vanity, the engineer's capacity for organization, leadership, and sympathy has rare opportunities. Even in these days which we often think to be so far advanced, the sway of prejudice and of certain kinds of superstition is still profound. It awaits the light of reason and human understanding.

Executions for witchcraft were once a common part of everyday life. At the time when Salem shocked the colonies by a series of 19 such executions, literally thousands of witchcraft executions every year were carried out in Europe. Over a period of 40 years there were 8,000 such executions in intelligent Scotland alone. The least unusual circumstance or unexplained phenomenon was liable to be charged to occult and demoniac causes, and constantly brought the penalty of death by flames upon upright and innocent persons or upon individuals who were unpopular or politically inconvenient, or who were merely intellectually independent. This madness, which had spread over most of the civilized world, was dissipated by the same great light that founded the engineering profession. About that time the dawn of the scientific method began to shed its beams of intelligence into the darkness of human prejudice. The results it accomplished in the social sphere through the dissipation of superstition, although overshadowed by the results in the sphere of the material world, have been of immeasurable importance.

The social sphere today is still a field that needs the light, a field in which the engineer with his training and point of view has open to him doors of rare opportunity. While not as sinister as the witchcraft problems, there are problems of prejudice in our social field that are, like witchcraft, based upon distrust and ignorance—problems that act as a brake on industry and separate man from man.

While I have dwelt upon the essentially economic character of the engineer's field and the social service rendered by him in the cultivation of that field, such social service is an indirect one, effected by his function rather than by a disinterested will to serve. For performing his function he receives compensation, and therefore it often is urged that he is not entitled to personal credit for social service, since he is paid for it. In the case of certain engineers, there is much weight in this criticism. It also is urged that much of an engineer's work comes under the head of business for which the professional status cannot be claimed, and that the only really professional engineer is the consulting engineer; who, it must be admitted, is usually an ornament to the profession and perhaps more conscious of a professional responsibility than many of his fellow engineers.

Similar questions have beset the older professions; and they have been worked out in a tolerably satisfactory way. No lawyer considers it a reflection, especially an ambitious young lawyer in a country district, to be referred to as conducting a law business; nor does a lawyer consider that he is not a member of the legal profession if he accepts an annual salary from a corporation for continuous service. Equally unaffected as to his professional status is the physician who works for a salary as distinguished from fees for general practice.

The essence of the professional status lies in the moral obligation involved in the act of professing. This act is always personal; and it is in the engineer's personal relations to his fellows and to society and the obligations therein involved, wholly over and beyond obligations for which he is compensated, that his professional status resides.

These moral obligations are the reasons why such particular weight is put upon character and integrity by the boards of examiners of the great national engineering societies before admitting to membership, and why violations of professional ethics rather than failures in professional competence have been practically the only grounds on which expulsions from these societies have been based.

Turning to the older professions for our models, we find that questions of personal obligation to fellows and to society constitute the very foundation of the professional conception. In these older professions the engineering profession has noble examples of the practice of obligations that are self-assumed and disinterested. The medical profession has its Hippocratic oath peculiarly pledging its novitiates to the service of mankind, irrespective of compensation. The legal profession, in its defense of penniless defendants and the vast amount of uncompensated service it renders to the courts and to the public as an arm of the law, illustrates its conception of professional service outside the field of compensation. As to the clergy, its objective is exclusively social, and its devotion is unmeasured by compensation.

Engineers themselves have been the first to recognize obligations that inhere in a growing consciousness of the professional status. Their great societies have been created not merely for self-education and intellectual development, but to give expression, in their relations with each other, with other professions, and with the public, to a desire for a standard of personal relations and for the recognition of obligations, beyond those which are pecuniary. Just as the peculiar equipment of the clergyman, the lawyer, and the physician gives him a peculiar power and authority when disinterestedly devoted to social betterment, so does the equipment of the engineer.

The engineer today finds himself in a pivotal position in industry, intermediate between capital and labor, with the problems of both of which he deals intimately and is in a position to understand, interpret, and judge. In consequence, there is offered to him entirely in addition to the service he performs through his engineering function, an opportunity for social service through his professional and personal status which, if he rightly conceives and seizes it, gives him a strategic advantage to render social service, which at this moment, the representatives of the older professions do not possess.

Is it too much to hope that with an enlightened method of approach and the habit of factual investigation which are the intellectual birthrights of the engineer, his increasing participation in management may bring to the solution of some of the social problems of industry a prejudice-dissolving light? Such a light is capable of showing the

path to a new happiness in work, in which there is a recompense greater than all wages—joy in the act of creation. If there could come about a spirit of reciprocal confidence on the part of all elements, we could not fail to see increased production and increased leisure go hand in hand, securing those satisfactions deep in the consciousness of all Americans, which the immortal Declaration of Independence describes as the inalienable rights of life, liberty, and the pursuit of happiness.

To seize these opportunities for social service necessarily involves a demand upon the souls of engineers as well as upon their minds, which will be a test of their love of their fellow man. It is a case of *noblesse oblige*. Every engineer certaintly will have some occasion for meeting this test. When and as often as the test shall come, may none ever ask, in the words of Cain, "Am I my brother's keeper?" unless he already has resolved in his heart the intention to answer "I am."

# Our Sons Specialize

## But most scholars and industrial leaders consider a foundation in science and the humanities more valuable to the engineer than specialized technical training

By GILBERT E. DOAN

THE engineer's influence in modern society may be pictured by considering him as an energetic surgeon operating in a large and effective way upon the social organism. He is skilled in the use of instruments, but generally quite ignorant and unconcerned about the nerves and endurance of his suffering patient. His one-sided interest in tools and techniques begins in the engineering college where his teachers are content if he learns technology. Later, when he comes to apply the knife of modern science to the vitals of society, does he inflict needless pain? Does he suffer too? But can it truly be said that the average engineering graduate is uneducated? The academic-minded scholars may say he is, but that proves nothing. These scholars have forced a liberal education upon our physicians and lawyers. After all, the captains of industry employ the engineers. They might tell what training leads to long-range success. What do they say about our modern engineering education?

These leaders are keenly aware of the many strong features of engineering, but they condemn the narrowness of the present system in no uncertain terms. As men of vision as well as men of practical affairs they preach the same doctrine as the scholars: "Get the humanities and the foundations of science, but don't get technology. Industry will teach the man its technologic methods quickly enough. But industry cannot undertake to give him a liberal education or a sound scientific background if he comes without these."

What is this narrow training that the engineering schools give their students? A survey of representative engineering schools, conducted several years ago by the Society for the Promotion of Engineering Education, shows that the student in these schools received 30 per cent of his credits in basic science, 60 per cent in technology, and 10 to 15 per cent in subjects that can be called broadening or cultural—a little English, a taste of a foreign language, a bit of economics. A report published by the SPEE this year shows that the situation remains essentially unchanged. Evidently the student gets a good foundation in science and technology, but very little else. This evidence does not contradict the industralist's charge.*

But the 10 to 15 per cent of liberalism may be misleading. Perhaps the *spirit* of the engineering school is broad and liberal as it was in Germany before Hitler. It could be, but 20 years of experience in and out of such institutions both here and abroad seems to indicate that the American curriculum is not misleading. It truly represents the student's preparation for life. In spirit as in subject matter the typical engineering education offered in this country, possibly with a few exceptions, is essentially the same narrowly specialized schooling, involving for many fine boys the same spirit-stifling ordeal, the same growth-stunting régime today that it did when these industrialists were students. In fact, with the rapid advance of technology into new fields less room is left in the curriculum for the humanities than there was 35 years ago. The social upheaval of the thirties resulted in a measure of soul-searching on the part of engineering faculties, but so

Essential substance of an article "Our Sons Specialize" published in the summer 1937 issue of *The American Scholar*, official publication of the United Chapters of Phi Beta Kappa, pages 294–303.

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*In September 1936, Massachusetts Institute of Technology took an important step toward liberalization by raising the percentage of humanistic subjects to approximately 17 per cent, running a band of 3 hours in humanistic fields through the entire 4 years. These courses have been integrated to avoid haphazard selection. Most important, perhaps, is the liberal point of view encouraged in the faculty by this step.

far it has led to little effective action.

Fresh out of high school the boy comes to college eager as boys are for a deeper understanding of the big things of life. He trusts his college to know what industry wants him to learn and to steer him wisely—a sacred trust if ever there was one. Enrolled as a freshman engineer he faces a stiff schedule of chemistry, physics, mathematics, and drawing. From 3 to 5 afternoons a week in the laboratory accompany them. He sees that he must shut out everything but science from his serious attention or fail his courses. In his sophomore year the intensity of specialization increases. The humanism encouraged in him at high school is effectively submerged. His budding intellect passes through a desiccating desert of abstract science—science which furthermore, so far as he can see at the time, has little significance for his chosen special field of engineering. For his vacations he gets practical experience by working in an industrial plant, and in his junior or senior year a little economics. That is all. His course contains 60 per cent of technology, including much semivocational training. Rapidly his broader interests atrophy under this pressure. Human problems become extraneous to his chief concerns, pale into unreality and vanish from his ken. If you want to see the result try reading a college magazine published by engineering students or talking to them about social security. The student is so busy learning new techniques that he has no leisure left for contemplating the significance of anything in college or out of it. He has no contact with history, biology, or philosophy.

As a result of this diet the most stimulating intellectual adventure that many a boy can remember at college is the fraternity "bull-session" prolonged into the wee hours of the morning. Here such vital topics as success, religion, morals, and marriage are discussed. If one boy in such a group were soundly informed on these subjects the discussion might be enlightening, but the engineering student must rely on casual heresay for the answers to humanistic problems, and the interests which such sessions stir in him are next day stifled.

Is this sacrifice of breadth in the boys' education justified? Fifteen years after these students have left their alma mater we expect to find them practicing engineering. Actually, less than 50 per cent of them are. Even the more successful of the engineering group are in positions where the managerial and administrative problems completely overshadow the technical. The farther these engineers advance, the less is the relative value of their technical training and the greater would be the benefit of a liberal education. Is the sacrifice justified for the boys of either group?

We have always believed that the "mental discipline" acquired in engineering studies will make men keener analysts in all the other problems they will meet. Many engineering educators still preach that doctrine. They don't realize that psychologists long since have shown that "mental discipline" is at best only partially transferable from one field of knowledge to another. Does your training in calculus, for example, enable you to grasp the roots of a labor situation one whit more surely than you could without it? No. We are compelled to accept what the scholars have long maintained: The engineer's schooling is of minor value in the advanced stages of his career and of even less value in his private life. Engineers we certainly must have, but must there be a lack of cultural balance in their preparation? If they are uneducated, has the college kept faith with the boys?

Even in the truly professional group a chemical engineer will find himself employed in the production of electric power, while a civil engineer manages a group of metallurgical furnaces. The conclusion will not down: The investment of undergraduate time in specialization is unwise.

Thus it is not the study of science that prevents our engineering students from getting a balanced preparation for life. It is the crowding out of an education by semivocational training. This overemphasis goes on in spite of the fact that industries can and do give vocational training to the graduates they select and do it better than the colleges.

Why, then, is the student given courses of this kind at college? In the first place the student gets them because his parents want him equipped to earn a better living, and they believe specialization is the best preparation. Having, in the majority of cases, no college experience of their own, they seek out the shortcuts offered by schools giving the earliest and most intensive specialization. In the second place the director of a student's curriculum is usually an engineering graduate and his own training was largely of this specialized kind. Specialties seem to the director essential to an engineering curriculum. They give it distinction, differentiate it from the indefinite "arts" curriculum. If it were too much like other curricula it might indicate lack of faith in the value of the special field. Certainly it would attract fewer students. Finally, the student gets the specialized course because he wants it. He can see what it did for the professor. It promises to prepare him for a definite career, which is more than "philosophy" promises. He hears there are good jobs open in that field. He likes the label, too. It has a ring of modernity that history and biology lack. Look at the expensive laboratory equipment used in the couse! That is what his high tuition buys. He should get all of it he can while the opportunity lasts. The enrollment for the course will be large, the students pleased with their opportunity and eager. What attitude could more surely warm the heart of a professor?

But don't the boy and his parents know that industrial leaders as well as scholars disapprove of specialized courses for undergraduates, that they consider a foundation in science and the humanities far more valuable than technical training? The answer is "no." They think that at least industrial leaders would strongly approve. Don't they know that at graduation the boy will take the best job offered, whether it is in his specially chosen field or not, and that the chances are several to one that it will not be?

When the subject of engineering school curricula is studied broadly, as was done in 1926–29 by the Society for the Promotion of Engineering Education, the need for liberalization is unanimously acknowledged. The society recommends that the proportion of liberal subjects be increased from 13 to 17 per cent. What have the engi-

neering educators done about this recommendation, inadequate as it is? The report was read, no doubt, by the president of each institution and passed on to the curriculum directors with recommendation that it be perused thoughtfully. Each director will agree half-heartedly that liberalization probably is desirable, but always in another department, not in his own. The director of civil engineering will feel strongly that the electrical-engineering curriculum should be liberalized by dropping specialized courses, but that with civil engineering it is different. Perhaps as a concession to appearance a course in "railroads and terminals" would be moved from the "required" list and made "optional" with one in economics. He dosen't think "arts" courses are worth much anyway. He never felt the lack of them. The report gets as much action as the 1923 Carnegie report on professionalism in college football, although for a different reason. Our question "Why does the student not get the kind of education the industrial leaders and the scholars say he should have?" has now been answered; parents seek speculative shortcuts. The engineering educators are steeped in their own tradition, and that tradition is not liberal. Perennially the scholars have said engineering education was wrong from the idealistic standpoint. The industrial leaders now find it wrong from a practical standpoint.

The teachers of engineering are a group of sincere and capable men. Many have made noteworthy contributions to the technical aspects of engineering. But the price they paid was a life of narrow devotion. Only the exceptional man escapes the restricted outlook thus entailed. Their chief fault, if it be one, is this intense devotion to their own field and their undeveloped vision, often amounting to partial blindness in other fields. Usually they are not concerned with the broader problems of industry. In many cases it is their sincere belief that industry prefers men with a maximum of technical training, whether they are soundly educated or not. Thus even the changes that the farsighted leaders of engineering education agree upon in this direction do not receive very wide adoption.

Do the alumni who invested in these technical specialties at college later criticize their alma mater or feel resentment at the faculties which trained them so narrowly? Generally not. The alumnus enjoyed the prospect of an engineering career and the sincere enthusiasm of his teachers for their subjects. He saw the practical usefulness of the studies he pursued—even if they never were useful to him. When he left engineering he did so of his own free will. He had bettered himself by so doing. Anyway, college had been fun. "If I had it to do again I would take the same course" says the engineering graduate who has become a nontechnical executive. But you must note that the liberal-arts graduate who holds a similar job says exactly the same thing. One cannot expect him very ardently to long for what he doesn't understand. Few men regret what they did in a period of life which on the whole they enjoyed; few will bewail a deficiency they have later partly overcome. Most of the highly successful graduates are too busy and too tolerant to try to influence the educational policies of their alma maters.

This unsound state of affairs in the education of 50,000 bright boys a year should not continue. The preparation of engineering students should attain the standard agreed upon by both scholars and leaders of industry. And I believe it will. An adequate grounding can be achieved in 4 years. Most of the engineering specialties will have to be eliminated. To those who want them, specialties will be available in a fifth year.

Equally important, the attitude of engineering educators toward liberal education must change, for they hold the boy's complete confidence. What they tell him in these matters he accepts and will continue to accept as final truth. There is some evidence recently that their attitude may change but new and attractive fields of special technology are constantly being developed and parents and their sons will for some time continue to seek them as speculative shortcuts to success. So long as they are willing to pay the price the temptation to meet their wishes, however unwise, is great. The scientific foundation of the student's education will be preserved and augmented. But the capable graduate of the new type will have been prepared to act wisely in a broader sphere of affairs. When a labor crisis arises out of the use of one of his labor-saving machines, for example, his background of history, and perhaps psychology, will enable him to see the industrial situation in a clearer perspective. When a social security program is proposed, perhaps by thoughtless politicians, he will be able to understand at least the basic biological significance as well as the fundamental economic implications bound up in it for the future of the human race. He will have a right conception of the ends of life. Such vital questions as women in industry, the liberty of the individual in society, and crime will present themselves to him not as simple problems, it is true, but as matters resolvable into their component parts in the broad light of the great fundamentals of biology, economics, and history. He will be competent to see his engineering activities in their proper background and perspective, that is, he will be an educated man and not merely a technician.

Certain superiorities inherent in engineering education will certainly be preserved in the new version. Engineering education is professional education; it is purposeful and definite. In its liberalized form it will continue to supply dynamic and purposeful motivation to the student. Through this focus of his mind he will integrate the liberalizing and humanistic studies which must accompany professional training.

The faults of the present engineering education are not inherent in it. They can be eliminated without sacrifice and with great gain. Let one first-class college cut through the meshes of its illiberal traditions and the inertia of its vested interests. Let it frankly and wholeheartedly abandon the training of technicians in behalf of the education of engineers. Such a college need not fear for its future. To it will inevitably be attracted both a faculty to provide sympathetic administration of its program and a student body capable of profiting thereby. They will come from the better backgrounds where engineering education is now increasingly condemned. But the first step must be to set up a sound and attractive program.

# Physics and the Engineering Curriculum

## "Instruction in physics has been not only the mother of engineering, but for the future must be the heart of its instruction—its guide, philosopher, and friend"

By O. W. ESHBACH
FELLOW AIEE

ENGINEERING was originally the despised child of science. At the time of its birth, which occurred in a period of invention, it was not very welcome. In the second stage of its development, that of curriculum building which followed through a concurrent period of commercialization of inventions, many mistakes were made; and now since the beginning of the twentieth century, when it has been accepted the tremendous development of new ideas brought about by research in both colleges and industry have so swamped the all-inclusive efforts of curriculum builders that there is a threat of filial ingratitude. No matter how great the pressures are to limit time devoted to this instruction, it seems to be a false step to subordinate the importance of instruction in physics and likewise its financial support.

In recent literature on engineering education 3 ideas predominate as possible ways out. The first is, instruction should be more fundamental; second, the curriculum should be longer; and third, graduate study must be developed. All are in progress. This contribution, if it may be so graced, is a plea for the effective use of time, and it is in this relationship that instruction in physics is discussed. The simile for this thesis is taken from the field of electric traction, the speed-time curve. The principle is physical, common, and simple—the speed at which one travels determines the distance one can go in a given time and also the time to go a given distance.

Effective instruction in physics determines the quality and tempo of engineering teaching. Two of the important portions of a speed-time curve are the periods of acceleration and the portion when, after the maximum accelerating force has been applied, the motor operates in accord with its own characteristic. The peak velocity it will reach in a given time, operating on this characteristic, is affected by its rate of acceleration. Likewise, the stimulation given during the first 2 years of an engineering curriculum will be the determining factor in the speed of comprehension and effectiveness of learning of students during the latter part of their courses when, to a large extent, their own characteristics should determine the dimensions of their education.

This truth is axiomatic, but what most educators would like to know is how to do it. Some have attempted, with success, to crowd the maximum of mathematics into the freshman year, thus forming the background for a more effective study of physics in the second year. Those who have tried to introduce physics during the first year have found the necessity of continuing the instruction through the sophomore year. In either case it becomes perfectly obvious that a knowledge of mathematics and how to get it soon enough are 2 of the principal problems involved. The solution would seem to lie in an effort at integrating the early instruction in both physics and mathematics, limiting the instruction in early years to those new concepts in each field which are basic to the understanding, and early introduction of instruction in the several professional branches of engineering. To stop with the mere organization of instruction along these lines is insufficient. It is just as important that a procedure be made for stimulating teaching through a stimulating environment of adequate physical facilities. And to stop *there* is insufficient, because it would merely relegate physics to a subordinate influence in the professional thinking of students in later years. It would seem necessary to continue more advanced instruction through the junior and senior years.

This probably would mean the elimination of some of the specialized courses or options in the professional branches. The loss would not be serious, however, if time were saved by allocating everything that properly belongs in physics to that department. If such a procedure were attempted, it could only be accomplished through a cooperative effort on the part of the teachers of physics, mathematics, and engineering, which I believe would have to result in the scrapping of much of our standard text material, the development of a new technique of teaching, and a more advanced approach to the applications of science to engineering practice. An attempt in this direction would bring about an early development of intellectual capacity, a much greater speed of learning, the acquisition of more knowledge in the present 4-year period, and ultimately a more competent and better-educated professional body.

There are many weaknesses in our present situation. First, there is a failure to capitalize the interest which has led the most promising freshmen to select engineering as a career. This could be accomplished by an early introduction to physical concepts through the familiar types of

Essential substance of a paper presented at a meeting of the Society for the Promotion of Engineering Education, Rutgers University, New Brunswick, N. J., May 15, 1937.

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engineering apparatus, giving both exactness of concept and quantitative approach. Because of large numbers of freshmen and inadequate facilities both in laboratories and teaching staffs there is not the personal contact with individual students which could be used for guidance and stimulation in a period now one of the most discouraging in a college student's career. In short, the physics department may be the first vocational guidance agency of the college.

Second, as instruction in engineering is now organized, it too often lacks co-ordination with physics, which often results in duplication of effort. While repetition is a good thing, it does not seem reasonable to a student that a curriculum frequently should require instruction in exactly the same subjects at exactly the same time, in 2 different departments. Co-ordination can be accomplished only by sympathetic understanding and willingness on the part of the faculties of both groups, not only to get together occasionally, but through faculty meetings of each group to meet regularly.

The problem of the physics department of engineering schools may be regarded as embracing 3 general objectives:

1. To instruct undergraduates in those principles of physical science which are essential to an understanding of engineering practice, and develop an appreciation of the relationships in these fields which will encourage the further development of their application.

2. To develop physicists, in addition to engineers, who will be able to carry on the future work in education and research which this important branch of science demands.

3. To develop in all students, technical or nontechnical, an appreciation of the scope, place, and importance of physical science in the modern world.

Considering the question from the limited view of a service function of the physics department should not be construed as a lack of appreciation or resentment toward glorifying the study of exact science as a plane of higher intellectual learning, but rather facing the fact that much of engineering is synthetic in character and must meet compromising and temporizing reactions of economic and human forces. Putting it in another way the engineer takes a utilitarian or practical attitude toward the study and application of physical principles. This fact does not alter the selection or determination of what should be taught, but is a vital factor in the stimulation derived from the way it is taught.

For example, if one were to examine good textbooks in each of the several engineering courses and list the physical principles involved in the understanding of them, by summarizing the results one would still say, teach mechanics, heat, light, sound, and electricity to freshmen and sophomores. These are basic physical phenomena from which applications have arisen through innumerable combinations of principles. Further investigation together with consultation with the faculty of the engineering college should hold promise of advantageous adjustments in time and emphasis given to the several basic courses, but the greatest values are to be obtained from understanding the body of engineering knowledge with a thoroughness that makes possible the selection of projects and problems to vitalize instruction in fundamental principles. Bluntly put, teachers of physics to engineers need to study engineering.

Another phase of the topic may be emphasized by rather sketchy illustrations. Progress in engineering is not stationary; in fact, it is one of the most swiftly advancing professions. With it the body of scientific and engineering knowledge has grown to proportions where serious consideration must be given to the time element in undergraduate education. Whether the situation will result in an extension of time or a modification of curricula, with greater emphasis on subjects in the field of mathematics and pure science, remains to be seen. In the meantime, teachers who are preparing engineers for careers 10 or 15 years hence cannot overlook the changes going on in practice and must attempt to anticipate the relative importance of new developments and viewpoints in the field of science. This refers more to instruction beyond the scope of what in the past has been regarded as the minimum fundamentals.

For example, in electrical engineering the last student generation has been giving increasing attention to the development of electronics with accompanying interest in the understanding of the physical nature of matter. Atomic physics, radiation, and high-frequency current phenomena are, as a consequence, edging into every curricula; in mechanical engineering the orthodox instruction in thermodynamic principles and applications is under pressure, and involves better understanding of the phenomena of internal energy, heat, and heat transfer and insulation; the industry of heating and ventilating and air conditioning is in a state of change; design is affected by the development of the art of welding; in civil engineering building materials are changing—the theoretical approach to stress analysis and fluid mechanics are viewed with a broader technical approach, in which the subjects of dimensional analysis and model structures are of increasing importance; in aeronautical engineering there is the most complicated application of mechanics to structures and fluids. All this seems to point to the necessity of greater exactness in physical concepts and the importance of perspective in dealing with related fields of practice.

It would seem, therefore, that the objectives of service functions of the physics department to the engineers should be: first, to teach thoroughly the minimum fundamentals necessary or prerequisite to beginning engineering subjects; and second, to organize the advanced courses so as to anticipate future requirements. The balance or emphasis given the subject matter must come from a knowledge of engineering practice and trends, in which cooperation with the engineering faculty is essential.

In closing, there are 2 aspects of the human side of the problem which are a part of the service. The first has to do with levels of ability and interest and the second with flexibility of occupational opportunity. Many students would profit by an engineering education; only a portion of them, however, will make successful engineers in a professional sense, and some never should study engineering because they have less than the minimum of ability required to profit by it. Can physics teachers in their

instruction help the engineering division to solve these problems?

Regarding flexibility of opportunity, many engineers seem to be restricted in possibility of accomplishment by too early specialization, a good deal of which comes from a failure to appreciate the scope of application and co-ordination of technical knowledge in practice. Is it possible to bring under the influence of an independent department those subjects of engineering which are elementary, the co-ordination of which will broaden a student's viewpoint and stimulate his interest and curiosity? If there is any justification for such an attempt it would seem to be in the fact that industry is both a crucible and a catalyst for science, where personal opportunity easily can be hampered by premature decisions and prejudices.

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# Use of the Slide Rule for Adding

## By combining its ability to perform addition with its other functions, the usefulness of the slide rule may be greatly increased


By E. B. FERRELL


AS IT commonly is used, the slide rule serves as a set of tables and as a multiplying device. As the latter it also is used in performing the inverse operation division. By combining the 2 functions one may perform such operations as division by a sine, or multiplication by the square of a tangent. For many users the technique of slide rule operation goes no farther than such simple combinations.

By the inclusion of one more concept, however, the technique can be extended to include many addition problems, and a whole new field of usefulness may be opened up. The idea may be illustrated by a simple example. Suppose 18 and 45 are to be added; this may be written

$$18 + 45 = 18\,(1 + 45/18)$$

This reduces a general addition problem to one involving division, multiplication, and a very special addition. The division and multiplication can be performed on the simple slide rule. The special addition can be performed mentally. The only thing remaining is to arrange the work conveniently.

It is helpful to look upon the problem as a continued proportion. A series, 1, $n$, $n + 1$, is set up such that its third term is the sum of the first two. Next any other series is set up whose terms are proportional to those of the first series. Then the second series also satisfies the condition that its third term is the sum of the first two. The setting up of such a continued proportion is one of the easiest things to be done on the slide rule. In the numbers of the example,

$$\frac{1}{18} = \frac{n}{45} = \frac{n+1}{63}$$

This ability of the slide rule to serve as an adding device may be combined with its ability to serve as a set of tables. Squares and reciprocals may be added. To the communication engineer this immediately suggests the combining of impedances, either in series or in parallel.

Suppose the value of the impedance resulting from connecting 5 ohms in parallel with $j4$ ohms is to be computed. Since this is a parallel combination, reciprocals are involved. Since it is a vector combination, squares also are involved. In particular, a series of 3 numbers, 5, 4, and $Z$, are to be set up such that the squares of their reciprocals will form one of those series whose third term is the sum of the first two. Now on the ordinary polyphase slide rule, the numbers on the $B$-scale are the squares

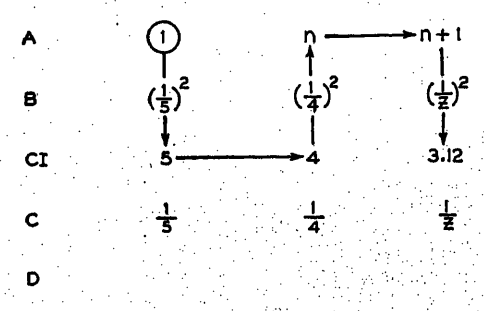



**Figure 1. Setting of the slide rule for computing the absolute value of the combination: 5 ohms in parallel with j4 ohms**


Written especially for ELECTRICAL ENGINEERING.



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of the reciprocals of numbers on the *CI*-scale. And numbers on the *A*-scale are proportional to numbers on the *B*-scale. Therefore, the problem may be solved by reading the numbers 5, 4, and *Z* on the *CI*-scale so that the squares of their reciprocals, on the *B*-scale, lie opposite the series 1, *n*, *n* + 1, on the *A*-scale. The face of the slide rule as set up to perform the required operations is shown diagrammatically in figure 1. The letters at the left of the figure are the names of the scales involved. A vertical line indicates the alignment of 2 numbers on different scales, as may be done with the aid of the runner. The

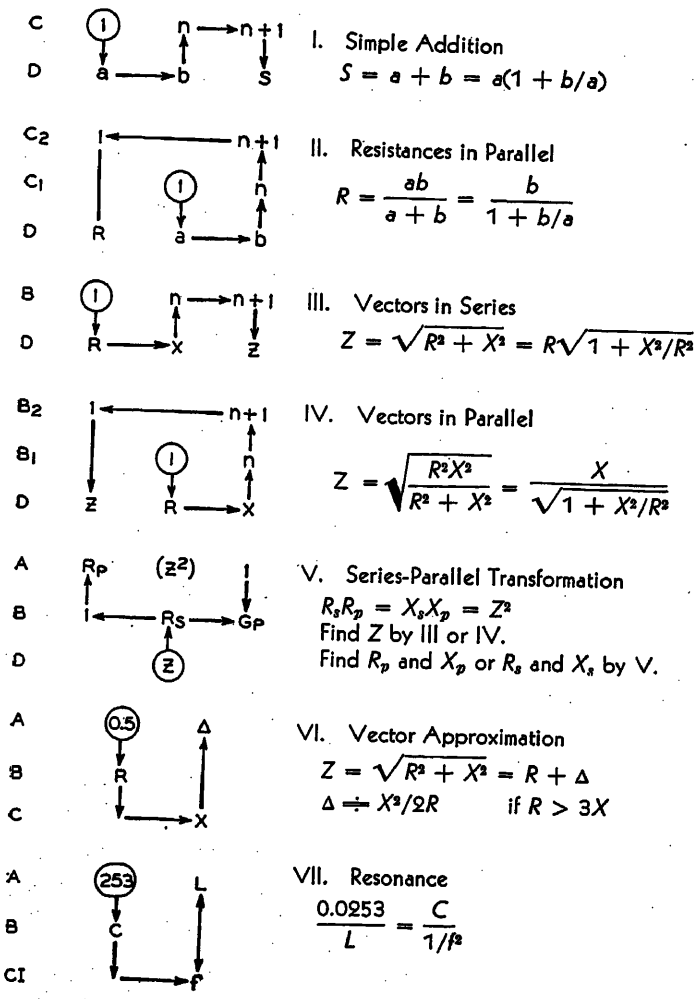



**Figure 2. Diagrams showing some of the operations that may be performed with a slide rule**

circle encloses the number first used and the arrows lead to the various numbers of the problem in the order in which they are used. No explicit use is made of the number $^1/_5$ on the *C*-scale, or the number $(^1/_5)^2$ on the *B*-scale.

In undertaking to apply this extended technique to various problems, there are several possible ways of performing the actual operations—just as there are several ways of performing a simple multiplication. The particular arrangement chosen for the last example, while good for purposes of illustrating the principle, has 2 disadvantages from the operating viewpoint. The result appeared on the slide, where it could not be used directly

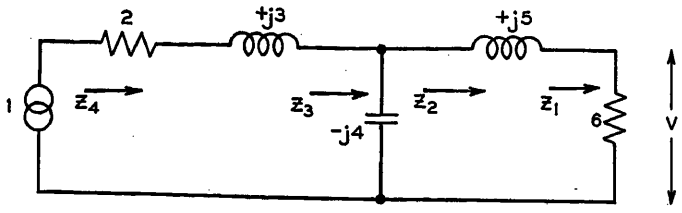



**Figure 3. Work sheet showing computations made with a slide rule**

The voltage *V* is computed from the constants given in the circuit diagram. Arrows are used to indicate equivalences, and show the order in which the operations are performed. The symbol ‖, an adaptation from elementary geometry, indicates "in parallel with"

$Z_1 = 6.00 \qquad = 6.00 \ \angle 0°$

$Z_2 = \dfrac{+j\,5.00}{6.00 + j\,5.00} \rightarrow 7.81 \ \angle +39.8° \rightarrow 10.17 \| + j\,12.20$

$Z_3 = 2.59 - j\,4.43 \leftarrow 5.14 \ \angle -59.6° \leftarrow \dfrac{-j\,4.00}{10.17 \| -j\,5.95}$

$Z_4 = \dfrac{2.00 + j\,3.00}{4.59 - j\,1.43} \rightarrow 4.81 \ \angle -17.3°$

$V = \dfrac{1 \times 5.14 \times 6.00}{4.81 \times 7.81} \angle 0° - (-17.3°) + (-59.6°) - (+39.8°) + 0°$

$= 0.820 \ \angle -82.1°$

for subsequent operations. The arrangement involves the use of the *CI*-scale which does not appear on the simple Mannheim rule.

The set of diagrams in figure 2 shows convenient methods of performing a few of the operations that may be of interest to the communication engineer. In some of these operations the slide, instead of the runner, is shifted. Successive positions of the movable scale are indicated by subscripts. It may be noted that only a single shift of either the runner or the slide, but not of both, is required to complete most of the operations indicated.

Nothing has been said about the location of the decimal point. Rigorous rules for this are both complicated and unnecessary. In vector work more help will be obtained from a visualization of the vector triangle.

No mention has been made of the phase angle. Unfortunately the trigonometric scales of the Mannheim rule are not located conveniently for inclusion in the technique described. Fortunately the angle itself is often not of great importance. When needed it can be found by a separate simple operation. But it may be noted that the "*n*" in either of the vector operations is the reciprocal of the tangent of the angle. If at the start the index always is set over the *smaller* of the 2 vectors, then only the addition of an inverted tangent scale on the face of the slide is required to make a full-fledged vector slide rule out of the simple Mannheim rule. The first decade of this scale is sufficient for most purposes.

In preparing this discussion the objective has been not the presentation of a new formula or a new trick, to be forgotten as easily as learned, but the encouragement of a viewpoint that would lead to wider and more satisfactory use of the simple slide rule.

# Protective Multiple Earthing in England

## From the results of an investigation conducted in 4 typical villages in England, recommendations for improving the protective earthing (grounding) of rural electric circuits in that country have been made

INVESTIGATIONS to ascertain to what extent consumers of electricity in rural areas of England are protected from risk of shock with methods of earthing at present in use, and what changes in practice might be desirable, with special reference to "protective multiple earthing," were reported in a paper by H. G. Taylor entitled "The Use of Protective Multiple Earthing and Earth-Leakage Circuit Breakers in Rural Areas" which was read before The (British) Institution of Electrical Engineers, April 14, 1937. The term "protective multiple earthing" as used here means the connection to earth of the neutral conductor at some or all consumers' premises and the connection of metal frameworks to the neutral, using a separate insulated earth-continuity conductor that is run through the house and connected to all metal-work of appliances, to a separate earth, and to the neutral service conductor on the service side of the fuses at the meter board.

The investigations show that present safeguards are inadequate. Recommendations are made which it is believed will lead to material improvement, but further experience and experiment are said to be necessary before the matter can be put on an entirely satisfactory footing. Figures 1 to 4, reproduced from figures 1, 2, 3, and 10, respectively, of the paper, give some of the principal results.

It has been realized for some time that in rural areas fed by overhead lines where no water mains exist the protection afforded by "ordinary earthing" is not entirely satisfactory. With this in mind an investigation was undertaken by the British Electrical and Allied Industries Research Association with a view to finding means for improving the situation. Alternative methods of protection are provided by earth-leakage circuit breakers, or the use of the neutral to carry the fault current. This latter method, known throughout the paper as "protective multiple earthing" is subject to the disadvantage that the frameworks of apparatus connected to the neutral rise to the same voltage above earth as the neutral conductor. It was found from field tests, however, that the voltage rise of the neutral did not exceed a value dangerous to human beings under normal operation, and that even animals would be protected if the statutory voltage drop were not exceeded. No interference with the satisfactory working of the telephone system was observed during any of the tests.

Other possible sources of trouble due to the use of the protective multiple earthing system were considered in some detail. An investigation also was made to find the tripping voltage of earth-leakage circuit breakers that have been in use for a period of about 2 years.

## Conclusions and Recommendations

The paper concludes with the following major deductions reached from the practical tests, conclusions re-

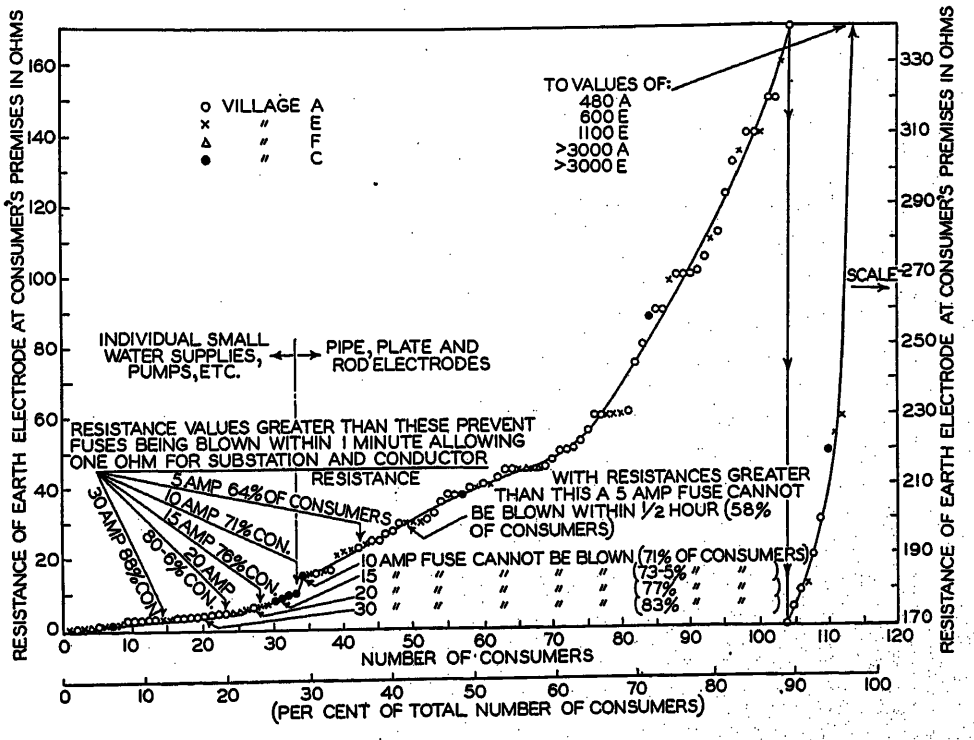



**Figure 1. Resistance of earth electrodes at consumers' premises**

In none of the villages does a general system of water mains exist, though in many cases it was found that consumers had a pump which drew water from a well in the garden, and these were generally used for earthing. The value was always 10 ohms or less, and the figure shows a clear discontinuity in the curve at 10 to 15 ohms, between the resistance of pumps, water systems, etc., and that of earth rods or plates

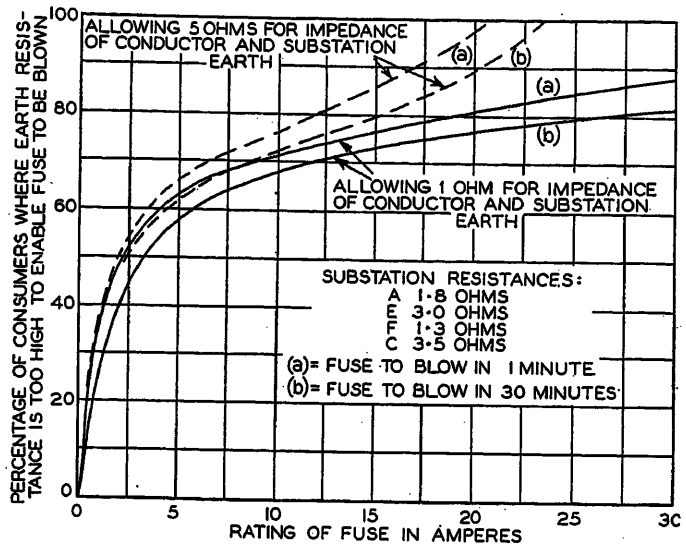



**Figure 2. Percentage of consumers at each of the villages where fuses of various sizes cannot be blown**

specting protective multiple earthing in general, and recommendations respecting existing and new installations and certain proposed conditions which should be complied with before protective multiple earthing is permitted:

### Conclusions on the Practical Tests

1. If the results of measurements made at 4 villages in different parts of the country may be regarded as typical, in $^2/_3$ of the installations in rural areas fed by overhead networks, where no water mains exist, fuses could not clear an earth fault due to an insulation breakdown on electrical appliances.

2. Tests in an area where the earth resistivity is high have shown that earth-leakage circuit breakers, while not in all cases functioning at a voltage below the danger limit (*viz.*, 30 volts), have contributed materially toward eliminating the risks of electric shock. Moreover, many of the tests were conducted on early types of circuit breakers, and with the improved types now available and the development of technique there is good reason to expect better results in the future.

3. Tests on protective multiple earthing have shown that the voltage-rise of the neutral with respect to earth under quite abnormal conditions of loading does not exceed 30 volts and is therefore not dangerous to human beings, though it may be dangerous to animals.

4. When using protective multiple earthing, immediately prior to the blowing of fuses the voltage rise of the neutral at the end of distributors and near the substation may be 60 volts to earth for a short period.

5. If the statutory limits of voltage variation are adhered to, the voltage rise of the neutral will not be dangerous to either human beings or animals.

6. The voltages picked up on pilot lines to test earths adjacent to power earths were smaller than would be required to produce false ringing of telephone bells in the C.B.S. No. 1 type of exchange, and listening tests on the telephone lines did not reveal any disturbance.

7. Substantial improvement could be effected in existing installations using the present method of earthing by—

(*a*) Ensuring that an electrode not less than 6 feet long and not less than $^3/_4$ inch in diameter is always used, and that, if necessary, 2 are used at least 6 feet apart.

(*b*) Making use of a small water-pipe system, if one exists in the village, as the earth for the neutral, instead of attempting to provide an earth of low resistance at the substation.

(*c*) Making greater use of a protective earth wire for interconnecting the metal-work in a group of houses, and joining it to earth at a house where a low earth resistance exists.

8. The effect of multiple earthing of the neutral is to reduce the voltage drop in the neutral and earth in parallel to a greater extent than would be expected from the change in resistance; at the same time the voltage-drop in the phase wire is increased.

9. Multiple earthing of the neutral does not appreciably improve the voltage regulation.

### Conclusions on Protective Multiple Earthing in General

1. If the connection between the protected metal-work and the (insulated) neutral is made only at the meter board, a fracture of the neutral wire inside the installation does not represent a hazardous condition—the appliance merely ceases to function. If a fault to frame exists, current returns through the neutral wire and the earth-continuity conductor in parallel, and entirely through the latter if a break in the neutral occurs. As this may constitute a fire hazard if it continues for any length of time, it is essential that no fuses or switches should exist in the neutral.

2. The voltage rise of protected metal-work in the event of a fracture of a neutral service conductor, without the phase wire, is determined by the connected load and the earth resistance at the consumer's premises. For example, on a 240-volt supply, if the resistance is 10 ohms and the load switched on is 1 kw the voltage rise is 36; if the resistance is 100 ohms the value is 152 volts. The voltage rise is in no case equal to the full supply voltage, which is the voltage which may occur on metal-work ineffectively earthed in the ordinary way, unless there is no earth at all on the consumer's installation.

3. In the event of a break in a neutral distributor without the phase wire all the metal-work on the system rises to a certain voltage with respect to earth, which is determined by the connected load on the remote side of the break from the substation, and the resistance to earth of the neutral on either side; if the break is near the substation the voltage on the frameworks of appliances connected to the sound section of the neutral is higher than that on those connected to the disconnected section; if the break is nearer the end of the distributor than the substation the reverse is the case. From the point of view of general danger the worst position for the break if the system possesses only a single distributor is at 30 to 40 per cent of the distance from the substation to the end of the distributor with a

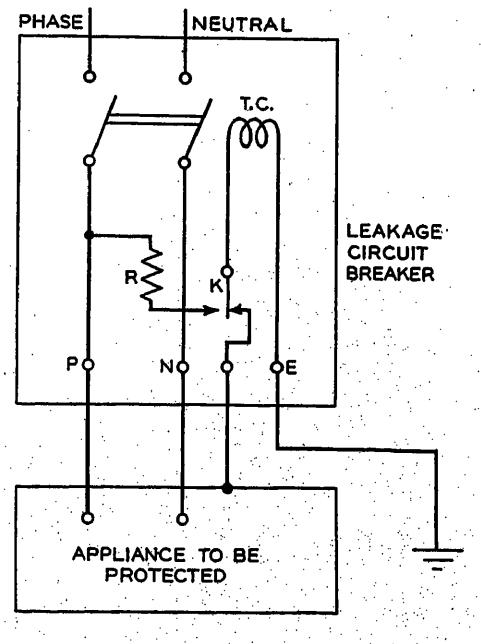



**Figure 3. Diagram of connections of earth-leakage circuit breaker**

uniformly loaded and symmetrically earth system. The lower the general resistance to earth of the neutral, the less the voltage rise.

4. Comparing the system of protection by earthing which is at present used, with protective multiple earthing, from the point of view of shock risk, it is estimated that the latter system is several times as safe as the former.

5. With protective multiple earthing, a line-to-neutral fault on the distributor of a 240-volt system would not result in a greater voltage than 60 volts on protected metal-work, provided precautions were taken in effecting the earth connections to ensure that the true neutral point is near the load center of the system.

6. A disadvantage of protective multiple earthing of the neutral is that current returning from an earth fault on the phase wire cannot be distinguished from normal neutral return current.

7. Existing installations may readily be converted to the protective multiple earthing system by connecting the earth-continuity conductor to the neutral at the meter board and linking across all neutral fuses.

### Recommendations

1. That protective multiple earthing be permitted, subject to compliance with the conditions laid down below.

2. That farm installations where animals may come into contact with protective metal-work should be treated differently from house installation, in view of the greater sensitivity of animals to shock than human beings.

3. Since small water systems frequently occur at farms it is suggested that such installations only continue to be earthed in the usual way, provided that the total resistance in the earth circuit at any time of the year is low enough to pass $2^1/_2$ times the current normally carried by the largest fuse on the installation. If this is not possible then earth-leakage circuit breakers should be used on each distinct piece of apparatus and *all* frameworks and metal-work in the installations, liable to become alive, should be protected, where there is danger of animals making contact with the metal-work. The trip-coils should operate at not more than 15 volts.

4. If undertakings decide to continue to rely on ordinary earthing, the resistance in the total earth circuit should be such that the earth current which will flow at any time of the year, in the event of an earth fault, will be $2^1/_2$ times the current normally carried by the largest fuse in the installation. If this cannot be ensured then ordinary earthing should not be relied upon, and protective multiple earthing or earth-leakage switches should be used.

5. If earth-leakage circuit breakers are used, care should be taken to ensure that *all* metal-work throughout the installation which is liable to become alive is protected.

6. That a British Standard Specification be prepared for earth-leakage circuit breakers.

7. That greater attention be given, in the construction of all electrical appliances, to the provision of a higher standard of insulation.

### Proposed Conditions Which Should Be Complied With Where Protective Multiple Earthing Is Used

1. The size of the neutral distributor should not be less than that of the phase wire, and both conductors should preferably not be less than 0.05 square inch.

2. The neutral should be connected to earth at all consumers' terminals—the earth electrode consisting of any water pipes that are available or a single 6-foot mild-steel rod of not less than $^3/_4$ inch diameter or a pipe of 1 inch diameter. The pipe or rod should be driven as nearly vertically as possible, and the connection to the electrode should be made above the ground surface so that it may be inspected.

3. The neutral distributors should be connected to earth at the base of poles at 4 points per route-mile, in addition to the earth at the substation. Including the substation the ratio of any 2 of these resistances should not exceed 4, and the greatest should not exceed 10 ohms,* and should preferably be considerably less.

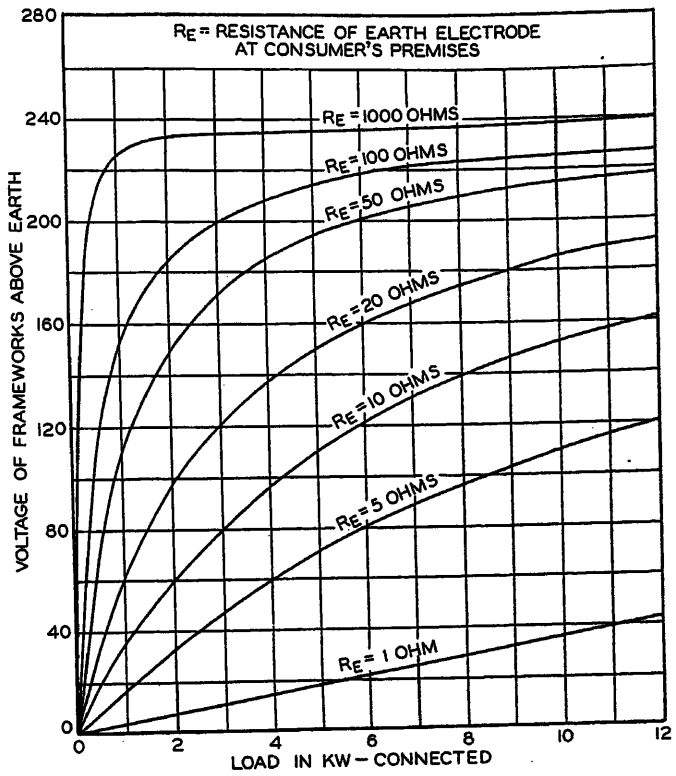



**Figure 4. Voltage above earth of protected frameworks for various values of earth resistance and installed capacity when a break occurs in a neutral service conductor**

4. Water mains should not be used for earthing at the substation.

5. An earth-continuity conductor should be used throughout each installation, and should be connected to the neutral conductor and earthing lead at the meter board.

6. No switch or fuse should be used in the neutral throughout the installation, but removable links may be provided for test purposes where required.

7. The resistance of the earth continuity conductor from any appliance to the meter board should not exceed 0.5 ohm, and this should be verified in each installation by means of a current of at least 10 amperes flowing for 5 minutes, before protective multiple earthing is used.

8. Two separate electrodes should be provided for earthing: (*a*) the high-voltage system neutral point and/or any metal-work related to the high-voltage system and electrically separate from the metal-work of the low-voltage system, e.g., the earth wire; and (*b*) the low-voltage system neutral point and the metal-work of the low-voltage system. These should be so situated that the low-voltage earth electrode is not within the resistance area of the high-voltage earth electrode. If this precaution were not taken, then a breakdown on the high-voltage system, causing current to flow through the high-voltage earth electrode, would result in the potential rise of the high-voltage earth electrode being communicated to the neutral of the low-voltage system and all apparatus frames connected to it.

9. The distribution system should be so protected that in the event of contact between a phase wire and neutral at any point up to the consumer's terminals the supply would be automatically cut off from the defective section.

* In areas where the resistivity is exceptionally high it may be necessary from economic considerations to permit a higher value of resistance than 10 ohms.

# A Review of Radio Interference Investigation

By F. E. SANFORD
MEMBER AIEE

WILLARD WEISE
NONMEMBER

Development of radiobroadcasting and reception has been paralleled by development and extensive use of devices that may cause interference with reception. The purpose of this paper is to review several factors of particular interest to the electric utilities, who supply service to both the radio and many of the interference sources. A relatively new form of interference effect—external cross modulation—is described. In conclusion, a parallel is drawn to the familiar co-ordination activities on wired communication lines and electric power systems.

RADIO has advanced from a little known hobby of 15 years ago to a publicly accepted source of entertainment, news, and education today. Modern receivers with high sensitivity, wide frequency coverage and high fidelity, represent an almost phenomenal development from the battery-operated sets of 10 years ago, and the crystal sets of a few years previous.

Self-contained, compact receivers, capable of being operated without special antenna and ground connections, have replaced the older sets which required a large cabinet, miscellaneous connections, and an outside antenna. A short piece of wire along the floor or wall for an antenna, and no connection to a ground post, are features of minimum installation trouble. A connection to the nearest electric outlet has replaced the batteries and eliminators.

Expectancy on the part of listeners for absolutely noise-free reception has increased the level of freedom from interference expected. In contrast to the thrill of hearing a distant station, even if only faintly and between crackling noises, is today's immediate annoyance at any snap, buzz, or break in good, clear reception. This attitude is, in itself, highly complimentary to those who have made it possible.

## Increase of Interference Sources

In this same period, development and increase in use of electrical appliances has paralleled radio development. Along with lights there are now in the same homes with radio receivers, one or more of the new appliances—electric refrigerators, mixers, cleaners, blowers on heating and cooling systems, oil igniters, stokers on furnaces, and now even electric razors. These devices employ motors, thermostats, control contactors, etc., which may contribute to radio-frequency disturbances.

High-frequency equipment, such as X-ray and therapeutic apparatus, formerly confined to hospitals, is now located in doctors' and dentists' offices in every commercial center. Flashing commercial neon signs are common and electric precipitators and other industrial devices may contribute to radio-frequency disturbances over a wide area.

In the majority of cases, interference from these sources is confined to the same building or room, but in other cases the disturbance may be severe enough to carry over electric service lines which are common to several buildings and reach receivers in the neighborhood. In particularly severe cases, the high frequency has been known to spread through space and over distribution circuits and cause interference over an area of several miles radius.

These conditions summarized briefly are:

(*a*) Sensitive, compact a-c receivers with short inside antennas.

(*b*) A wide band of frequencies to be received and an increasing interest in short-wave foreign broadcasts.

(*c*) A more discriminating and widespread group of listeners.

(*d*) A large increase in possible sources of interference and in the density of these sources.

## Utility Interest in Interference

Electric distribution equipment of the utilities was originally one of the principal causes of radio interference. Loose connections at cutouts, taps and terminals, and arcing at insulators and to grounds, were the principal causes encountered. Tests, inspections, laboratory research, design changes, and maintenance have, in general, removed this source as a widespread cause, but cases of loose and corroded connections and faulty equipment still occur often enough to require investigation of complaints. Investigation on the lines has now been largely reduced to locating individual cases of breakdown and repairing or replacing of defective parts.

Interference carried by distribution lines, service wires, and inside wiring, is of more importance now, partly because it is not so easily eliminated. Some of the interference from appliances is directly transmitted, but in other cases electric circuits serve to carry it. The principal rôle of the electric circuits is shifted from that of direct influence or cause to the field of carrier or coupling.

Investigation of radio interference complaints has generally been taken care of by the public utilities, in the United States. This rather liberal policy has been a gradual development and may be considered as promoting customer good will. The utility cannot say that its equipment is not causing trouble, without an investigation, because such cases still occur. The utility's inspector can

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The authors wish to acknowledge the assistance given by W. J. Wuest and W. L. Thompson, Cincinnati Gas & Electric Company, in the interference inspection procedure outlined, and by the technical supervisors of Cincinnati radio stations, particularly R. J. Rockwell, of Crosley Radio Corporation, for co-operation which has led to a practical application of the co-ordination idea.

usually trace down the real cause at a moderate additional cost.

A less tangible result of public acceptance of radio is of inestimable value to the rest of the electrical industry. Radio has contributed to the public's knowledge and intimate familiarity with electrical apparatus. This must inevitably help to stimulate an interest in all electrical development.

Portable radio receivers have been used by a number of companies in line patrol work, to locate trouble in its initial stages. Investigation of radio interference complaints, which lead to the location of defective distribution and transmission line parts and loose connections before they develop far enough to result in line outages, may in itself go far to balance the cost of such investigation.

Where the utility's policy is to investigate all complaints received, an average of about 20 per cent justified complaints from power causes has been found during the past few years by The Cincinnati Gas & Electric Company. The number of power causes is only about 25 per cent of what it was in the first years of this investigation work. The frequency rate of complaints averages one complaint per year per 300–400 residential customers. The cost of these investigations to the utility, in general, approximate only about 1 or 2 per cent of the revenue derived from radio. Incidentally, Edison Electric Institute statistics show radio receivers as a consumer of total kilowatt-hours second only to electric refrigerators, among domestic appliances.

## Causes of Interference

Radio receivers respond to impulses of minute quantity, in the range of frequency for which they are designed and adjusted. Whether these impulses come entirely from a desired broadcast station, or partly from other nearby sources, determines the degree of freedom from interference. The ratio of signal strength to noise level is important. Radio interference is a purely relative situation. Many of the causes of interference today would have been entirely unnoticed with the old-type receivers and antenna installations.

Excluding natural or atmospheric static and set troubles, there are 2 common classes of interference, and a third class that is less known. The most common causes are those associated with load current passing through poor

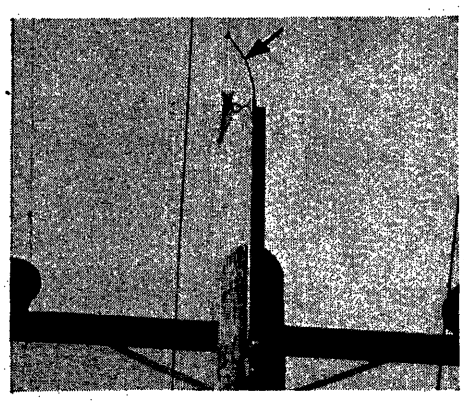


**Figure 1. Flexible jumper on swivel static clamp**

The loose connection of these clamps to ground the static wire is sufficient for lightning surges but not as a drain for radio-frequency energy picked up by the static acting as an antenna

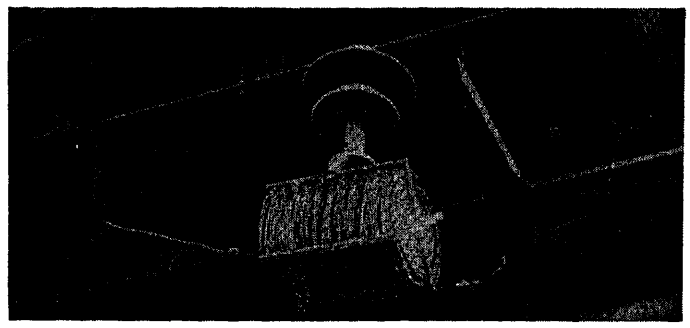


**Figure 2. Radio-frequency choke applied to an industrial precipitator**

Before this source of interference was located, interference had been found as far as 2 miles distant

or loose connections in circuits or equipment and generating radio-frequency energy.

Somewhat less common are the cases of static discharges to ground, from electrical conductors or charged bodies, but not associated directly with load current. External cross modulation is a relatively new class of interference, somewhat similar to static discharges but with other factors associated with broadcast energy.

Some of the more common causes associated with sparking or loose contact are: connections in the house wiring; at the appliance or outlet receptacle; in the entrance connections or outside in the service connections; secondary lines; or transformer installation equipment. Other causes include slip-ring and commutator sparking in motors; thermostatically controlled loads of all types, from the household aquarium heater of a few watts to the industrial electrical heaters of many kilowatts capacity; synchronous rectifiers of X-ray equipment and industrial precipitators; therapeutic devices; elevator controls; dial telephones; electric railway equipment, trolley and motors; and a host of others.

A few of the common causes of the static discharge type of interference are the alternate charging and discharging of household refrigerators by belt static; worn extension cords touching metallic frames; armored cable loosely touching against grounded piping and discharging whenever vibration causes contact. Primary distribution line causes include insulated conductor arcing to hardware; line wires arcing to guys or trees; street lighting fixture troubles; loose tie wires at insulators; and loose ground connections on overhead ground or static wires.

Fortunately, the majority of the more common causes of arcing type of troubles are fairly easy to locate and eliminate. Remedy may vary from tightening of connections to the application of chokes or condensers. Many electrical devices now have built-in capacitors which are very effective. Static discharge causes are eliminated by increasing clearances, by bonding, or solid grounding.

There is no "cure-all" type of corrective or mitigative measure, nor does there appear to be any general rule for the elimination of interference. Some of the commercial so-called interference eliminators have been nothing more than small condensers. Other "eliminators" ground the

receiver antenna terminal and use the house wiring for an antenna.

The conclusion may be stated that in most instances, elimination of severe interference requires location and correction at the source. Since, however, the absolute elimination of all sources does not appear feasible or practical, it is essential that receiver antennas should be properly installed, and free from, or shielded from, surrounding wires. Short inside antennas, which pick up the broadcast energy by reradiation from the house wiring, will naturally be much more susceptible to even slight influences.

## External Cross Modulation

This is a relatively new term in the field of interference investigation. The explanation is at present more theoretical than proven, although the evidence of it is definite enough. To the radio listener the effect is that one station is heard in the background when the receiver is tuned to another. In extreme cases, the background station may actually predominate. This form of interference must be differentiated from cross modulation within the receiving set itself.

External cross modulation is a field strength modulation produced by a strong signal in conjunction with another signal, where both act upon a system of wires or metallic structures in which there is a variable impedance element affected by the radio-frequency-current pulsations. This metallic system then reradiates the desired signal which, due to the variable impedance, contains the modulation of the other signal.

If the receiver antenna is in the field of the reradiated signal, there will be both direct radiated and reradiated energy entering the receiver. The severity of cross talk or cross modulation depends on the ratio of these 2 energies.

Rectification at a poor connection will also result in the generation of harmonics of the actuating frequencies, as well as heterodyne frequencies obtained by the addition and subtraction of fundamental frequencies and combination of fundamental and harmonic frequencies.

Elimination of this type interference requires properly installed antennas, solid grounding of neutral service wires, and clearing of loose connections in surrounding piping, plumbing, and metallic surfaces. Contact between any metal bodies of sufficient size, if the contact is oxidized, will cause rectification and hence cross talk or cross modulation.

## Investigation of Complaints

In the interest of service and good will, it is necessary that the electric utility investigate radio-interference complaints made by its customers. Considerable variation in the company policy is possible—from one of investigating every complaint, tracing the trouble to its source and correcting the condition regardless of its nature, to investigating only those assigned definitely to the utility by a competent radio service man. Efforts to curtail the field work involved have included letters listing several questions to be answered by the complainant before the investigation is made, as well as, in a few cases, a charge for investigations made that do not disclose a utility source of interference.

In some cases, an extremely liberal attitude has resulted in the utility becoming almost the first point of call for all sorts of radio trouble. This is, perhaps, as undesirable as the opposite extreme of having customers feel that the utility is barely willing to clear its own trouble to correct interference.

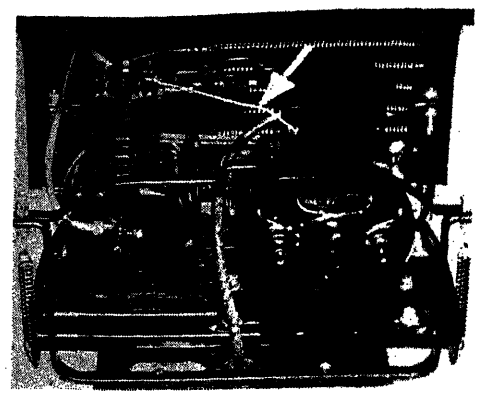


**Figure 3. Eliminating belt static in a domestic refrigerator**

A small copper-wire jumper is used to bond the motor and compressor

A moderate policy seems to be that the utility should have an inspector make personal contact as promptly as possible, identify the interference, classify its intensity, and locate the cause of trouble. If interference is found to be caused by utility equipment, the condition should be corrected, or mitigative measures applied. If the interference is found to be caused by appliances or devices owned and operated by utility consumers, an attempt should be made to either apply or suggest corrective or mitigative measures.

Cases of radio-receiver trouble should be referred to the customer's radio repairman. Many, and perhaps a large percentage of complaints will lead to trips by the inspector only to find that the interference was only on a short time and has disappeared, or that the complainant has found the trouble, or also called a service man to check the receiver. Here, as in cases of actual interference, tact and an attitude of personal interest on the part of the inspector, are a definite asset to the utility in maintaining consumer good will.

The most useful tool of the inspector in following this policy of investigation, is a standard receiver. Use of this set isolates the cases of receiver trouble. The procedure is then to follow back and by elimination of possibilities finally isolate the source of trouble. During this part of the investigation, the inspector should also check the antenna.

In most cases, it is permissible to open the entrance switch in residences, and a test made here with the test receiver connected on the line side of the switch, will definitely show whether the trouble is within the premises. If it is, the branch circuit can be located in a similar manner.

These first steps are made on the supposition that the

trouble is on the premises of the complainant. The average experience under the moderate policy outlined above, is that two-thirds of the total complaints received will be cleared or isolated at this point, including the cases of receiver trouble, unfounded complaints, and disappeared interference.

The next step in the remaining one-third of investigations, is outside the complainant's premises. Here the investigation becomes more technical in nature and follows along the lines of experience in the past. The principal point of difference under conditions of the last few years, compared to the earlier years of radio, is the very large proportion of complaints that can be eliminated without the use of special investigation equipment for use in the field.

It is important that a record be kept of each complaint received and the investigation made. It is helpful to have a method of classifying the complaints on this record, so that summaries may be made and the work reviewed. Instruments are available for technically classifying interference levels, but a practical method that is easily applied on the first investigation is to compare the signal to noise ratio, at various points on the dial. The essential information is field strength or intensity of the interference and its duration.

A notation $R_2\ ABC\ F_4$ on the complaint report, representing an interference that is equal in interference to station $ABC$ at the location of the test with the antenna system on the premises, and that the interference is continuous, gives a helpful record.

With this method of notation, $R_0$ is used to represent inaudible interference and the grading is up to $R_3$ where the interference blankets the signal. For time frequency notation, $F_0$ represents very infrequent, $F_1$ minutes per day, up to $F_4$ representing continuous.

This method is being used to replace exact data obtained from field-strength instruments and the notations are more easily understood in this form than in terms of microvolts per meter. This does not preclude, however, the necessity of accurate instruments for more technical field strength and interference investigations.

## Radio Co-ordination

Radio-interference elimination is essentially to co-ordinate this use of electricity with its other uses for light, heat, power, and transportation, in order that the growth of each may not be restricted by the requirements of the other.

The complete elimination of all radio interference would involve an enormous sum of money. A reasonable level, which is economically feasible, is the best that can be hoped for. Ratio of broadcast field strength to noise level field strength, both natural static and man-made interference, is an important part of the problem.

Legislation has, in a few instances, been provided by states and cities in the United States. Serious enforcement of such laws and ordinances would be cumbersome and expensive. Individual offenders who knowingly and persistently operate interference-producing devices and refuse to co-operate in application of necessary remedial measures, are rare.

A highly effective approach to the inductive interference problem caused by proximity of telephone communication circuits and power circuits, has been through recognition of 3 subdivisions of the factors involved: (1) inductive influence of the power circuit, (2) inductive susceptiveness of the telephone circuit, and (3) inductive coupling between the 2 types of circuits.

A similar approach to the radio-interference factors is practical. The approach is much more complicated in its broad aspects, however. In the one case, it involved a telephone utility and electric utility working together, or national committees representing the 2 interests, working out a program for investigation and research. In the present problem, equivalent interests are widely scattered and following widely divergent lines.

1. Reliable manufacturers of appliances have given attention to radio-interference effects of their products. In other cases, the same care has not, evidently, been given. A thermostatically controlled fish-aquarium heater selling for about $1.00 has in several instances been found to cause radio interference in neighboring houses. Freedom from radio interference is a general, if not yet universal, indication of merit.

2. Radio-receiver manufacturers have devoted a great deal of research and experimental work to proper shielding from outside influences. When all these influences are compared to radiobroadcast waves, in field intensity, it may be said a good job has been done. In too many cases, however, careless installations have been allowed to offset these efforts. Further co-operation along this line is in order, to reduce the factor of susceptiveness.

3. In this consideration, the rôle of the electric circuits may be shifted from that of influence to one of coupling. While the primary

**Table I. Classification of Interference Sources**

Found by Cincinnati Gas & Electric Company Investigation (1936)

| | Per Cent | |
|---|---|---|
| Disappeared or unfounded | 43.0 | |
| Receiver trouble | 18.0 | |
| Ground or antenna | 1.0 | |
| Cleared on call or check at receiver | | 62.0 |
| Loose connection at meter board | 4.5 | |
| Refrigerator connection or static conditions | 4.5 | |
| Thermostats | 1.0 | |
| Miscellaneous appliances | 3.5 | |
| Secondary customers' equipment | | 13.5 |
| Note: 2/3 on complainant's premises, 1/3 in neighborhood | | |
| Street railway equipment | 4.0 | |
| Commercial signs | 2.0 | |
| Industrial equipment | 1.0 | |
| High-frequency equipment | 0.5 | |
| Miscellaneous | 3.0 | |
| Outside sources other than electric utility | | 10.5 |
| Loose connections of primary circuits | 5.0 | |
| Secondary connections and grounds | 2.0 | |
| Loose static wire connections | 3.5 | |
| Defective equipment | 1.0 | |
| Electric distribution lines and equipment | | 11.5 |
| Miscellaneous | | 2.5 |
| | | 100.0 |

lines are most important in the influence field, both in inductive co-ordination and where electric lines cause radio interference, the secondary circuits are usually most important in the coupling effect. It is important to note that secondary circuits include house wiring. Even in cases of exceptionally strong influences, the radio frequency waves do not pass through the impedance of transformers to the primary.

A very important possibility for co-operation in this field includes a workable understanding among the 3 groups in any particular locality, most interested in good radio reception, namely:

(*a*) Radio and appliance commercial group and repairmen.

(*b*) Radiobroadcast technical group.

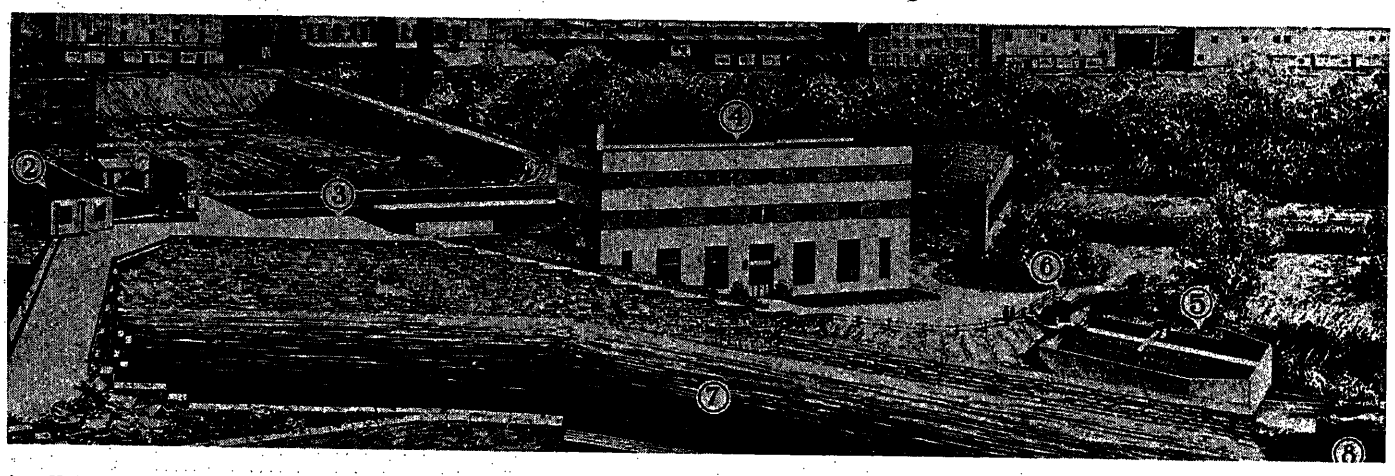
(*c*) Utility distribution engineers and inspectors.

In Cincinnati, where there are 5 broadcast stations, joint efforts of this group and the utility group has led to a procedure for the elimination or alleviation of individual cases of external cross modulation. This information has been put in the hands of all radio service men. Considerable research and field inspection work has been carried on by both groups.

Care is exercised by inspectors on the general and outside influence end, not to step into the field of the service men, whose proper sphere includes correction of any faults in the receiver installation as well as other efforts on the complainant's equipment. On the other hand, there is no attempt to avoid the responsibility of interference elimination when it is caused by outside influences.

There can hardly be a question of the value of joint efforts toward co-ordination of: (1) influence, (2) susceptiveness, and (3) coupling, in the field of electric appliances, radiobroadcast and reception, and electric service. Continued co-operation will lead to control of interference and lessen the need for mitigation and individual corrective measures.

## Minnesota Hydraulic Laboratory Being Constructed



NEAR the headwaters of the Mississippi River, 90 miles from its Lake Itasca source, the United States Works Progress Administration is constructing at St. Anthony's Falls a large-scale hydraulic laboratory for the college of engineering of the University of Minnesota. Located on Hennepin Island, in the heart of Minneapolis and near the center of the city's famous milling district, the laboratory will be primarily an experimental and research institution. Its function will be to promote greater knowledge of the use of water power, together with the improvement of hydroelectric machinery, and its facilities will be used by all students studying hydraulics at the University of Minnesota. Reproduced from an artist's drawing of the laboratory as it is expected to be when completed, the figure on this page shows: (2) the intake to the laboratory and the gate-control house; (3) main experimental laboratory for open-channel experiments and river hydraulics; (4) hydraulic machinery and turbine laboratory; (5) discharge measuring basin; (6) wasteway; and (7) tail-water pool.

Because a head of 48 feet is available at the site at all times the location is unusually good for a hydraulics laboratory. A long horseshoe-shaped weir constructed above the falls provides close regulation of head, and facilities are being provided to handle discharges of more than 300 cubic feet of water per second.

The building has been designed to utilize approximately half of the available head for model rivers and other experiments on flow in open channels, the level of the main experimental floor being 20 feet below the main headwater level. The remainder of the drop in the experimental plant permits large-scale volumetric measurements of flow, for which twin basins supplied with pneumatically operated cylinder valves are to be constructed.

The Hennepin Island laboratory is said to be the only one in the United States in which the testing of a full-size turbine will be possible. Its possibilities already have attracted national attention in the field of hydraulics, and experimental work is being planned in co-operation with federal, state, and commercial interests. Much of the research on sediment transportation by rivers being conducted in the University's existing hydraulic laboratory will be transferred to the new quarters when they are completed.

# Lightning Strokes in Field and Laboratory—II

By P. L. BELLASCHI
MEMBER AIEE

THE LIGHTNING-STROKE generator has made possible the investigation of lightning-stroke phenomena in the laboratory.[1,2] This paper deals with the fundamental aspect of the problem, particularly with the characteristics of the lightning-stroke channel. The data and findings here presented reveal further the nature of the channel core and of the resulting column.[3] Field observations are also indicated for comparison, to enhance the value of the laboratory investigation.

## Test Method

The lightning-stroke generator consists of a high-voltage generator, a heavy-current generator, and a "microsecond switch." A steep-fronted high-voltage impulse from the voltage generator initiates flashover or dielectric breakdown of the test object. Then, within a time measured in microseconds the current generator is switched on thus supplying to the test object a current of lightning-stroke intensity and duration.

A lightning-stroke test is illustrated in figure 2. The voltage generator first breaks down the 36-inch rod-to-plate gap, this occurring on the front which rises at somewhat more than 3,000 kv per microsecond (figure 1*D*). Then, as oscillogram *A* shows, the "microsecond switch" operates and in 5 microseconds the current generator begins discharging across the gap a current which reaches 57,000 amperes and of a total duration of 100 microseconds or more. More rapid and slower follow-up of the current occurs, respectively, for oscillograms *B* and *C*. A lightning-stroke to a distribution-line wood pole appears in figure 9 in which case the voltage to break the pole down rises to 2,500,000 volts, followed by the current of lightning-stroke intensity and duration. These tests are typical of the lightning-stroke testing in this investigation.

## Characteristics of Lightning Channel

### Tests on Paper and Similar Materials

The results from tests on paper and similar materials are summarized in table I. In these tests a large sheet would be mounted on an insulated wood frame and inserted in the path of the discharge as in figure 2. Test samples indicating the area "blown" are shown in figure 3.

For rather strong, yet quite thin, white paper (first 8 samples), the average area "blown" for a current of 53,000 amperes (average) is close to 0.15 square inch. One test at 23,500 amperes gives an area of 0.07 square inch. On thicker paper (samples 12, 13, and 21) the area is 0.16 square inch for 55,000 amperes. At higher currents, tests on the heavier paper only were possible because of tearing. An area of 0.24 square inch is obtained with 74,000 amperes (samples 15 and 16). The areas "blown" in the paper for currents of 24,000, 54,000, and 74,000 amperes are then, respectively, 0.07 square inch, 0.15 square inch,

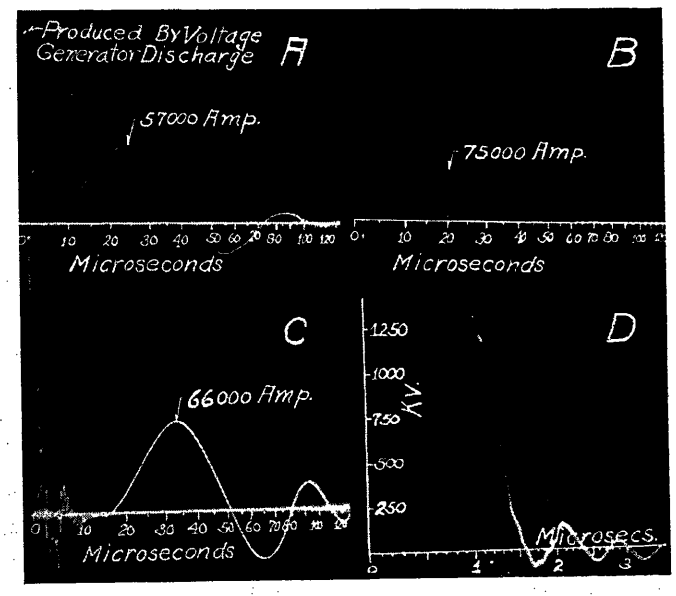



**Figure 1. Voltage and current oscillograms of lightning-stroke tests**

and 0.24 square inch, that is, the area is proportional to the current of the discharge.

A blast effect is also present on the specimens. It is in the nature of a surface "erosion" resulting from the combined action of the blast and the associated high temperature. This blast effect extends out radially from the area "blown" and can be seen best on the photograph of the glassine-paper (sample *H* of figure 3), where it assumes a $1\frac{3}{4}$-inch diameter at the outer edge. The blast action appears also on the photograph of the discharge in figure 2; here the average diameter of the incandescent column measures close to 3 inches for a current of 55,000 amperes.

Tests were made on tracing cloth. This consists of cloth as a base and a filler material solidly enclosing all interstices between threads. In these tests a dozen small holes are found within a circle of approximately $\frac{1}{8}$ inch diameter (sample *G* in figure 3). "Burning" at the surface

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1. For all numbered references, see list at end of paper.

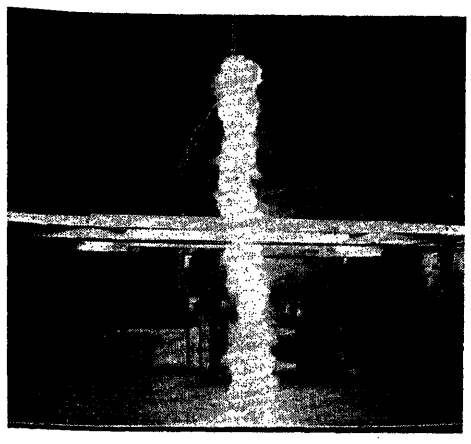


**Figure 2. Lightning-stroke discharge through paper sheet**

is concentrated within this circle, which indicates that the "core" is maintained here during part of or the whole current discharge then expanding abruptly into the column (figure 2). This explosive expansion of the core into the column is also evidenced from the paper specimens and from the radial tearing of the paper out from the area "blown." It should be noted from the small area "blown" that the current is restricted in its passage through the tracing cloth to some 5 per cent of the area indicated for the core (table I).

The area "blown" in the specimens is generally circular in form, this configuration being even more prevalent for the resulting column. The area "blown" is not always a single hole; at times it would be the combination of a large hole and smaller holes all closely huddled together. The path or paths of breakdown are established by the voltage discharge. The current associated with it, as can be seen from the area "blown" in sample *E* (figure 3), is relatively small compared to the current of lightning-stroke intensity which follows the voltage breakdown (samples *D* and *F*). In 2 cases distinct paths were established, about 10 inches apart, as evidenced from the large "twin" holes of equal size on the specimen (samples $I_1$ and $I_2$).

### Tests on Surface of Insulation

In these tests the sample was inclined so the discharge would hug the surface (figure 5) leaving thereon a "record." On porcelain the "burning" of the thin glaze, as in figure 4, comprises the record. From table II, the width of the "burning" is $1^1/_4$ inch for a discharge of 60,000 amperes (average). On photographs the incandescent column measured approximately 4 inches in width. At the center part of the burning in figure 4 the glaze is flaked, this effect indicates that the highest temperature has been maintained there. Away from the center the "burning" becomes progressively less. Upon rubbing the hand along the length of the "burned" surface the flakes are removed leaving a $^1/_2$-inch "core." In this "core" region the more intense "burning" appears to have been concentrated at the center part within a $^3/_8$-inch band.

The tests on Micarta gave records on the glossy layer of the surface such as in figure 6. The parts of the record where the discharge hugged the surface are particularly pertinent. They indicate an "inner core" $^3/_{32}$- to $^1/_8$-inch wide and a thinner shell enclosing it, then a sheath or "outer core" $^1/_2$- to $^5/_8$-inch on the outside and finally the region of the column extending outward to the total width of $1^3/_4$ to 2 inches. The explosive action of the "core" into the column is evidenced from the indications appearing on the surface (figure 6) as well as on the photograph of a similar test in figure 5. On the photograph the intense part of the channel is approximately 2 inches; however, the incandescent gases extend out a total width of some 5 to 6 inches. The current in these tests was close to 50,000 amperes.

The "records" in figures 6 and 4, though primarily the result of temperature and bombardment effects on the surface layer, suggest nevertheless that the "core" is apparently a complex of parts and processes. The current varying with time complicates somewhat further the mechanism and structure of the lightning discharge. Even then, without entering into the complex formulation of the detail phenomena which may occur, an estimate of the pressure and temperature in the "core" of the lightning channel should be possible from relatively simple considerations of the experimental findings presented hereto.

The expansion of the "core" from $^1/_2$-inch diameter or even less to the resulting channel of 3 to 4 inches diameter or more suggests a pressure in the "core" some 40 to 60 times the atmospheric. The corresponding gas temperature in the "core" would then be in the range of 11,000 degrees to 17,000 degrees Kelvin (absolute). These are estimates; for a closer determination, account should be taken in the gas formula of the process of expansion such as the turbulent interaction of incandescent gas and air (see photographs), the recombination into molecular form of the atomic elements, the positive and negative ions, besides other effects.

From a consideration of the electromagnetic force on

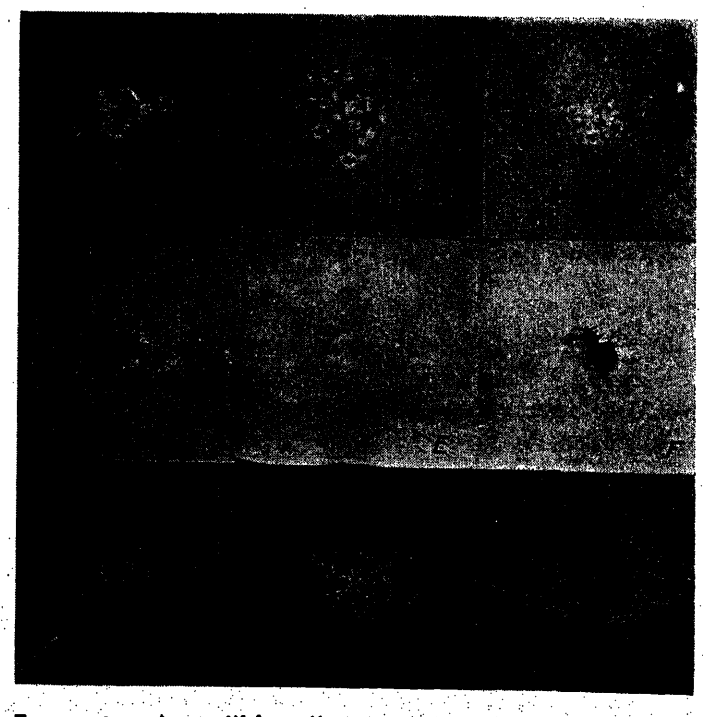


**Figure 3. Area "blown" in paper and similar materials (see table I)**

the current elements (the electrons comprise the bulk of the current flow), a further approach may be obtained on the internal pressure and whether this compression force accounts in part or all for the balancing of the gas pressure in the core. Both the circular form of the core and its abrupt expansion as the current ceases to flow are consistent with the rôle of the electromagnetic force balancing the gas pressure in the core during the current flow. Considering a current $I$ (abamperes) uniformly distributed in a core $R$ centimeters in radius, the "electromagnetic pressure" at $x$ centimeters from the center is (see appendix)

$$P = \frac{I^2}{\pi R^2}\left(1 - \frac{x^2}{R^2}\right) \text{ dynes per square centimeter} \qquad (1)$$

The deduction of interest from equation 1 is that the electromagnetic force can account for a pressure on the current elements (electrons) in the order of the estimated gas pressure and thus appears as a major factor in balancing the gas pressure in the core. The "electromagnetic pressure" is applied directly to the electrons as these comprise the bulk of the current flow. Furthermore, the "electromagnetic pressure" decreases with increasing distance from the core center so other processes both internally and at the surface of the core play a part in the general equilibrium of forces, charges, and matter. Attempts to analyze rigorously these processes have been made[4] and in this connection the experimental data presented in the paper should be a guide to such theoretical analyses.

From a consideration of the large force acting on a relatively small mass, the time for the core to expand into the column estimates to be in the order of microseconds. The large impact resulting from this expansion explains the concussion experienced by persons that have been hit or were within a few feet of the lightning discharge. This explosive action likewise explains the detonation or thunder produced by lightning, either in the field or in the laboratory.

## Negatives of Photographs

The lightning discharge, when analyzed from the photograph negatives, appears as a white streak (the core) surrounded by a dark sheath (the resulting column), such as shown in a measure in figures 7 and 8. These are, respectively, photographs of the negatives of figures 2 and 5. The white streak is about one inch wide, the more intense part is $1/2$ inch or less. This intense part comprises the core proper where the temperature is highest and maintained longer.

The negatives indicate some expansion of the core proper, partly perhaps due to the variation of the current during the discharge, besides a natural expansion, and in part possibly due to the apparent photographic effect of the high temperature of the core. The abrupt or explosive expansion of the core into the column is also indicated on the negatives. The temperature of the gases appear to suffer a considerable reduction with this expansion. A determination of the relative or absolute temperature in the core and in the resulting parts of the channel may be possible from further study of the effects appearing on negatives.



**Figure 5. Lightning-stroke discharge on Micarta surface**

## Tests on Wood Poles and With the Rotating Camera; Deionization of Lightning Channel

Not all poles struck by lightning are damaged, for as long as the discharge is external of the pole, relatively small splintering results. When the discharge is internal, as in a seasoned crack (figure 9), then the pole is generally badly damaged (figure 10) due to the explosive force of the core. In the photograph of figure 9 the source of light for the exposure came from the flash of the core and from the incandescent column which persists for some time after the discharge. Figure 10 was taken after the test and shows fully the resulting damage to the pole. From these and similar other photographs it is amply apparent that the mechanical effects produced by lightning are impulsive in character.

In the process of the shattering of the pole, a force $F$ is applied to the wood mass $m$ for a time $t$. A part of the momentum

$$\int F\,dt$$

is consumed to "blow out" the wood mass; the remaining momentum $mv$ imparts motion $v$ to the wood mass. Considering the relative magnitude of force $F$ and considering the time $t$ with mass $m$ of the wood blown as indicated in figure 10, even though the momentum

$$\int F\,dt$$

were consumed largely in imparting motion alone, some hundredths of a second appear necessary to displace the mass of wood blown a few centimeters away from the

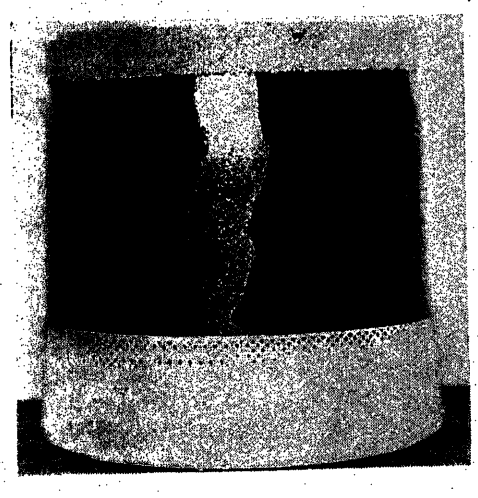


**Figure 4. "Record" on glaze of porcelain (see table II)**

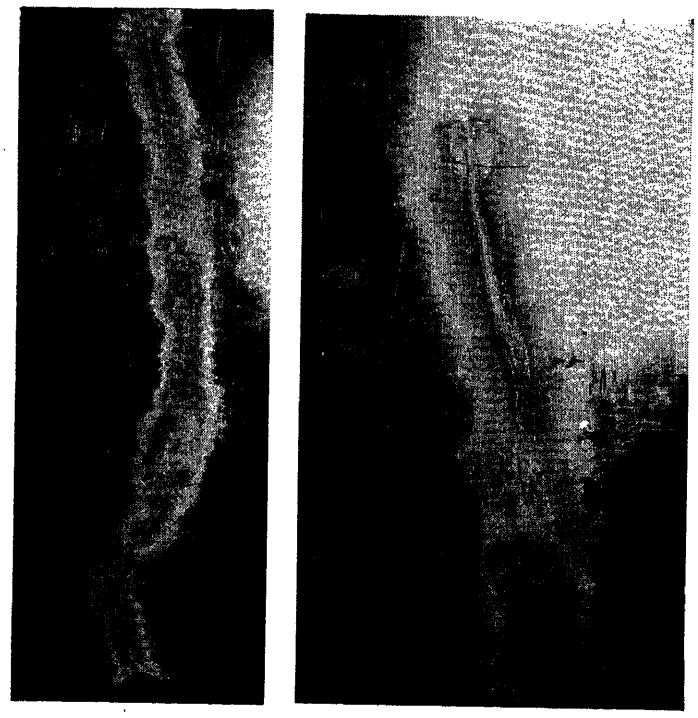


**Figure 6. Surface effect on Micarta indicating character of lightning channel (see table II)**



**Figure 7. The lightning channel from negative of figure 2**

pole proper as shown in figure 9. It can be seen then from the relatively small displacement of the wood blown during the time the column is incandescent (figure 9) that the lightning channel remains ionized for some hundredths of a second and more.

To establish more fully the deionization process of the lightning discharge, photographs were recorded with a rotating camera. The camera employed consists of a fixed lens and a 10-inch diameter circular film rotating one revolution in 0.02 second. A photograph of the discharge between the rod and plate (figure 2) is shown in figure 11*A*. In this test the lens is approximately 7 feet from the discharge. The voltage discharge appears first, followed in 15 to 20 microseconds by the indication of heavy current. The column is particularly intense during the first 50 microseconds due to the heavy current discharge (figure 1). It remains relatively intense for some 300 microseconds, diminishing continuously to a much reduced intensity at 0.002 second. Only a faint trace remains on the negative at 0.005 second. Incandescence at the electrode ends persists longer but all traces of incandescence in the column completely disappears in 0.01 second.

Two other photographs are shown in figure 11*B* and *C*. In these tests the camera was moved closer to the arc and the lens was opened wider, so naturally these records are more intense throughout than the first one. All 3 records indicate essentially the same process of deionization. The combined results of 8 records establish that incandescence of the channel completely disappears in 0.01 to 0.02 second after the lightning-current discharge. Therefore, the path of the lightning discharge reaches an advanced stage of deionization in this order of time.

### Tests on Fiber Tubes and Metal Surfaces

Tests on fiber tubes were briefly reported in the first paper.[3] The tubes were from 2 to 3 feet in length and $^1/_4$ to $1^1/_4$ inches inside diameter. Wall thicknesses ranged from 0.2 to 0.6 inch. Lightning currents from 100,000 to 130,000 amperes and of some 200 microseconds duration to one-half value were discharged through the tubes. In these tests the discharge was initiated with a fine copper wire. It was found that the tubes would discharge these severe lightning currents without shattering when the internal diameter of the tube exceeded approximately $^3/_4$ inch. For the smaller diameter tubes shattering would result but even then the ends of the thicker tubes remained intact for several inches. These tests suggested the relatively small size of the core and the explosive action produced from its expansion.

Tests comprised of discharging a current by a fine copper wire (0.08 in diameter) to the center of smooth copper plates were then conducted. A very small hole was bored at the center of the plate to carry the fine wire straight through. The averages from 10 tests are summarized in table III. These tests indicate that the area of the surface "fused" by the discharge is proportional to the current. A core of 0.60 inch in diameter is indicated in figure 12 for a current discharge of 134,000 amperes. The column resulting from the explosion of the core measured from 4 to 6 inches in diameter on photographs. A close examination of the fusion in figure 12 indicates that the fused metal on the surface is beaded quite uniformly with some grading on approaching the edge of the circle. The beads covering the center part of the circle are somewhere in the order of a hundredth of an inch. The surface fusion terminates quite abruptly at the edge

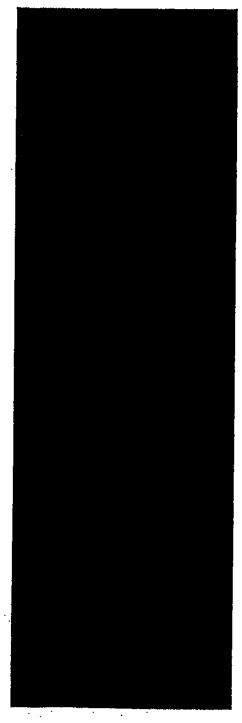


**Figure 8. The lightning channel from negative of figure 5**

of the circle. These observations confirm further that the core is sustained for the greater part of the whole duration of the current discharge and they also indicate some expansion or variation in the size of the core. A series of concentric regions appear just beyond the core circle. These apparently indicate a uniformly circular expansion of the gases in the initial stages and they suggest from the graded colors of the copper oxide the relative

in one case 4 centimeters and in the other 2 centimeters approximately. In a report on airplanes hit by lightning,[8] holes the size of a penny, or larger ones where the fabric would be torn, were found. Fulgurites in dry sand are described[5] that take "the shape of vertical tubes which may be nearly half an inch in diameter and several feet long. Externally they are rough somewhat whiter than the surrounding sand; inside they are enamel-like, from

**Table I. Effects Produced by Lightning Discharging Through Paper and Similar Materials***

| Sample Number | Material | Lightning Current** (Amperes) | Area "Blown" in Sample by Discharge (Square Inches) | Diameter of Blast Visibly Indicated on Surface of Sample (Inches) | Comments |
|---|---|---|---|---|---|
| 1 | White paper 0.0025 inch thick | 47,000 | 0.18 | 1½ | See figure 3*A* |
| 2 | | 55,000 | 0.16 | 1½ | See figure 3*B* |
| 3 | | 56,000 | 0.18 | 1½ | Two large holes and few smaller ones grouped together within 1-inch-diameter circle |
| 4 | | 50,000 | 0.14 | 1¾ | One large hole and 2 smaller ones adjacent |
| 5 | | 23,500 | 0.07 | 1 | See figure 3*C* |
| 6 | | 53,000 | 0.11 | 1¾ | One large hole and smaller one adjacent |
| 7 | | 55,000 | 0.13 | 1 (approximately) corresponding to each group | Two groups of holes 9 inches apart |
| 8 | | 55,000 | 0.12 | 1¼ | Two large holes and few smaller ones grouped together within 1-inch-diameter circle. See figure 2 |
| 9, 10, and 11 | | 57,000, 69,000, and 82,000 | Samples torn | 1½, 1¾, and 2 | Samples torn 1 to 3 inches radially out from area "blown" |
| 12 | Light brown paper 0.0075 inch thick | 54,000 | 0.16 | 1½ | See figure 3*D* |
| 13 | | 54,000 | 0.18 | 1½ | One large hole and small one adjacent |
| 14 | | | 0.003 | | Voltage only applied. See figure 3*E* |
| 15 | | 75,000 | 0.24 | 1½ | See figure 3*F* |
| 16 | | 73,000 | 0.23 | 1½ | One large hole and smaller one adjacent |
| 17 | Tracing cloth 0.0035 inch | 54,000 | 0.01 | 1½ (center part within ⅝-inch circle heavily burned) | A dozen small holes within ⅝-inch-diameter circle. See figure 3*G* |
| 18 | | 54,000 | 0.01 | Center part of each group heavily burned within ½-inch circle | Two groups of 6 and 10 small holes 1½ inches apart |
| 19 | Glassine paper 0.0015 inch thick | 56,000 | 0.08 | 1¾ | Group of 7 holes within 1-inch-diameter circle and 8 (smaller) holes further out. See figure 3*H* |
| 20 | | 56,000 | 0.09 | 1¾ | Sample torn 1 to 3 inches radially out from area "blown" |
| 21 | Wrapping paper 0.007 inch thick | 57,000 | 0.14 | 1-inch diameter (approximately) corresponding to each hole | Two large holes 10 inches apart. See figure 3 ($I_1$ and $I_2$) |
| 22 | Cotton cloth 0.005 inch (light brown) | 56,000 | | | Faint indication of singeing |

* For test set-up see figure 2.
** (*a*). Wave form of current for tests on samples 1, 2, 3, 4, 6, 7, 8, 12, 13, 17, 18, 19, 20, 21, and 22 given in figure 1*A*.
(*b*). Wave form of current for tests on samples 9, 10, 11, 15, and 16 given in figure 1*B*.
(*c*). Wave form of current for test on sample 5 is aperiodic, rising to crest in some 7 microseconds and receding close to zero in 60 microseconds.
(*d*). In the tests on samples indicated in (*a*) and (*c*) the spacing between the rod and plate (see figure 2) was 36 inches with the sample 14 to 17 inches from the plate. In the tests on samples indicated in (*b*) and for sample 14 the spacing between rod and plate was 18 inches with the sample 10 inches from the plate.
(*e*). In the test on sample 14 the voltage generator alone discharged. The current associated with the voltage generator discharge is relatively small in amplitude and duration compared to the lightning currents (column 3).
(*f*). The voltage initiating breakdown of the 36-inch gap is shown in figure 1*D*.

temperature drop. The irregular "blotches" of oxidized surface beyond these concentric regions confirm that in the later stages of the abrupt expansion of the core into the column, the expansion process is of a turbulent character.

## Field Records Compared With Laboratory Data

Considerable field data on lightning[11-24] are now available but observations bearing on the lightning stroke channel are rather limited yet. A few typical instances will be considered for comparison with the laboratory data.

Holes have been "blown" in windows by lightning. In one case[5] the hole was in the order of a couple centimeters. The edges of the hole were melted. Two interesting observations have been reported recently to the writer by M. Ch. Morel (see also references 6 and 7). In these 2 instances the holes "pierced" in window panes measured the glassy surface of fused silicon." Rock blasted by lightning indicates a fusion streak some one-half inch wide marking the path of discharge. These experiences alone show good agreement on the size and general characteristics of the core of the lightning strokes in the field with the corresponding though more complete measurements in the laboratory.

The explosive character and damaging effects of lightning discharges are well known.[3,6,7] Wood poles splintered by lightning evidence the same character of damage and explosive effects as have been found from the laboratory tests.

The size of the lightning-stroke channel has been measured from photographs or estimated from visual observation. Considering the heaviest lightning flash, Walter estimates[9] by photographs the breadth of the channel to be only 10 centimeters. In one case recently

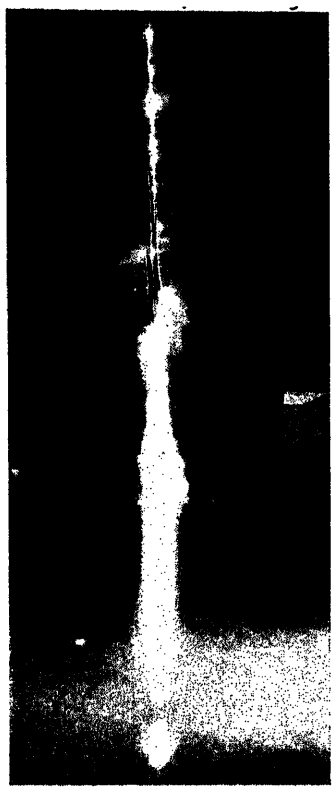


Figure 9. Lightning stroke to distribution-line wood pole

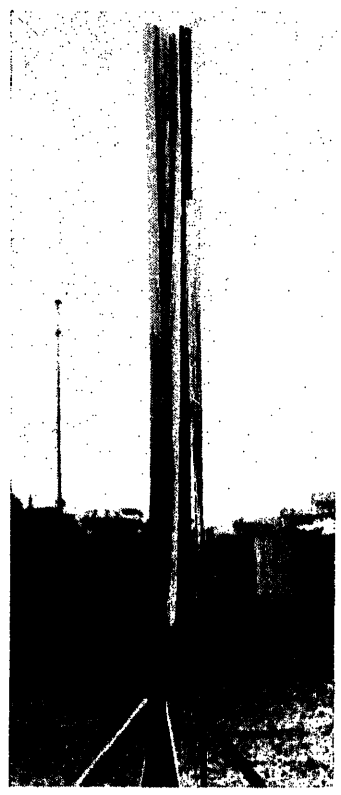


Figure 10. Resulting damage of wood pole from test in figure 9

called to the writer's attention, the observer was at about 50 feet in direct line of vision from a tree struck by lightning. Number 18 copper wire was hanging from midway of the tree to several feet above ground. Lightning splintered the top of the tree, following the copper wire then to ground. The current in this stroke is estimated to not exceed 50,000 amperes, since the copper wire was fused in segments but not completely volatilized.[10] The size of the channel by comparison to the trunk of the tree was estimated at 15 to 20 centimeters. Even these few cases are quite indicative that the dimensions of the lightning channel observed in the field are comparable to those measured in the laboratory.

A recent contribution by Doctor B. F. J. Schonland has come to the author's attention entitled: "The Diameter of the Lightning Channel," *Philosophical Magazine*, series 7, page 503, March 1937. A photograph of a lightning flash consisting of 11 discharges is discussed therein which shows the first and last separate strokes of the discharge to have had their channels shifted a distance exceeding 3.7 meters by the wind. It is found that the average diameter of the lightning stroke channel is about 16 centimeters. The heaviest stroke gave a diameter of 23 centimeters and the weakest branch one of 11 centimeters.

## Summary

1. The lightning-stroke effects on paper, tracing cloth, porcelain, Micarta, and photograph negatives indicate an area (circular) for the core proportional to the current in the lightning discharge. This apparent area is, respectively, 0.08, 0.16, and 0.24 square inch for currents of 25,000, 50,000, and 75,000 amperes. Tests on fiber tubes at 140,000 amperes indicate an area of 0.44 square inch.

2. The surface fusion on copper plates, the photograph negatives, the glaze burning on porcelain, the record on Micarta, and other effects all show that the core is sustained the greater part of or the whole duration of the lightning-current discharge. The center part, some two-thirds or one-half, of the above-mentioned area comprises the core proper where the temperature is highest and maintained longer. Some expansion or variation in the core proper takes place during the discharge apparently resulting in the larger area. The actual current in the discharge (electrons for the greater part) naturally occupies but a fractional part of the core. The above records and observation suggest that the core structure is a complex of parts and processes.

3. When or as the current ceases the core then expands abruptly or explodes into the column. The expansion appears from the records relatively uniform (circular), the gases suffering a corresponding temperature drop with expansion. The later stages of the expansion process be-

Table II. Effects Produced by Lightning Discharging Along Surface of Insulation Materials*

| Sample Number | Material | Lightning Currents** (Amperes) | Diameter of Center Part Indicative of Concentration of Discharge (Inches) | Diameter of Blast Visibly Indicated on Surface of Sample (Inches) | Comments |
|---|---|---|---|---|---|
| 23 | Porcelain tube 9½ inches high, 9½ inches diameter, ½ inch thick (see figure 4) | 58,000 | ½ | 1⅜ | Length of discharge along the glazed surface along height = 5 inches. See figure 4 which shows effect of discharge |
| 24 | | 57,000 | ½ | 1¼ | |
| 25 | | 58,000 | ½ | 1¼ | |
| 26 | | 60,000 | ⅝ | 1½ | |
| 27 | Fullerboard 9 by 17 inches, ⅛ inch thick | 64,000 | Center part not outstanding | 2½ (average) | Length of discharge = 10 inches |
| 28 | Micarta panel 12 by 30 inches, ¼ inch thick | 51,000 | Inner "core" 5/32-inch-diameter. Outer "core" ⅝-inch-diameter | 1¾ (average) | Length of discharge = 20 inches. See figure 6 for effects of discharge |

* Typical test set-up shown in figure 5.
** (*a*). Wave form of current for tests on samples 23, 24, 25, 26, and 27 given in figure 1*C*.
(*b*). Wave form of current for test on sample 28 similar to figure 1*C* except period is 20 per cent longer.

come turbulent in character. Thus for a current discharge of 50,000 amperes, uniform expansion apparently extends some one to 2 inches in diameter. Turbulent action then follows and the totally expanded incandescent column (measured on photographs) approximates a 3-inch diameter. For a current discharge of 140,000 amperes the incandescent column measures on photographs 4 to 6 inches in diameter.

4. The expansion of the core into the size of the channel suggests a pressure in the core some 40 to 60 times the atmospheric and a corresponding gas temperature in the range of 11,000 degrees to 17,000 degrees Kelvin (absolute). A more rigorous determination would require that account be taken of the turbulent interaction of the expanding incandescent gas with the surrounding air, the recombination of disrupted elements and ions (positive ions and electrons) into molecular form, besides a consideration of the complex core structure and other effects.

5. The electromagnetic force produced by the current can account for a pressure on the current elements (electrons) in the order of the estimated gas pressure deduced from the expansion. Thus the "electromagnetic pressure" (directed centrally inward) appears as a major factor in balancing the gas pressure in the core (directed outward). Other processes both internally and at the surface of the core play a part in the general equilibrium. The experimental data and findings presented in the paper offer the basis for more extensive theoretical analysis.

6. From a consideration of the large force acting on the relatively small mass of the core, the time for the core to expand into the column is estimated to be in the order of microseconds. The experimental findings confirm the estimate. The large impact resulting from the expansion accounts for the concussion experienced by persons that have been hit by or were within a few feet of the lightning discharge. This explosive action likewise explains the detonation or thunder produced by lightning.

7. The shattering of wood poles and similar destructive effects show that the mechanical forces and impact produced by lightning are impulsive in character. It can be deduced from these tests and the corresponding photographs that the lightning channel remains incandescent (ionized) for some hundredths of a second.

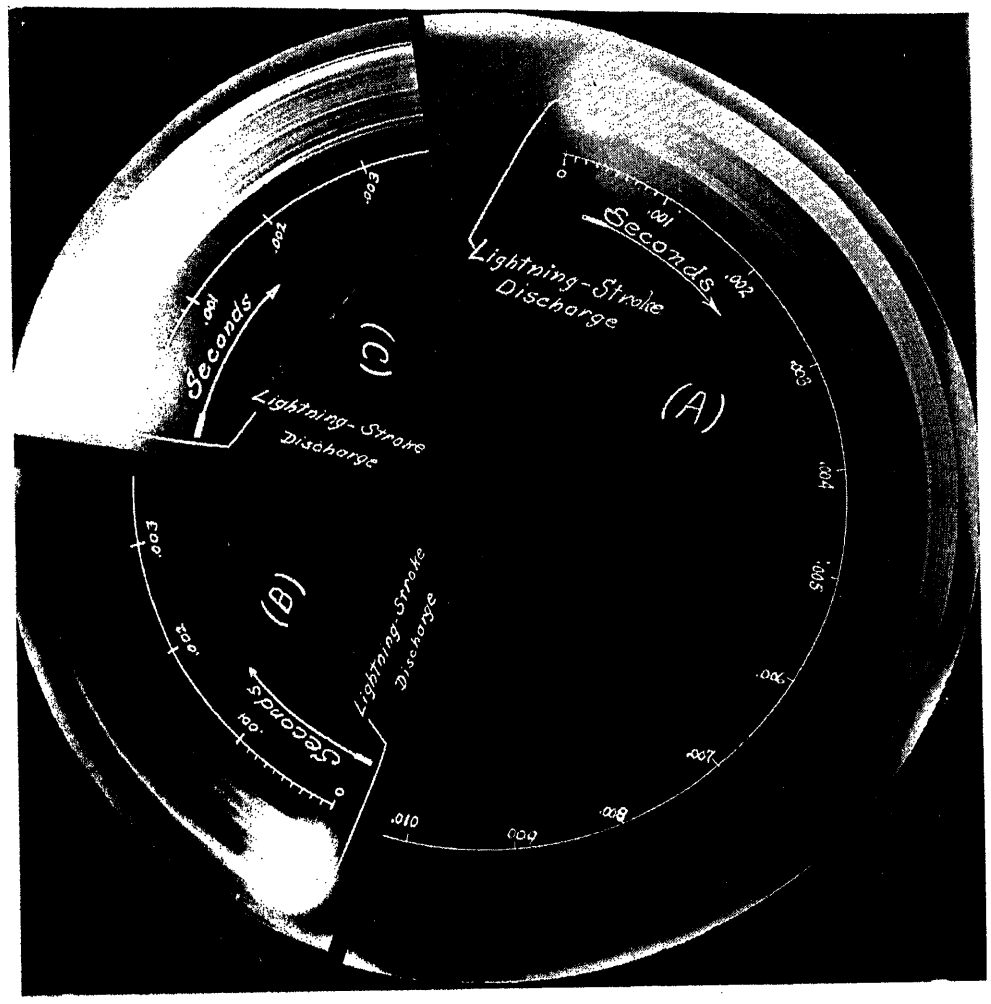



Figure 11. Photographs of lightning flash with the rotating camera to determine duration of incandescence (deionization of lightning path)

8. Records of the lightning flash with a rotating camera establish that the lightning path is particularly intense during the current discharge (50 to 100 microseconds). The established channel remains relatively intense for some 300 to 500 microseconds, diminishing continuously to a much reduced intensity in about 0.002 second. The results of 8 records establish that incandescence of the channel completely disappears in 0.01 to 0.02 second after the lightning-current discharge. Therefore, the path of the lightning stroke reaches a stage of advanced deionization in this order of time, a finding well in accord with the field data on the time interval between repetitive strokes.

9. The field records and data on the core and channel of the lightning stroke, though relatively few, indicate general accord with the more extensive laboratory findings here presented.

## Appendix

The derivation of equation 1 is based on the following fundamental consideration: To be in equilibrium the pressure gradient

$$-\frac{\partial P}{\partial x}$$

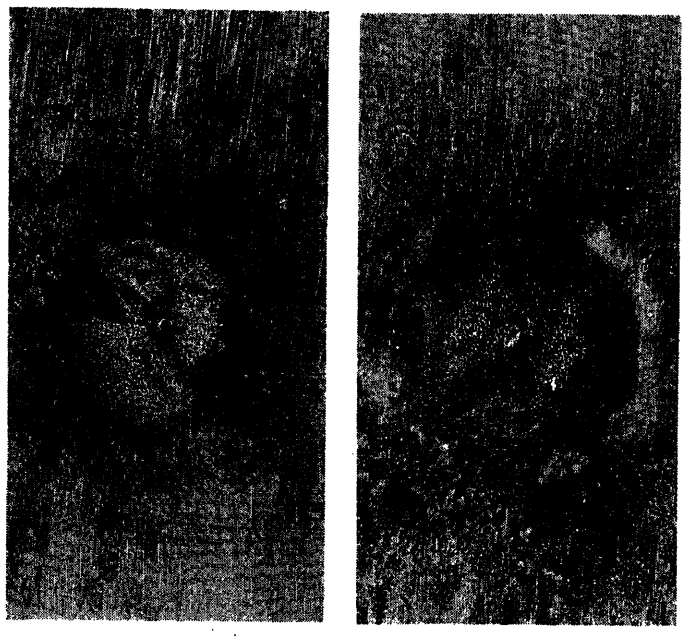


**Figure 12. Surface "fusion" on copper plates indicating nature of core and resulting channel of lightning stroke (see table III)**

**Table III. Surface Fusion Produced by Lightning Discharge to Polished Copper Plates**

| Number of Samples | Lightning Current | Diameter of Core (Inches) | Diameter of Blast Indicated on Surface (Inches) |
|---|---|---|---|
| Four | 134,000 | 0.61 | 1 1/2 |
| Two | 105,000 | 0.51 | 1 1/8 |
| Two | 79,000 | 0.46 | 1 |

at any point $x$ must balance the volume forces acting on the gas. The equation is derived elementarily by considering a shell of the core of radius $x$ centimeters and thickness $dx$. The current $I$ (abamperes) is considered uniformly distributed in the core of $R$ centimeters in radius.

The magnetic force (volume force) on the shell per centimeter length is the product of the magnetic field at $x$ and the current in the shell, i.e.,

$$2\Delta\pi x \cdot \Delta 2\pi x dx$$

where

$$\Delta = \frac{I}{\pi R^2}$$

is the current density.

The force on the shell due to variation in gas pressure balances the magnetic force, so

$$-\frac{\partial P}{\partial x} 2\pi x dx = 2\Delta\pi x \cdot \Delta 2\pi x dx$$

$$-\frac{\partial P}{\partial x} = 2\Delta^2\pi x$$

i.e., pressure gradient equals volume force. Then,

$$p = -\Delta^2\pi x^2 + \text{constant}$$

From the boundary conditions $p = 0$ when $x = R$, thus making $p$ merely excess over atmospheric pressure at the outer boundary of the core,

$$p = \Delta^2\pi R^2\left(1 - \frac{x^2}{R^2}\right)$$

or since $\pi\Delta R^2 = I$, equation 1 is obtained:

$$p = \frac{I^2}{\pi R^2}\left(1 - \frac{x^2}{R^2}\right) \text{ dynes per square centimeter} \qquad (1)$$

At $x = 0$

$$p_{(max)} = I\Delta$$

Substituting the experimental data of a core section 0.15 square inch for 54,000 amperes, then

$$p_{(max)} = \frac{5400 \times 5400}{6.45 \times 0.15} = 30 \times 10^6 \text{ dynes per square centimeter}$$

or about 30 atmospheres.

Even at $\frac{x}{R} = 0.9$, $p = 30\ (1\text{–}0.81) \cong 6$ atmospheres.

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# A System Out of Step and Its Relay Requirements

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## Synopsis

This is a study of the current, voltage, and power values throughout a simple transmission system when machines are operating out of step. The investigation was made to determine the proper relay protection for some large frequency changers which supply power to an electrified railroad. The object was to find means for protecting machines that had already fallen out of step or, if possible, to prevent them from falling out due to overload.

The treatment of the problem is geometric, probably the easiest method to comprehend. The assumed conditions have been kept as simple as possible, but it is hoped that the method of treatment is complete enough to permit anyone interested in the subject easily to apply it to more complex problems. It is to be particularly observed that the common method of assuming that a system consists of pure reactance leads to errors that are noticeable on 25-cycle systems where the reactance is low.

As a by-product of the study of machine protection, it was discovered that the behavior of different types of line-sectionalizing relays under out-of-step conditions can be easily predetermined and proper adjustments made to obtain a more desirable performance of such relays.

## Two Machines Fall Out of Step

WHEN A GENERATOR and a motor are connected together and the motor is loaded, the generator poles advance and the motor poles retard, the angular difference being a measure of the power transfer. This angular difference produces a flow of current which tends to keep the 2 machines in step. The accompanying series of small sketches show what happens as the motor pole lags farther and farther until it is definitely out of step and until it comes back into step again after completing one full revolution, that is, after it has slipped 2 poles. The sketches shown in figures 1*A* to 1*J* form a sort of primer on the elementary conditions which exist when 2 machines are out of step. Figure 1*A* shows that if the motor poles lag behind the generator poles, the voltage which induces interchange of current between the 2 machines is $E_G - E_M$. These voltages are generated voltages and are not the quantities which are ordinarily measured at machine terminals. Figure 1*B* shows that the voltage difference between the 2 machines is the greatest when the poles are 180 degrees out of phase but as the motor continues to lag behind the generator, it comes back into step with the next pole as shown in figure 1*C*. Whether or not the motor will slip another pair of poles in the same manner depends upon the conditions existing in the system. The resultant voltage, as shown in figure 1*D*, increases from a zero value when the poles are exactly in step to its maximum when they are 180 degrees out of step and back to zero again following a circle as a locus. As will be observed, the shift in phase angle of this resultant does not go through a 360-degree cycle but only through 180 degrees. Also at the start and at the finish position the voltage value is zero. Since a complete slip

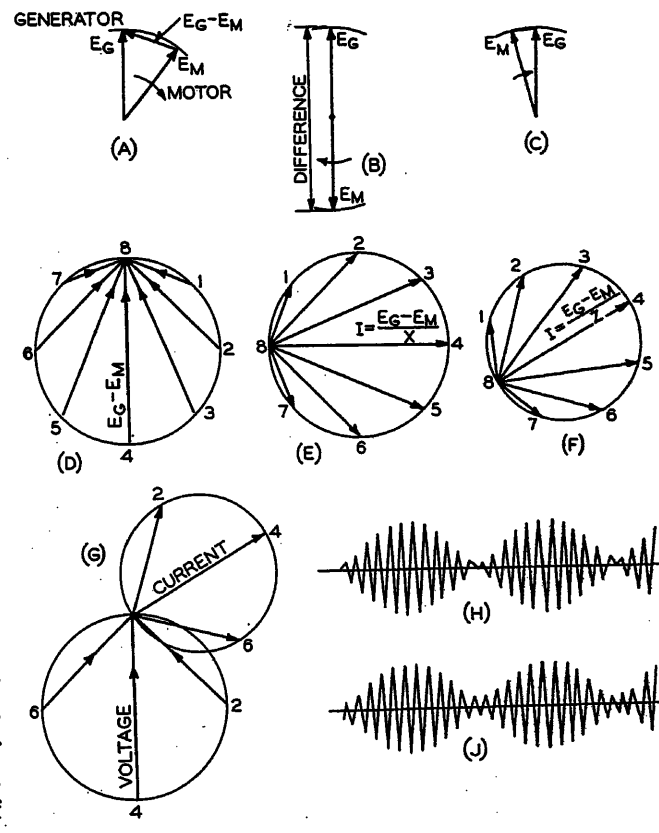



**Figure 1. Two machines out of step**

*A*—As the motor lags, the voltage difference increases until—

*B*—It reaches a maximum when the poles are 180 degrees out of phase

*C*—As the lagging pole continues around the circle, the difference approaches zero again

*D*—The voltage ($E_G - E_M$) moves around this circle through a complete cycle of 180 degrees

*E*—The current that flows between the 2 machines is at right angles to the voltage (resistance neglected)

*F*—Resistance in the circuit decreases the current and tilts the axis of the circle

*G*—The combined diagram

*H*—The current surges if the machines have equal excitation

*J*—If the excitations are unequal

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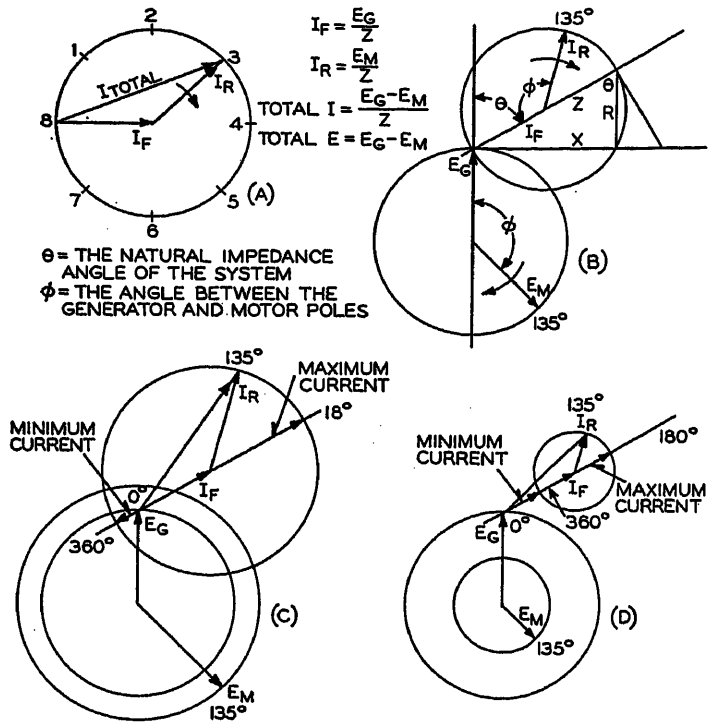



**Figure 2. Analysis of the current through the system and the voltage difference between the generated voltages at each end of the line**

*A*—A current or voltage vector oscillating through 180 degrees may be resolved into 2 components, one fixed and the other rotating through 360 degrees in step with the slipping pole

*B*—This is another way of representing figure 1*G*. $E_G = E_M$

*C*—If the generator and motor voltages are not equal, the current will never become zero. Here the motor voltage is higher

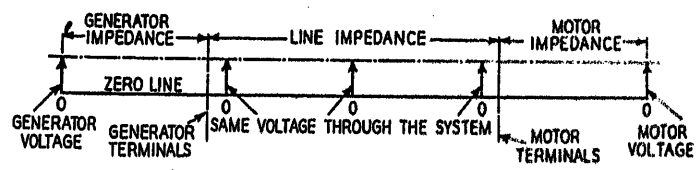
*D*—Here the motor voltage is lower and the difference greater, hence the minimum current is greater

cycle of 360 degrees of the poles results in a shift in phase in the resultant voltage of only 180 degrees, confusion will be avoided by applying the angle in degrees always to the slip of the poles. In the figures the pole slip is also shown in positions, 1, 2, etc., so that simultaneous current and voltage vectors can be readily compared.

The behavior of the current is the same as that of the voltage except that the current lags behind the resultant voltage by an angle determined by the natural power factor of the system. This angle is the same as the angle which the current lags behind the generated voltage under short-circuit conditions. In figure 1*E* the current is shown lagging 90 degrees behind the voltage. This, of course, cannot exist in practice, although there are some generators where the short-circuit current can lag as much as 88 degrees. In figure 1*F* is shown the conditions in a system having an angle of 60 degrees. It will be convenient to use these 2 angles, namely, 60 and 90 degrees, for purposes of illustration throughout this discussion.

The current locus and the voltage locus for a 60-degree system are combined in figure 1*G* to show that the angle between the current and the voltage is the same, throughout all points of the slip cycle, although their values vary from zero to zero. The current surge, which occurs in the system under out-of-step conditions, is shown in figure 1*H*. These are the values shown in figures 1*E*, 1*F*, and 1*G* and is a similar picture to that given by the ordinary oscillogram taken on a system which is out of step. This is also the shape of the voltage pulsation through the system, but does not represent the voltage between wires or across the terminals of any machine. For purposes of comparison, a current surge in figure 1*J* is given to show what happens if the excitation of the 2 machines is unequal This will be explained later.

In order to analyze more thoroughly the conditions throughout a system consisting of 2 machines at each end of a transmission line, it is convenient to separate the current and voltage vectors into 2 components. For example, $E_{(total)} = E_G - E_M$. Here $E_G$ is a fixed quantity and $E_M$ is a rotating vector. It will, therefore, be convenient at other places on the system to refer to the voltage between wires as $E_{(total)} = E_F - E_R$ where $E_F$ is a fixed and $E_R$ is a rotating vector. Similarly, the current vector, as shown in figure 2*A*, can be resolved into 2 components and $I_{(total)} = I_F + I_R$. It will be observed that the voltage vector is a difference of 2 components and the current vector a sum of 2 components. As will be shown later, this means that at any particular point on a



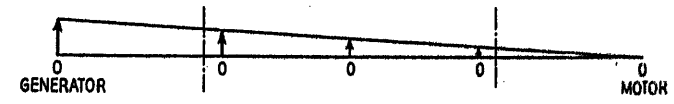




**Figure 3 (top). Machines in step—no load—equal excitation**

**Figure 4 (bottom). Motor without excitation, showing the impedance drop in the system**

system the current value is a maximum when the voltage between conductors is a minimum. In figure 2*B* the the quantities that were previously shown in figure 1*G* have been broken up into their 2 components. There are, therefore, 2 voltage vectors and 2 current vectors or a total of 4 quantities instead of a total of 2 quantities. A reason for doing this becomes immediately apparent in the next figure.

In studying out-of-step conditions the effect of changes in field strength is usually of primary importance. In figure 2*C* the generator and motor voltages have been laid out, and corresponding values of $I_F$ and $I_R$ have been added to the diagram. The value of these vectors has been determined from the equations given in figure 2*A*. It will be observed that the locus of the current does not go through the zero point. This is because the 2 generated voltages are unequal. The interpretation of this is easily made—the machine having the greater field strength (in this figure, the motor) supplies a constant magnetizing current to the other machine. This is probably more easily understood in figure 2*D* where the motor voltage is less than the generated voltage and consequently the ro-

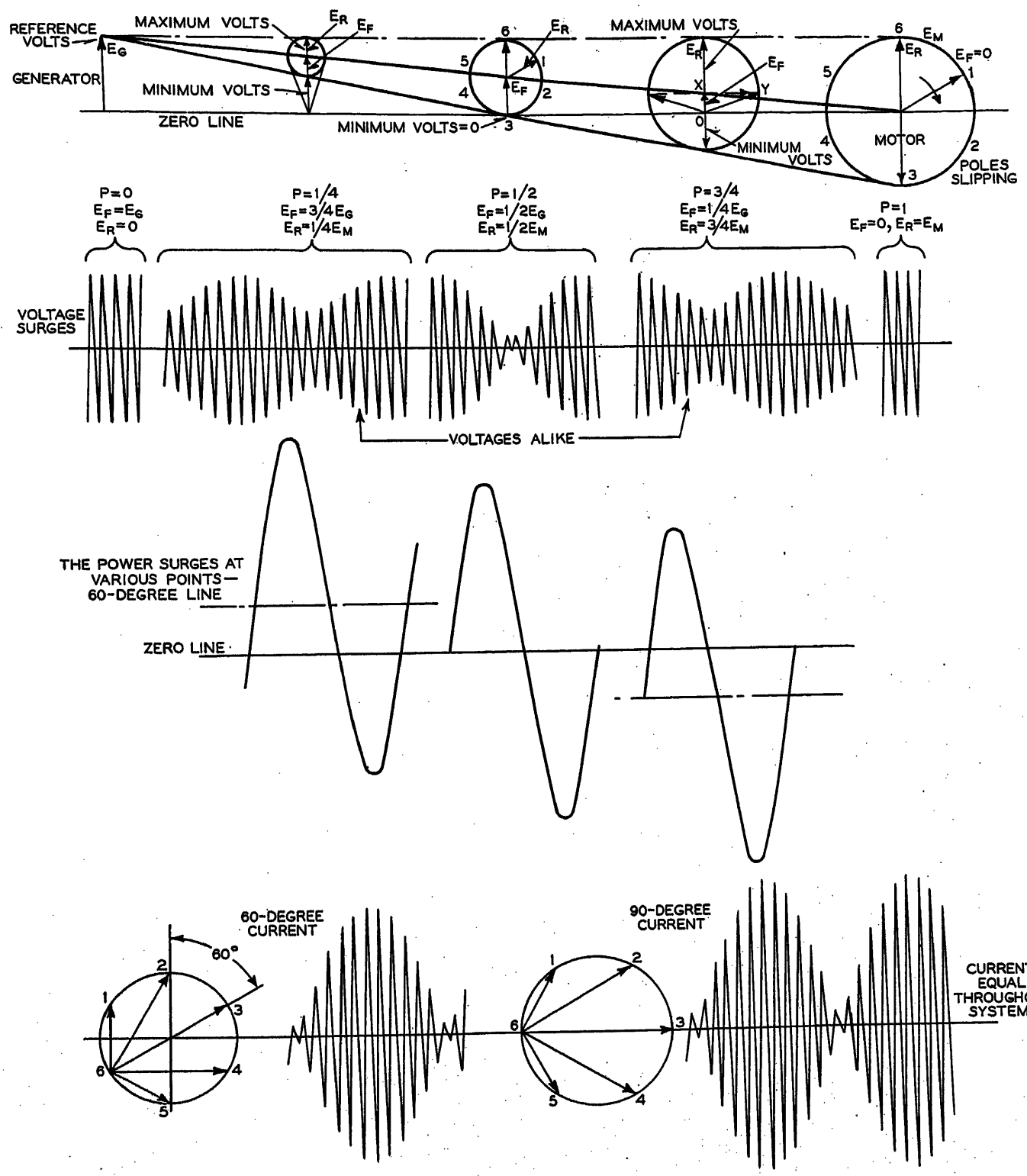



**Figure 5. The voltage, current, and power surges on a system where the generator and motor voltages are equal**

tating current vector less than the fixed vector. The conditions shown in both figures 2*C* and 2*D* produce a current surge such as that shown in figure 1*J*.

A study of figures 1 and 2 has shown the following conditions to exist:

1. The flow of current between the machines is not a sinusoidal pulsation but it varies from zero to zero through only 180 degrees.

2. The same thing is true of the voltage difference between the 2 machines.

3. Each of these variables can be resolved by geometric methods into a fixed component and a rotating component. The fixed current component is dependent on the fixed voltage component and likewise the rotating current component is determined by the rotating voltage.

4. If there is assumed to be no resistance in the circuit the current vectors will be 90 degrees behind their respective voltages. Resistance in the circuit will decrease this angle and also decrease the magnitude of both the current components.

5. A change in generated voltage of either of the machines affects

the value of the fixed or the rotating current and voltage vectors. This is the factor which must be given particular consideration when studying the protection of machinery because it is most likely to affect some of the protective methods which have been considered in the past.

It should be borne in mind that the voltages shown in this series of sketches (figures 1 and 2) are internal generated voltages. These will differ from terminal voltages or voltage values available out on the line in the manner shown in the second series of diagrams.

## Two Machines With a Transmission Line Between Them

The series of vector diagrams, figures 3 to 6, showing what happens on this simple system is useful because it can be applied in different ways. By way of illustration, some of the figures represent the machine terminals to be at a point $^1/_4$ of the distance from each end of the system. In practice, however, other points may be readily assumed to be machine terminals. Also, a number of machines may be grouped together to represent the "generator" of this simple system. In these figures the neutral of the generator has been taken as the zero point and all distances measured from that point to the neutral of the motor, and the complete distance being assumed to be one unit. Any measurement of distance will, therefore, be given as a fraction, *P*.

The figures previously discussed dealt only with internal generated voltages—quantities which are not ordinarily read by switchboard instruments. The zero line may be considered to be the neutral point of the entire system or it may be considered merely the reference point from which voltage is measured at any one location. It applies just as well to a delta voltage as to a star voltage measurement, but in these illustrations the star voltage is represented in its proper relation to the current.

In figure 3 is illustrated a simple system having the machines equally excited and carrying no load. The voltage will, therefore, be equal throughout the system and will everywhere be the same as the generated voltage. If one of these machines has no field, the conditions shown in figure 4 will exist. If all the different parts of the system have the same relative resistance and reactance, the voltage between wires will decrease uniformly along the line from the center of the generator to the center of the motor and will have the same phase relation throughout. The reason for showing the conditions in figure 4 becomes apparent in the next figure where, to the condition first shown are added the rotating vector conditions of the second machine. Here circles are drawn at 3 different points on the system for $^1/_4$, $^1/_2$, and $^3/_4$ of the distance

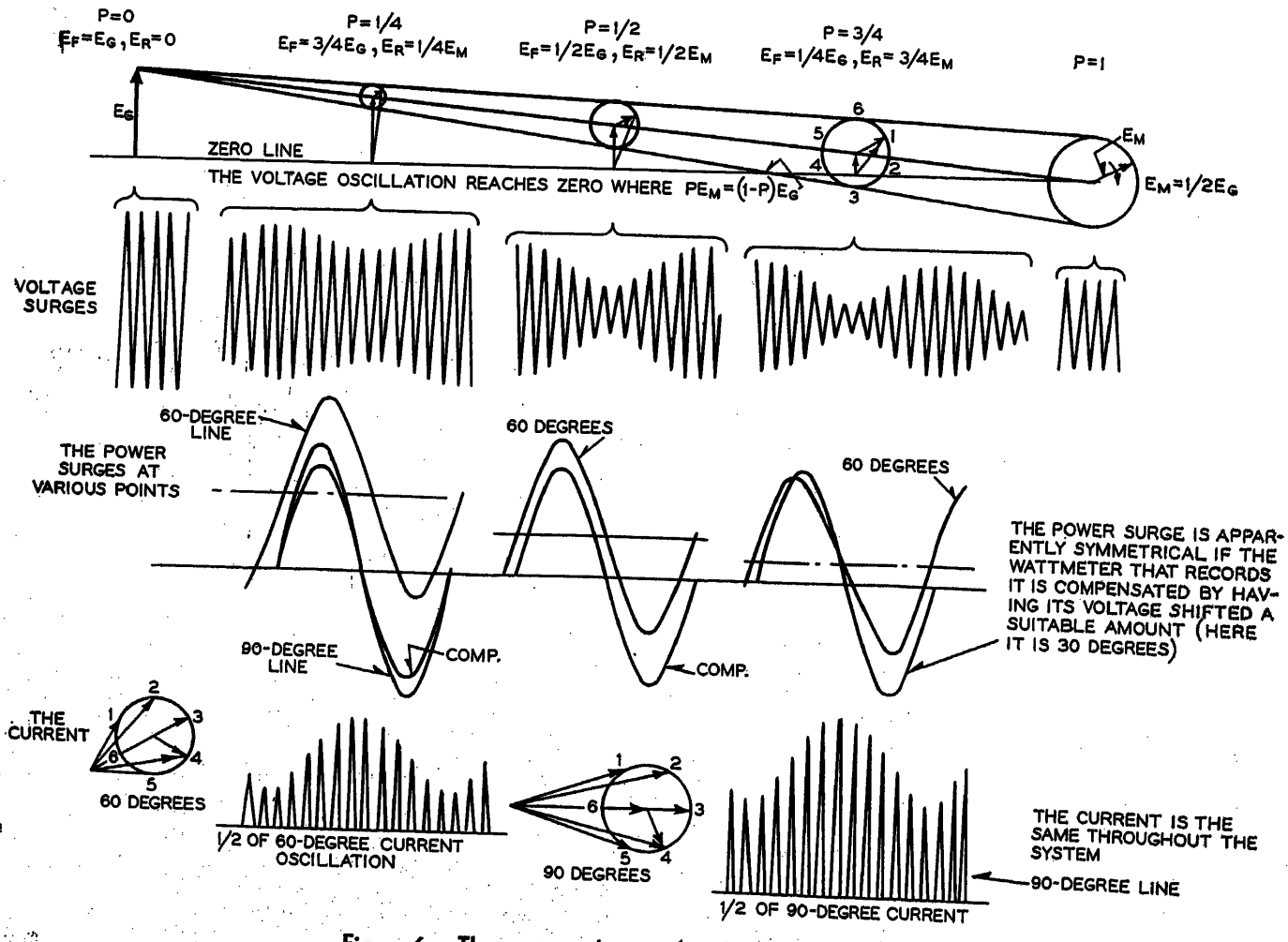



**Figure 6. The motor voltage is $^1/_2$ the generator voltage**

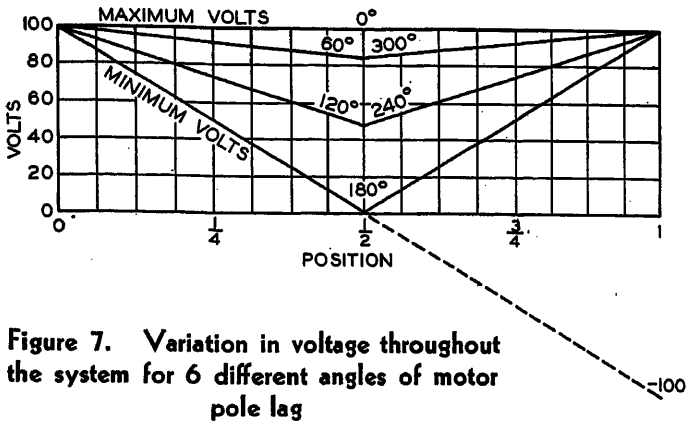



**Figure 7. Variation in voltage throughout the system for 6 different angles of motor pole lag**

between the generator neutral and the motor neutral.

Below each of these points is shown a cycle of the voltage oscillation at that point. It will be observed that the voltage oscillates to zero only at one point on the system which will be the center of the line if the 2 generated voltages are equal. If the voltages are unequal, as shown in figure 6, the point of zero voltage occurs in some other location on the system. Another way of showing this is by the curves in figures 7 and 8. These 2 figures will be of importance in studying the performance of line sectionalizing relays, particularly those of the distance-measuring type. Since minimum voltage and maximum current occur at the same time, it will be possible from these figures to determine what line relays are in danger of tripping during out-of-step conditions.

This system, with generator and motor voltages equal, is symmetrical and at first sight it seems strange that the vectors where $P = {}^1/_4$ appear to be so different from those where $P = {}^3/_4$. However, closer inspection will show that the resultant vectors are the same. It will be observed that although the swing of the vectors is different in the 2 positions, their absolute values are equal at any given time of reference. When they are plotted as scalar values they will be equal, as is shown in the voltage wave plotted below each point.

This is a good time to again emphasize that these are not vectors of instantaneous values. For example, in figure 5 the vector $OY$ is the sum of the vector $OX$ and $XY$ and this sum never reaches zero. This is shown in the voltage waves below the diagrams. The following additional facts concerning the current and voltage surges may be summarized:

1. When 2 machines are out of step there is only one point on the system where the effective voltage between wires drops to zero.

2. The position of zero voltage depends upon the relative excitation of the 2 machines.

3. The current will not become zero unless the excitation of the 2 machines is equal.

4. The system can be assumed to be symmetrical even though the machines may have different reactance values. Under such conditions, the terminals of the 2 machines are assumed to be at different distances from their centers.

5. Similarly, in considering a large generator or a group of generators connected to a small motor, the center of the system may be within the motor windings.

6. In this latter case there is no point outside of the machines where the voltage between wires will drop to zero during out-of-step conditions.

## Determining Power Surges

The most interesting part of this study is the analysis of the power flow. It has been generally recognized that the power oscillations are not the same throughout the system, but the way in which the oscillations vary at different points has been hard to understand.

The current is, of course, the same throughout the system, but the voltage is different at every point. As mentioned previously, the current vector consists of an unchanging quantity plus a rotating component which rotates with the slipping pole. The same thing is true of the voltage vectors. The flow of power between the centers of the 2 machines at any point is the product of the current and voltage vectors and the cosine of the angle between them. These vector diagrams for several points on the system are shown in figures 5 and 6. Below each of the vectors showing the voltage variations is plotted the envelope of the voltage pulsation at that point. Below this is plotted the average value of the power surge. This has been obtained by multiplying the current and voltage values by the cosine of the angle between them for various positions. Corresponding points on the current and the voltage reference circles have been marked 1, 2, 3, etc. The angles between corresponding voltage and current values are not shown, but they can easily be determined from the various figures by simple manipulations of a straight-edge and a triangle.

When plotting a power surge, a table should be prepared having the following headings:

| $\phi$ | $I$ | $E$ | Angle Between $E$ and $I$ | Cosine Angle | Watts |
|---|---|---|---|---|---|

This is about as easy a method as any. A trigonometric formula for the power surge at any point has been derived, but the final quantity that is obtained consists of the sum of a numerical term, a cosine term, and a sine term. The addition of these 3 quantities, if they are to be plotted, is usually more laborious than the method outlined above.

The formula mentioned is:

$$\text{Watts} = \frac{R}{Z^2}(E_G^2 - PE_G^2 - PE_M^2) + \frac{R}{Z^2}(2P - 1)E_G E_M \cos\phi + \frac{X}{Z^2} E_G E_M \sin\phi$$

where:

$R$ = resistance, $X$ = reactance, $Z$ = impedance of the conductor from the neutral of one machine to the neutral of the other
$E_G$ = internal voltage of the generator
$E_M$ = internal voltage of the motor
$\phi$ = the angle of separation between the poles of the 2 machines
$P$ = point where the watts are being measured

The meaning of the symbols is shown in figure 5. If the system is assumed to have no resistance, the first 2 terms vanish, leaving only the expression:

$$\text{Watts} = \frac{E_G E_M}{X} \sin\phi$$

This is the only condition where the flow of power is equal in each direction. Its value is also the same throughout the system because there is no resistance to consume power.

The value of the watts depends upon the product of the 2 voltages. If one of the voltages is decreased to $^1/_2$, the power interchange is decreased by the same amount. If one of the voltages is decreased to zero, the power interchange becomes zero.

As to the actual angle of a real system, there are probably none having a natural angle of more than 85 degrees. Many have an angle of around 80 degrees and more of 75 degrees. Systems of 60 degrees or even 45 degrees do exist. On such a system the power surges are not equal in the positive and negative direction, except at its center.

By reference to figures 5 and 6, it will be observed how this value varies at different points on the system under different conditions of excitation. The assumed angle in all these diagrams is 60 degrees.

Several different power curves are shown in figure 6. First, are the 3 normal curves for a 60-degree system having its motor excited to half voltage. Second, there is shown the symmetrical power wave which exists on a similar line having no resistance. The 2 sets of current vectors for these 2 different cases are shown on the diagram for comparison. Third, a set of compensated power curves is shown.

These compensated curves have particular application to the relay problem of protecting synchronous machinery. It has previously been shown that the voltage surges at a

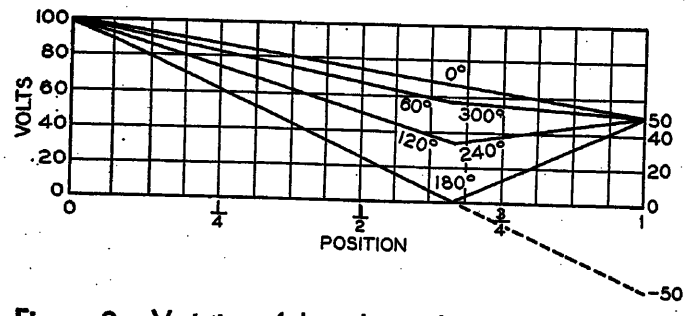
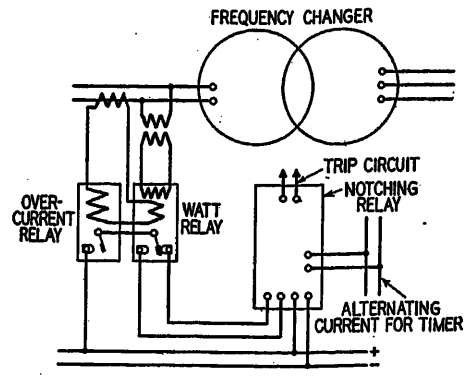



**Figure 8. Variation of the voltage when the motor voltage is 50 per cent of the generator voltage**

definite point cannot be predetermined if the excitation of the 2 machines varies in an unknown manner. The same is true of the current surges. But the power waves can be compensated so they are symmetrical. The reason for the symmetrical wave on the ideal system having no resistance is that the axes of the voltage diagram and of the current diagram are at right angles to each other. On a system where the current lags less than 90 degrees, the same effect can be obtained by compensating the wattmeter or the watt relay so that it has its zero torque at the natural angle of the system. On a 60-degree system this can be easily done by connecting the watt relay to utilize the star current and the delta voltage of the phase which is leading by 30 degrees. This differs from the usual arrangement of watt relays for line protection in that such

**Figure 9. Protecting frequency changers from operating out of step**




relays are connected to the star current and the voltage that lags by 30 degrees.

It is of interest to observe that the power wave has the same frequency as the voltage and current surges—not double frequency, as would be the case, if it were the product of 2 sine waves.

## Constants Used in the Calculations

The resistance and reactance of the transmission lines can be obtained from standard transmission line tables. The per cent resistance of the windings of machines and transformers may be assumed to be one per cent at their rated kilovolt-amperes. Synchronous machines have several different reactance values. The one that should be used in these calculations is the one now known as the transient reactance ($X_d'$). The following table of typical 60-cycle values is copied from the "Relay Handbook."

Turbine generator (2 pole): 12–22 per cent
Turbine generator (4 pole): 20–29 per cent
Salient-pole machines: 21–50 per cent
Condensers: 30–60 per cent
Power transformers:
up to 66 kv 5–7 per cent
88 to 110 kv 6–9 per cent
132 to 154 kv 8–10 per cent
187 to 220 kv 10–14 per cent

There are, of course, many factors which cannot be easily evaluated such as the effect of the load on the system and the proper method of grouping separated machines in order to simplify the setup. There is also an uncertain factor in the induction motor effect of the starting windings of the motors. Presumably, this will throw the power curve off the zero line.

Another variable is the effect of short circuits—the most common cause of out-of-step conditions. An unbalanced short circuit may cause machines to fall out of step before it is cleared. A 3-phase short circuit may, in effect, separate the machines during the time that it exists and, when the trouble is cleared by the proper breakers, the machines will be out of step. Sometimes they will pull back into step but often they will not.

## Out-of-Step Relay Protection

A synchronous machine can run out of step indefinitely and damage has been done to several machines of various types from this cause. One result of out-of-step operation

is overheating of the damper or starting windings. Another possible trouble with frequency changers and turbine generators is mechanical resonance of the rotor and the shaft, which form a torsion pendulum, with the out-of-step surges. Because of the rapidity with which dangerous resonant forces might conceivably be built up, some machines have been protected by out-of-step relays that will quickly disconnect a machine after it has slipped a definite number of poles, say 3 or 4 pairs.

The few installations of out-of-step protection with which the writer is familiar all use an out-of-step relay which actuates a notching relay. The notching relay in turn trips the breaker after the set number of notches has been registered.

Several forms of out-of-step relays have been used. On one system where it is desired to open sectionalizing breakers near the center of the system and at the lower capacity generating points, a low-voltage relay is used—a so-called "dip counter." This device can be applied when the out-of-step conditions, for which it must operate, are accompanied by dips in voltage below normal by a sufficient amount for operation of the actuating voltage relay once during each slip cycle.

Notching relays operated by current impulses are more common but it is probable that they will not fit all operating conditions. Such a current relay must be set high enough so that it will not operate if the machine is hunting—particularly after a short circuit has cleared. This high setting may be too high to allow operation under all values of field strength. Conditions may be such that the current relay will pick up and stay up because the current does not drop to a low enough value; or if the field is weak, the relay may not pick up at all.

An out-of-step relay that satisfies all of the conditions so far raised consists of a duodirectional watt relay and an overcurrent relay with their contacts in series. The watt relay can be compensated to have its zero-torque position agree with the angle of the line. This is done in the design of the relay itself when the angle to be compensated for is small. Such a relay will follow the power oscillations and make contact alternately in the positive and negative direction and step up the notching relay on each impulse.

The overcurrent relay should be set low, possibly below full load current. Its object is to insure that the watt relay will not operate when the machine is hunting. If the motor is lightly loaded the watt element may oscillate each side of zero but the current element contacts will be open. If, however, the motor is loaded so heavily that the current contacts are closed, the effect of hunting will be to cause the power to surge up and down without crossing over the zero line and becoming negative. A schematic diagram of the relay combination is shown in figure 9.

The notching relay may be a mechanical device or it may be constructed from a counting chain of auxiliary relays arranged so that each link will notch up in succession as successive impulses are given to it by the out-of-step relay. Any notching relay will be given a single energizing impulse whenever a short circuit occurs on the system. It is, therefore, necessary to reset the device after every short circuit on the system and it will also be convenient to reset it after every disturbance where it has stepped up a few notches but not enough to trip the breaker. This function may be performed automatically by means of a timing device which is set in motion by the first notch and will reset the relay, if the notching sequence is not completed within a specified time. In one commercial design of notching relay this timer can be adjusted for any value between zero and 10 seconds.

## Line Sectionalizing Relays Under Out-of-Step Conditions

The analysis given in this paper will be particularly useful in the study of transmission line relays where it is desired to prevent them from operating when the system is out of step. The factors involved are numerous and special attention must be given to every different type of relay installation. It is possible to determine the performance of the directional elements of the relays at every point taking into account the phase connection of the voltage terminals of the relay. The performance of impedance and reactance relays can likewise be determined for each location. From such a study it should be possible to prevent undesirable performance during out-of-step operation or to arrange the relays so that the line can be sectionalized at any desired point when out-of-step conditions exist. Although the principles herein outlined have been presented in a simple manner, they are fundamental and should serve as a useful guide in the study of any relay problems where out-of-step conditions are encountered.

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# Use of Electricity to Treat Disease Fulfills Half-Century-Old Prophecy

A PROPHECY made over half a century ago, that electricity would be used in treating disease, has come true, and the scientist who made it is still alive to see his then rash statement justified.

The scientist is the 86-year-old Professor A. D'Arsonval, of Paris, whose galvanometer is familiar to every high school physics student. He recalled his early statement in a message to the first International Conference on Fever Therapy recently held in New York. Professor D'Arsonval is honorary president of the French committee of the conference.

"I am forgiven today," Professor D'Arsonval concludes his message, "for the phrase which I am proud of having written in 1882 and to which, at the time, I owed the animosity of doctors and pharmaceutical chemists.

" 'I am persuaded,' I said, 'that the therapeutic of the future will employ, as a curative means, the physical modificators, heat, light, electricity, and other agents still unknown . . . and that the most poisonous drugs of chemistry will have to give place to these imponderables that have the advantage of introducing no poison into the organism.' "

# Alternator Short-Circuit Currents Under Unsymmetrical Terminal Conditions

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## General Introduction

IN A PREVIOUS PAPER[1] the solution for the ideal alternator under symmetrical terminal conditions was developed. In this paper the application of the equations developed in this previous paper are used, together with symmetrical components of currents, to obtain the solution of currents in the armature and field circuits of an alternator under unsymmetrical fault conditions. These equations and solutions are applied to a 3-phase alternator having a line-to-ground and a line-to-line fault condition, under various conditions. Oscillograms and calculated graphs are compared to check the method used in this solution, and excellent results are obtained. Due to the inclusion of resistance simultaneously in the armature and field circuits, the frequency of the harmonics in the circuits are seen to be somewhat different than usually given under less approximate assumptions. Also, the effect of resistance is more closely determined by this method of solution.

## Application of Symmetrical Components

The rigorous solution of the polyphase alternator assumes symmetrical terminal conditions of current. That is, the current in each phase was the same as that in every other phase, except for the difference in phase relationship.

This symmetrical terminal solution is extended to the solution of unsymmetrical fault conditions by assuming that the customary symmetrical components of positive-, negative-, and zero-sequence currents are simultaneously applied in such a fashion of phase and magnitude as will give the terminal conditions as actually exist. It is possible to so arrange these sets of sequence currents to duplicate any terminal condition chosen. Thus in a line-to-line fault, these currents (including the so-called "steady-state" and "transient" components of the solution) when added together in the open phase must give no current in that phase. Likewise, in a line-to-ground fault, the 2 open phases will have no current when the sequence currents obtained for these phases are added. The first case will require only positive- and negative-sequence components of current, while the latter will require positive-, negative-, and zero-sequence components. These statements refer not only to the fundamental component of current, but to harmonic components as well.

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1. For all numbered references, see list at end of paper.

Using these component symmetrical currents, the equivalent impedance of the alternator will need to be known for each. In general, in case harmonic armature and field currents are set up, the impedance to the fundamental and all related harmonics must be known, when flowing simultaneously.

Limiting the discussion to a line-to-line and line-to-ground fault, it would in general be expected that the impedance to the negative-sequence set of symmetrical currents would be different for the 2 cases. In the line-to-line fault the positive and negative fundamental components of current must cancel each other in the open phase; however, the negative-phase-sequence currents give rise to third harmonic currents, which in turn will require positive- and negative-sequence components that cancel each other in the open phase and so on. Since positive- and negative-sequence components of currents are involved, the impedance to the fundamental negative-sequence current will be dependent on these only. In the case of a line-to-ground fault, harmonics of positive, negative, and zero-sequence are set up by the fundamental negative-sequence component current. Because of this difference in the harmonics, depending upon the type of fault, different harmonics encountered require a different value of negative-sequence impedance. For the cases calculated in this paper, these impedances are discussed at some length in appendix $A$.

## Review of 3-Phase Short-Circuit Solution

In a previous paper by the authors[1] there were developed equations for finding the armature and field currents upon the application of a 3-phase short circuit to an alternator. There were also developed a number of equations for a 3-phase machine that could be applied for various conditions. These equations are important and will be repeated here although no derivation will be given.

$$e_d = -p\psi_d - \psi_q\,(p\theta) - i_d R \tag{1}$$

$$e_q = -p\psi_q + \psi_d\,(p\theta) - i_q R \tag{2}$$

$$E_{fd} = p\psi_{fd} + I_{fd}R_{fd} \tag{3}$$

$$\psi_{fd} = X_{ffd}I_{fd} + X_{fad}i_d \tag{4}$$

$$\psi_d = X_{afd}I_{fd} + x_d i_d \tag{5}$$

$$\psi_q = x_q i_q \tag{6}$$

These equations have been set up assuming that there is only the main field winding in the direct-axis rotor circuit and no windings on the quadrature-axis rotor circuit.

In order to solve for a 3-phase short circuit the 6 equations above are combined into the following 3 equations.

$$e_d = -(R + px_d)i_d - x_q i_q - pX_{afd}I_{fd} \quad (7)$$

$$e_q = x_d i_d - (R + px_q)i_q + X_{afd}I_{fd} \quad (8)$$

$$E_{fd} = pX_{fad}i_d + (R_{fd} + pX_{ffd})I_{fd} \quad (9)$$

These equations solved simultaneously by means of determinants give the following equations for the unknown currents.

$$\left.\begin{aligned} i_d &= [e_q(x_q R_{fd} + px_q X_{ffd}) - e_d(p^2 x_q X_{ffd} + px_q R_{fd} + pRx_{ffd} + RR_{fd}) - E_{fd}X_{afd}(p^2 x_q + pR + x_q)]/D(p) \\ i_q &= [e_d(pX_{afd}X_{fad} - px_d X_{ffd} - x_d R_{fd}) + E_{fd}(RX_{afd}) - e_q(p^2 x_d X_{ffd} - p^2 X_{afd}X_{fad} + pRX_{ffd} + pR_{fd}x_d + RR_{fd})]/D(p) \\ I_{fd} &= [E_{fd}(p^2 x_d x_q + pRx_q + pRx_d + R^2 + x_d x_q) - e_q(pX_{fad}x_q) + e_d(p^2 x_q X_{fad} + pRX_{fad})]/D(p) \end{aligned}\right\} \quad (10)$$

where

$$D(p) = p^3(x_d x_q X_{ffd} - X_{afd}X_{fad}x_q) + p^2(x_q x_d R_{fd} + Rx_d X_{ffd} + Rx_q X_{ffd} - X_{afd}X_{fad}R) + p(RR_{fd}x_d + RR_{fd}x_q + R^2 X_{ffd} + x_d x_q X_{ffd} - X_{afd}X_{fad}x_q) + (R^2 R_{fd} + x_d x_q R_{fd})$$

The currents in the various phases are found from the following equations.

$$i_a = i_d \cos\theta + i_q \sin\theta \quad (11)$$

$$i_b = i_d \cos(\theta - 120) + i_q \sin(\theta - 120) \quad (12)$$

$$i_c = i_d \cos(\theta + 120) + i_q \sin(\theta + 120) \quad (13)$$

where

$$\theta = t + \theta_0 \quad (14)$$

Also

$$e_d = \frac{2}{3}[e_a \cos\theta + e_b \cos(\theta - 120) + e_c \cos(\theta + 120)] \quad (15)$$

$$e_q = \frac{2}{3}[e_a \sin\theta + e_b \sin(\theta - 120) + e_c \sin(\theta + 120)] \quad (16)$$

and

$$x_{d'} = x_d - \frac{X_{afd}X_{fad}}{X_{ffd}} \quad (17)$$

## Theory of Single-Phase Solution

In order to satisfy terminal conditions in a line-to-ground fault, it is necessary to have positive-, negative-, and zero-sequence currents equal to each other and in-phase in phase $a$. The value of positive-sequence current is found by applying the voltage to a circuit consisting of positive-, negative-, and zero-sequence reactances in series. The sum of these reactances in the direct and quadrature axes will be $x_{dT}$ and $x_{qT}$ referred to as totalized reactances. The value of $x_2$ to be used is discussed in appendix $A$. These totalized values of direct- and quadrature-axis reactances are now used in equations 10 for the solution of a 3-phase short circuit and solutions will be obtained for $i_d$, $i_q$, and $I_{fd}$.

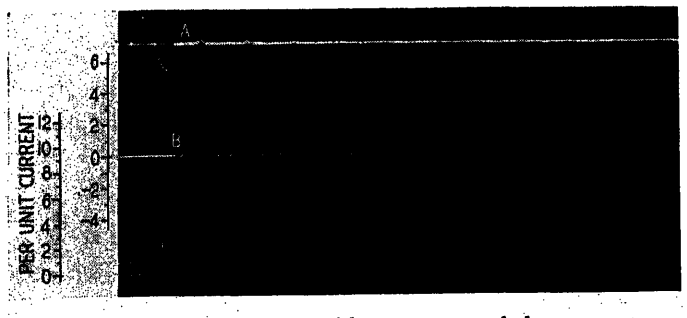



**Figure 1. Oscillogram of line-to-ground short circuit**

*A*—Phase a voltage; *B*—Armature current; *C*—Field current

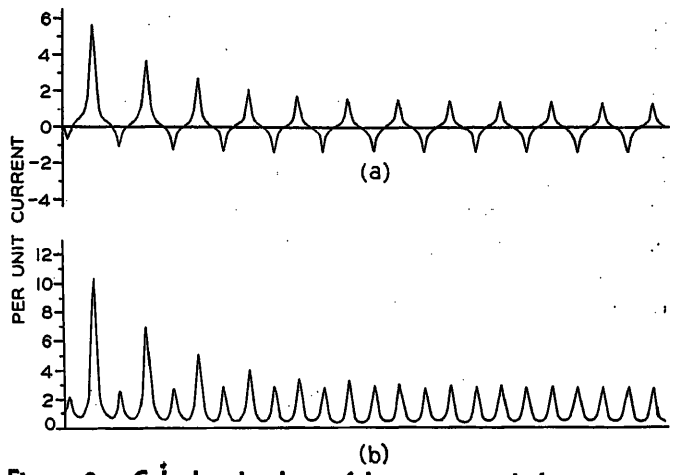



**Figure 2. Calculated values of line-to-ground short circuit**

(a) Armature current

$$i_a = \frac{0.396\sin(\omega t + 242°38') + 0.733\epsilon^{-0.09\omega t}\sin(\omega t + 242°38')}{1.224 - 0.946\cos(2\omega t + 288°)} + \frac{0.061\epsilon^{-0.103\omega t}\sin(1.991\omega t + 132°31')}{1.224 - 0.946\cos(2\omega t + 288°)} + \frac{1.109\epsilon^{-0.103\omega t}\sin(0.009\omega t + 59°40')}{1.224 - 0.946\cos(2\omega t + 288°)}$$

(b) Field current

$$I_{fd} = 1 + 1.84\epsilon^{-0.09\omega t} + 1.84\epsilon^{-0.103\omega t}\sin(0.991\omega t + 269°15') - \frac{0.946\sin(2\omega t + 201°6') + 0.447}{1.224 - 0.946\cos(2\omega t + 288°)} + \frac{[1.757\sin(2\omega t + 201°6') + 0.830]\epsilon^{-0.09\omega t}}{1.224 - 0.946\cos(2\omega t + 288°)} - \frac{[0.875\sin(2.991\omega t + 18°47')]\epsilon^{-0.103\omega t}}{1.224 - 0.946\cos(2\omega t + 288°)} + \frac{[1.82\sin(1.009\omega t + 22°11')]\epsilon^{-0.103\omega t}}{1.224 - 0.946\cos(2\omega t + 288°)} + \frac{[1.271\sin(0.991\omega t + 87°26')]\epsilon^{-0.103\omega t}}{1.224 - 0.946\cos(2\omega t + 288°)}$$

The armature currents that are found by this solution are only the fundamental-frequency positive-phase-sequence currents flowing in the armature, so that the value of $i_a$ obtained from the above values of $i_d$ and $i_q$ is ${}_1i_{a1}$. For a line-to-ground short circuit the total short-circuit current in phase $a$ is equal to 3 times the sequence current due to the fact that positive-, negative-, and zero-sequence currents are equal so that the true value of ${}_1i_a$ is equal to 3 times ${}_1i_{a1}$.

The fact that there is negative-sequence current flowing in the armature produces currents of frequency 2 higher than the fundamental solution, and gives rise to several series of terms of higher frequencies. These series will be

referred to as harmonic series throughout this paper although it will be seen that the series are not made up of harmonics but of a series of terms each of frequency 2 higher than the term that preceded it. In order to obtain the solution for the actual armature currents, the harmonics that go with ${}_1i_a$ must be found and added to it. The actual process of obtaining the total short-circuit current, including these harmonics, is given in appendix *B*.

The solution of $I_{fa}$ as found from equation 10 is, in a manner similar to the solution for armature current, only a

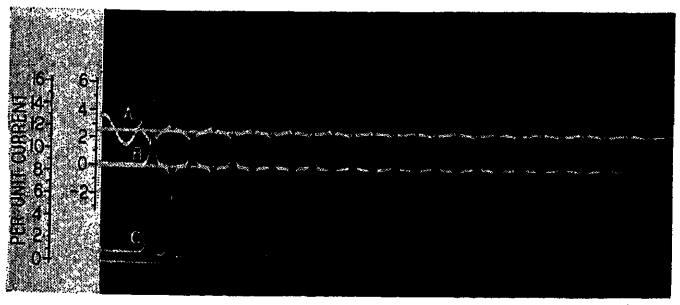



**Figure 3. Oscillogram of line-to-line short circuit**

*A*—Phase *a* voltage; *B*—Phase *b* current; *C*—Field current

part of the total current. The harmonics in the field current arise from the harmonic currents flowing in the armature. Therefore the harmonics in the field are calculated from the total $i_a$ flowing in the armature by solving equation 9 for $I_{fa}$.

Letting $E_{fa} = 0$

$$I_{fa} = \frac{pX_{fad}i_a}{R_{fa} + pX_{ffa}}$$

The series are geometric in form so that once 2 terms have been found the rest of the series is determined.

The same process is used to obtain the solution for a line-to-line short circuit. In this case there are no zero-sequence currents and the equation for $x_2$ will be different than that used in the line-to-ground solution.

## Conclusions

By the application of symmetrical components of currents to polyphase-alternator short-circuit solutions it has been possible to include the resistance in both the armature and field circuits in a much more satisfactory manner than is usually found in unsymmetrical alternator short-circuit solutions. In order to shorten the numerical calculations, some approximations have been made in the inclusion of the resistances of the machine circuits, but these approximations have only a negligible effect. Moreover, these solutions are similar to the general 2-reaction theory as developed for symmetrical short-circuit solutions, and give solutions which agree experimentally. The oscillograms included in the paper were taken on a small laboratory machine; even closer results could be obtained on larger commercial machines, in which the constants were known.

## Appendix A

NEGATIVE-SEQUENCE REACTANCE

By applying the constant-flux-linkage theorem to a line-to-ground fault, Doherty[2] has shown that the initial value of the fundamental component of current is

$$i = \frac{2e_0}{x_D' + \sqrt{x_D'x_Q'}} \tag{1a}$$

By the principle of symmetrical components, this is also equal to

$$i = \frac{3e_0}{x_d' + x_2 + x_0} \tag{2a}$$

Therefore

$$\frac{3}{x_d' + x_2 + x_0} = \frac{2}{x_D' + \sqrt{x_D'x_Q'}}$$

Park[3] has shown that the following relations exist between the single-phase static constants and the 3-phase constants.

$$x_D' = \frac{x_0 + 2x_d'}{3}$$

$$x_Q' = \frac{x_0 + 2x_q'}{3}$$

Substituting and solving for $x_2$

$$x_2 = \frac{\sqrt{(x_0 + 2x_d')(x_0 + 2x_q')}}{2} - \frac{x_0}{2} \tag{3a}$$

Park has shown that for a line-to-line fault the relation between single-phase and 3-phase constants differ from the line-to-ground relations.

$$x_D' = 2x_d'$$

$$x_Q' = 2x_q'$$

Thus the initial value of the fundamental current during a line-to-line fault as given by Doherty becomes

$$\frac{2\sqrt{3}e_0}{x_D' + \sqrt{x_D'x_Q'}} = \frac{\sqrt{3}e_0}{x_d' + \sqrt{x_d'x_q'}}$$

But by symmetrical components this current is also

$$\frac{\sqrt{3}e_0}{x_d' + x_2}$$

Now equation the 2 expressions and solving for $x_2$

$$x_2 = \sqrt{x_d'x_q'} \tag{4a}$$

Thus it is seen that $x_2$ varies with the kind of fault.

For a line-to-ground fault the external reactances of the sequence network are $x_2$ and $x_0$ in series.

Therefore

$$x_{dT} = x_d + x_2 + x_0$$
$$x_{qT} = x_q + x_2 + x_0$$

Similarly

$$x_{dT}' = x_d' + x_2 + x_0$$
$$x_{qT}' = x_q' + x_2 + x_0$$

For a line-to-line fault, the external reactance is only the negative-sequence reactance and the totalized impedances are

$$x_{dT} = x_d + x_2$$
$$x_{qT} = x_q + x_2$$
$$x_{dT}' = x_d' + x_2$$
$$x_{qT}' = x_q' + x_2$$

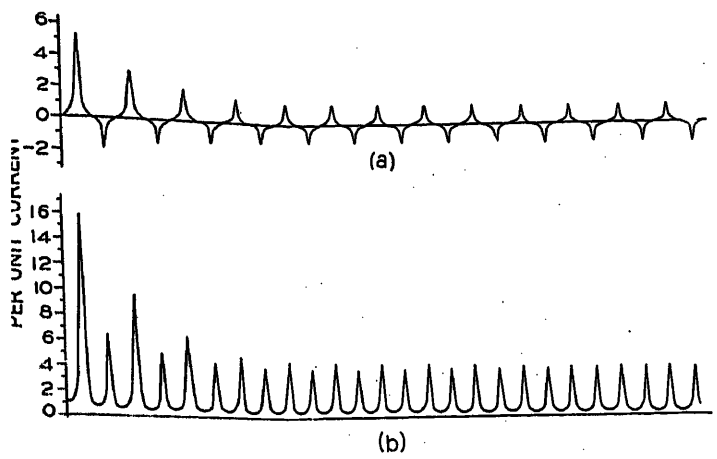



**Figure 4. Calculated values of line-to-line short circuit**

(a) Armature current

$$i_b = \frac{0.208 \sin(\omega t + 345°1') + 0.599\epsilon^{-0.123\omega t}\sin(\omega t + 345°1')}{1.342 - 1.170\cos(2\omega t + 132°)} +$$
$$\frac{0.064\epsilon^{-0.101\omega t}\sin(1.991\omega t + 248°22')}{1.342 - 1.170\cos(2\omega t + 132°)} +$$
$$\frac{0.798\epsilon^{-0.101\omega t}\sin(0.009\omega t + 161°1')}{1.342 - 1.170\cos(2\omega t + 132°)}$$

(b) Field current

$$I_{fd} = 1.0 + 2.88\epsilon^{-0.123\omega t} + 2.884\epsilon^{-0.101\omega t}\sin(0.991\omega t + 271°26') -$$
$$\frac{1.17\sin(2\omega t + 44°23') + 0.681}{1.342 - 1.170\cos(2\omega t + 132°)} +$$
$$\frac{[3.37\sin(2\omega t + 44°23') + 1.96]\epsilon^{-0.123\omega t}}{1.342 - 1.170\cos(2\omega t + 132°)} -$$
$$\frac{[1.68\sin(2.991\omega t + 224°35')]\epsilon^{-0.101\omega t}}{1.342 - 1.170\cos(2\omega t + 132°)} +$$
$$\frac{[2.87\sin(1.009\omega t + 224°26')]\epsilon^{-0.101\omega t}}{1.342 - 1.170\cos(2\omega t + 132°)} +$$
$$\frac{[2.657\sin(0.991\omega t + 89°25')]\epsilon^{-0.101\omega t}}{1.342 - 1.170\cos(2\omega t + 132°)}$$

If any impedance external to the machine is present, it must be added to $x_d$, $x_2$, and $x_0$, etc. Thus for an external impedance of $x_{ex}$ in a line-to-ground fault

$$x_{dT} = x_d + x_2 + x_0 + 3x_{ex} \tag{5a}$$

Similar equations must be written for $x_{qT}$, and for the transient reactances $x_{dT}'$ and $x_{qT}'$.

An external impedance in a line-to-line fault is taken into account similarly except that $x_0$ is not present; therefore only $2x_{ex}$ must be added.

$$x_{dT} = x_d + x_2 + 2x_{ex}, \text{ etc.} \tag{6a}$$

In order to see the formation of higher frequency currents, let a negative-sequence voltage of frequency $n$ be impressed.

$$e_a = \sin nt$$
$$e_b = \sin(nt - 120)$$
$$e_c = \sin(nt + 120)$$

And then from equations 15 and 16

$$e_d = \sin(n+1)t$$
$$e_q = -\cos(n+1)t$$

From equations 1 and 2

$$e_d = -p\psi_d - \psi_q(p\theta) - i_d R$$
$$e_q = -p\psi_q + \psi_d(p\theta) - i_q R$$

But using the totalized reactances

$$\psi_d = x_{dT}' i_d$$
$$\psi_q = x_{qT}' i_q$$

With $p\theta = 1$ and neglecting $R$

$$e_d = \sin(n+1)t = -p\,x_{dT}' i_d - x_{qT}' i_q$$
$$e_q = -\cos(n+1)t = -p\,x_{qT}' i_q + x_{dT}' i_d$$

Solving for $i_d$ and $i_q$

$$i_d = \frac{\cos(n+1)t}{n\,x_{dT}'}$$

$$i_q = \frac{\sin(n+1)t}{n\,x_{qT}'}$$

Then from equation 11 the value of $i_a$ becomes

$$i_a = \frac{1}{2n}\left(\frac{1}{x_{dT}'} + \frac{1}{x_{qT}'}\right)\cos nt + \frac{1}{2n}\left(\frac{1}{x_{dT}'} - \frac{1}{x_{qT}'}\right)\cos(n+2)t \tag{7a}$$

From equation 7a the formation of higher frequencies can readily be seen. A negative-sequence current of frequency $n$ will produce a positive-sequence current of frequency $(n + 2)$. That this is a positive-sequence current can readily be checked by finding the currents $i_b$ and $i_c$ similar to equation 7a. The important part of this equation is the relation of the magnitude of the 2 currents. This ratio is

$$\frac{\left(\frac{1}{x_{dT}'} - \frac{1}{x_{qT}'}\right)}{\left(\frac{1}{x_{dT}'} + \frac{1}{x_{qT}'}\right)} = \frac{x_{qT}' - x_{dT}'}{x_{qT}' + x_{dT}'} \tag{8a}$$

Therefore if a negative-sequence current of frequency $n$ is flowing there will also be flowing a positive-sequence current of frequency $(n + 2)$ whose amplitude bears the ratio to the first current as given by equation 8a.

## Appendix B

ARMATURE CURRENT

From the theory of symmetrical components, the current that will be found by dividing the voltage by the network impedance for a line-to-ground fault is only the positive-sequence current.

$$i_{a1} = \frac{E}{x_1 + x_2 + x_0}$$

However there is also flowing a negative- and zero-sequence current equal to this value of $i_{a1}$. It is a known fact that harmonics exist

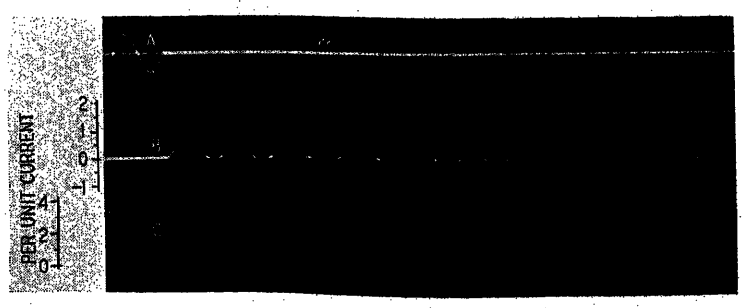



**Figure 5. Oscillogram of line-to-ground short circuit with external reactance**

A—Phase a voltage, B—Armature current, C—Field current

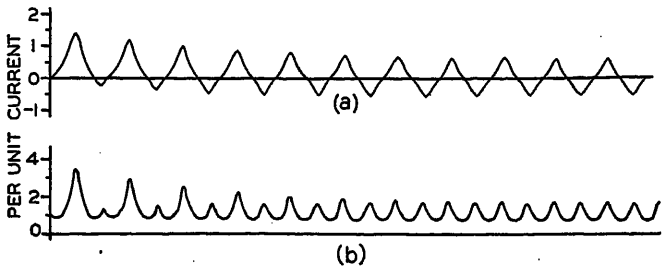



**Figure 6. Calculated values of line-to-ground short circuit with external reactance**

(*a*) Armature current

$$i_a = \frac{0.333 \sin(\omega t + 280°18') + 0.201\epsilon^{-0.051\omega t}\sin(\omega t + 280°18')}{1.053 - 0.462\cos(2\omega t + 10°)} +$$

$$\frac{0.022\epsilon^{-0.075\omega t}\sin(1.999\omega t + 180°)}{1.053 - 0.462\cos(2\omega t + 10°)} +$$

$$\frac{0.525\epsilon^{-0.075\omega t}\sin(0.001\omega t + 98°)}{1.053 - 0.462\cos(2\omega t + 10°)}$$

(*b*) Field current

$$I_{fd} = 1.0 + 0.60\epsilon^{-0.051\omega t} + 0.60\epsilon^{-0.075\omega t}\sin(0.999\omega t + 268°37') -$$

$$\frac{0.46\sin(2\omega t + 283°19') + 0.106}{1.053 - 0.462\cos(2\omega t + 10°)} -$$

$$\frac{[0.277\sin(2\omega t + 283°19') + 0.064]\epsilon^{-0.051\omega t}}{1.053 - 0.462\cos(2\omega t + 10°)} -$$

$$\frac{[0.137\sin(2.999\omega t + 107°5')]\epsilon^{-0.075\omega t}}{1.053 - 0.462\cos(2\omega t + 10°)} -$$

$$\frac{[0.60\sin(1.001\omega t + 102°51')]\epsilon^{-0.075\omega t}}{1.053 - 0.462\cos(2\omega t + 10°)} +$$

$$\frac{[0.170\sin(0.999\omega t + 89°24')]\epsilon^{-0.075\omega t}}{1.053 - 0.462\cos(2\omega t + 10°)}$$

in the armature so the current as found above shall be referred to as fundamental positive-sequence current in phase *a*, or, ${}_1i_{a1}$.

$${}_1i_{a1} = A\sin(\omega t + \theta_0 + \alpha) = A\sin(\theta + \alpha)$$

where $\theta_0$ is the angle between phase *a* and the direct axis at the instant of short circuit and $\alpha$ is the angle of lag of the armature circuit. This angle $\alpha$ is only slightly less than $-90$ degrees.

It was shown in appendix *A*, equation 8*a*, that if a negative-sequence current is flowing in the armature, there is set up a positive-sequence current of frequency 2 units higher and bearing a ratio to the original current of $\frac{x_{qT}' - x_{dT}'}{x_{qT}' + x_{dT}'}$. This ratio will be called *b* for convenience.

Now

$${}_1i_{a1} = A\sin(\theta + \alpha)$$
$${}_1i_{a2} = A\sin(\theta + \alpha)$$
$${}_1i_{a0} = A\sin(\theta + \alpha)$$

and

$${}_1i_a = 3A\sin(\theta + \alpha) \qquad (1b)$$

but ${}_1i_{a2}$ sets up a positive-sequence third harmonic current, ${}_3i_{a1}$, such that

$${}_3i_{a1} = b\,x\,{}_1i_{a2} = bA\sin(3\theta + \alpha)$$

and since

$${}_3i_{a1} = {}_3i_{a2} = {}_3i_{a0}$$
$${}_3i_a = 3bA\sin(3\theta + \alpha)$$

Now if

$${}_3i_{a2} = bA\sin(3\theta + \alpha)$$
$${}_3i_{a1} = b^2A\sin(5\theta + \alpha)$$

In similar manner there must be ${}_3i_{a0}$ and ${}_3i_{a0}$ and thus

$${}_3i_a = 3b^2A\sin(5\theta + \alpha)$$

or

$$i_a = 3A[\sin(\theta + \alpha) + b\sin(3\theta + \alpha) + b^2\sin(5\theta + \alpha) + \text{etc.}\ldots] \qquad (2b)$$

FIELD CURRENT

From equation 9

$$I_{fd} = \frac{E_{fd} - p\,X_{fad}\,i_d}{R_{fd} + pX_{ffd}}$$

$E_{fd}$ has the same value before and after the instant of short circuit so that in calculating any additional field current $E_{fd}$ is neglected.

$$I_{fd} = -\frac{p\,X_{fad}\,i_d}{R_{fd} + p\,X_{ffd}}$$

Neglecting $R_{fd}$

$$I_{fd} = -\frac{X_{fad}}{X_{ffd}}\,i_d \qquad (3b)$$

Therefore, in order to find the series of terms in $I_{fd}$, the series of terms in $i_d$ must be found.

$$i_d = \frac{2}{3}[i_a\cos\theta + i_b\cos(\theta - 120) + i_c\cos(\theta + 120)]$$

$$i_b = i_c = 0$$

therefore

$$i_d = \frac{2}{3}\,i_a\cos\theta \qquad (4b)$$

Putting in the value of $i_a$ term by term as found above gives for the first term

$${}_1i_d = \frac{2}{3} \times 3A\sin(\theta + \alpha)\cos\theta$$

$$= A\sin(2\theta + \alpha) + A\sin\alpha$$

In similar manner

$${}_3i_d = bA\sin(4\theta + \alpha) + bA\sin(2\theta + \alpha)$$

and

$${}_5i_d = b^2A\sin(6\theta + \alpha) + b^2A\sin(4\theta + \alpha)$$

or

$$i_d = A\sin\alpha + (1 + b)A[\sin(2\theta + \alpha) + b\sin(4\theta + \alpha) + b^2\sin(6\theta + \alpha) + \ldots] \qquad (5b)$$

To find the total armature current the harmonics due to negative-sequence current were found and added to the solution of ${}_1i_a$ as found from equation 1*b*. Therefore only the harmonics in the field current that come from the negative-sequence fundamental current must be added to the solution of $I_{fd}$ from equation 10.

$${}_1i_{a1} = A\sin(\theta + \alpha)$$

$${}_1i_{d1} = \frac{2}{3}[{}_1i_{a1}\cos\theta + {}_1i_{b1}\cos(\theta - 120) + {}_1i_{c1}\cos(\theta + 120)]$$

$$= A\sin\alpha$$

$${}_1i_{d2} = \frac{2}{3}[{}_1i_{a2}\cos\theta + {}_1i_{b2}\cos(\theta - 120) + {}_1i_{c2}\cos(\theta + 120)]$$

$$= A\sin(2\theta + \alpha)$$

Thus it is seen that in the equation for $i_d$ the first term $A \sin \alpha$ comes from the fundamental positive-sequence current and is not part of the additional harmonics. Therefore in order to get $I_{fd}$ only the terms in the bracket are applied to equation 3b. The additional terms of $I_{fd}$ are then

$$I_{fd} = -\frac{X_{fad}}{X_{ffd}}(1+b)\,A\,[\sin(2\theta+\alpha) + b\sin(4\theta+\alpha) + b^2\sin(6\theta+\alpha) + \ldots] \qquad (6b)$$

To obtain the total solution of $I_{fd}$, equation 6b must be added to the solution of $I_{fd}$ from equation 10.

### Harmonic Series

It is very inconvenient to plot the series term by term. For that reason the development of an expression for the sum of each series is now given.

The series that occur in the armature and field currents are both of the following general form where $X$ equals the sum.

$$X = \sin(n\theta+\alpha) + b\sin[(n+2)\theta+\alpha] + b^2\sin[(n+4)\theta+\alpha] + b^3\sin[(n+6)\theta+\alpha] + \ldots$$

Let $b = a^2$ and multiply both sides by $a^n$.

$$a^nX = a^n\sin(n\theta+\alpha) + a^{n+2}\sin[(n+2)\theta+\alpha] + a^{n+4}\sin[(n+4)\theta+\alpha] + \ldots$$

now

$$\sin(n\theta+\alpha) = \frac{\epsilon^{jn\theta}\epsilon^{j\alpha} - \epsilon^{-jn\theta}\epsilon^{-j\alpha}}{2j}$$

Writing the series with a summation sign

$$a^nx = \frac{1}{2j}\sum_{k=0}^{k=n}(a^{2k+n}\,\epsilon^{j(2k+n)\theta}\epsilon^{j\alpha} - a^{2k+n}\epsilon^{-j(2k+n)\theta}\epsilon^{-j\alpha})$$

but

$$\sum_{k=0}^{k=n} a^{(2k+n)} = \frac{a^n}{1-a^2}$$

$$a^nx = \frac{1}{2j}\left[\frac{\epsilon^{j\alpha}a^n\epsilon^{jn\theta}}{1-a^2\epsilon^{j2\theta}} - \frac{\epsilon^{-j\alpha}a^n\epsilon^{-jn\theta}}{1-a^2\epsilon^{-j2}}\right]$$

$$= \frac{1}{2j}\left[\frac{\epsilon^{j\alpha}a^n\epsilon^{jn\theta} - a^{n+2}\epsilon^{j\alpha}\epsilon^{j(n-2)\theta} - \epsilon^{-j\alpha}a^n\epsilon^{-jn\theta} + a^{n+2}\epsilon^{-j\alpha}\epsilon^{-j(n-2)\theta}}{1-a^2(\epsilon^{j2\theta}+\epsilon^{-j2\theta})+a^4}\right]$$

$$= \frac{1}{2j}\left[\frac{a^n(\epsilon^{j\alpha}\epsilon^{jn\theta} - \epsilon^{-j\alpha}\epsilon^{-jn\theta}) - a^{n+2}(\epsilon^{j\alpha}\epsilon^{j(n-2)\theta} - \epsilon^{-j\alpha}\epsilon^{-j(n_2)\theta}}{1-a^2(\epsilon^{j2\prime}+\epsilon^{-j2\theta})+a^4}\right]$$

$$a^nX = \frac{a^n\sin(n\theta+\alpha) - a^{n+2}\sin[(n-2)\theta+\alpha]}{1-2a^2\cos 2\theta + a^4}$$

$$X = \frac{\sin(n\theta+\alpha) - a^2\sin[(n-2)\theta+\alpha]}{1+a^4-2a^2\cos 2\theta}$$

but $a^2 = b$, therefore

$$X = \frac{\sin(n\theta+\alpha) - b\sin[(n-2)\theta+\alpha]}{1+b^2-2b\cos 2\theta}$$

where $\sin(n\theta+\alpha)$ is the first term of the series. Remembering that $\theta = \omega t + \theta_0$

$$\text{Sum} = \frac{\sin[n(\omega t+\theta_0)+\alpha] - b\sin[(n-2)(\omega t+\theta_0)+\alpha]}{1+b^2-2b\cos 2(\omega t+\theta_0)} \qquad (7b)$$

## Appendix C

### Line-to-Ground Short Circuit

Appendices $C$, $D$, and $E$ illustrate the method of calculating various types of faults on a small laboratory machine, the constants of which are given below.

| | | |
|---|---|---|
| $R_{fd} = 1.0$ | $x_d = x_q = 2.80$ | norm. $e_a = 63.5\sqrt{2}$ |
| $X_{afd} = 1.0$ | $X_{fad} = 81.7$ | $i_a = 10\sqrt{2}$ |
| $R = 0.073$ | $X_{ffd} = 31.5$ | $E_{fd} = 1.68$ |
| | $x_0 = 0.34$ | $I_{fd} = 13.95$ |

$$x_d' = x_d - \frac{X_{afd}X_{fad}}{X_{ffd}} \qquad (17)$$

$$= 2.8 - 2.59 = 0.21$$

$$x_2 = \frac{\sqrt{2x_d'+x_0)(2x_q'+x_0)}}{2} - \frac{x_0}{2} \qquad (3a)$$

$$= \frac{1}{2}\sqrt{(0.42+0.34)(5.6+0.34)} - 0.17 = 0.89$$

The totalized reactances are then

$$x_{qT}' = 2.80 + 0.34 + 0.89 = 4.03$$
$$x_{dT}' = 0.21 + 0.34 + 0.89 = 1.44$$

$$b = \frac{4.03-1.44}{4.03+1.44} = \frac{2.59}{5.47} = 0.473$$

Assuming that the 3 sequence resistances are equal

$$R = R_1 + R_2 + R_0 = 3 \times 0.073 = 0.22$$

Now, using $x_{dT} = 4.03$ instead of $x_d = 2.80$ and $R = 0.22$ in the equations for a 3-phase short circuit,

$$i_{d1} = -0.248 - 0.459\epsilon^{-0.09\omega t} + 0.705\epsilon^{-0.103\omega t}\cos(0.991\omega t - 2°34')$$

$$i_{q1} = 0.0135 + 0.0248\epsilon^{-0.09\omega t} + 0.250\epsilon^{-0.103\omega t}\cos(0.991\omega t - 98°46')$$

$$I_{fd} = 1.0 + 1.84\,\epsilon^{-0.09\omega t} + 184\epsilon^{-0.103\omega t}\sin(0.991\omega t + 269°\ 15')$$

From the oscillogram $\theta_0 = 324°$

$$i_{a1} = i_{d1}\cos(\omega t+\theta_0) + i_{q1}\sin(\omega t+\theta_0)$$

and the fundamental value of $i_a$ becomes

$$_1i_a = 3\,i_{a1}$$

$$_1i_a = 0.745\sin(\omega t + 237°6') + 1.38\,\epsilon^{-0.09\omega t}\sin(\omega t+237°6') + 0.687\epsilon^{-0.103\omega t}\sin(1.991\,\omega t + 54°47') + 1.43\epsilon^{-0.103\omega t}\sin(0.009\omega t + 58°11')$$

Each of these 4 terms is followed by a series of harmonics but the term $(\omega t + \theta_0)$ must be factored out of $(\omega t + 237°6')$, etc. Thus for the first term of $_1i_a$

$$0.745\sin(\omega t+237°6') = 0.745\sin[(\omega t+324°) - 86°54']$$

The series of harmonics following the first term is

$$0.745(\sin[(\omega t+324°) - 86°54'] + b\sin[3(\omega t+324°) - 86°54'] + b^2\sin[5(\omega t+324°) - 86°54'] + \text{etc.})$$

The first term is in the form $\sin[n(\omega t+\theta_0)+\alpha]$ and the equation developed in appendix $B$ can be used to get the sum.

$$\text{Sum} = \frac{\sin[n(\omega t+\theta_0)+\alpha] - b\sin[(n-2)(\omega t+\theta_0)+\alpha]}{1+b^2-2b\cos 2(\omega t+\theta_0)} \qquad (7b)$$

For the series following the first term of $_1i_a$

$b = 0.473$ $\quad n = 1$ $\quad (\omega t+\theta_0) = (\omega t+324°) = \theta$
$\alpha = -86°54'$

$$\text{sum} = 0.745\,\frac{[\sin(\theta - 86°54') - 0.473\sin(-\theta - 86°54')]}{1.224 - 0.946\cos(2\omega t+288°)}$$

$$= 0.745\,\frac{[0.532\sin(\theta - 81°22')]}{1.224-0.946\cos(2\omega t+288°)} = \frac{0.396\sin(\omega t+242°38')}{1.224-0.946\cos(2\omega t+288°)}$$

In a similar manner the sum of the series following the second term is

$$= 1.38\epsilon^{-0.09\omega t}\,\frac{[0.532\sin(\theta - 81°22')]}{1.224 - 0.946\cos(2\omega t + 288°)} = \frac{0.733\epsilon^{-0.09\omega t}\sin(\omega t + 242°38')}{1.224 - 0.946\cos(2\omega t + 288°)}$$

The same denominator will appear in all of the terms and for convenience it will be replaced by a symbol $D(1)$, where

$$D(1) = 1.224 - 0.946\cos(2\omega t + 288°)$$

In order to use the equation for the sum developed in appendix $B$, it is necessary to get the first term of each series in the form of

$$\sin[n(\omega t + \theta_0) + \alpha]$$

The third term of ${}_1i_a$ can be written

$$0.687\epsilon^{-0.103\omega t}\sin(1.991\omega t + 54°47') = 0.687\epsilon^{-0.103\omega t}\sin[1.991(\omega t + 324°) + 129°42']$$

where

$$\alpha = \phi - n(\theta_0) = 54°47' - 1.991\,(324°) = 129°42'$$

In similar manner for the fourth term

$$\alpha = 58°11' - 0.009\,(324°) = 55°16'$$

and

$$1.43\epsilon^{0.103\omega t}\sin(0.009\omega t + 58°11') = 1.43\epsilon^{0.103\omega t}\sin[0.009\,(\omega t + 324°) + 55°16']$$

The third and fourth term series become respectively

$$\text{Third} = \frac{0.687\epsilon^{-0.10\omega t}}{D\,(1)} \times \frac{[\sin(1.991\theta + 129°42') - 0.473\sin(-0.009\theta + 129°42')]}{D(1)}$$

$$\text{Fourth} = \frac{1.43\epsilon^{-0.103\omega t}[\sin(0.009\theta + 55°16') - 0.473\sin(-1.991\theta + 55°16')]}{D(1)}$$

These two can be combined in the following manner.

$$0.687\ \angle 129°42' + 0.473 \times 1.43\ \angle -55°16' = 0.061\ \angle 207°26'$$

$$1.43\ \angle 55°16' + 0.473 \times 0.687\ \angle -129°42' = 1.109\ \angle 56°45'$$

and the combination of the third and fourth term series gives

$$\text{Third + fourth} = \frac{0.061\epsilon^{-0.103\omega t}\sin(1.991\theta + 207°26')}{D(1)} + \frac{1.109\epsilon^{-0.103\omega t}\sin(0.009\theta + 56°45')}{D(1)}$$

Substituting $\theta = \omega t + \theta_0$

$$\text{Third + fourth} = \frac{0.061\epsilon^{-0.103\omega t}\sin(1.991\omega t + 132°31')}{D(1)} + \frac{1.109\epsilon^{-0.103\omega t}\sin(0.009\omega t + 59°40')}{D(1)}$$

Then the complete expression for the armature current becomes

$$i_a = \frac{0.396\sin(\omega t + 242°38') + 0.733\epsilon^{-0.09\omega t}\sin(\omega t + 242°38')}{1.224 - 0.946\cos(2\omega t + 288°)} + \frac{0.061\epsilon^{-0.103\omega t}\sin(1.991\omega t + 132°31')}{1.224 - 0.946\cos(2\omega t + 288°)} + \frac{1.109\epsilon^{-0.103\omega t}\sin(0.009\omega t + 59°40')}{1.224 - 0.946\cos(2\omega t + 288°)}$$

The value of $i_d$ can be found from each term of $i_a$ by using the following equation.

$$i_d = \frac{2}{3}\,i_a\cos(\omega t + \theta_0) \qquad (4b)$$

$$= \frac{2}{3} \times 0.745\sin(\theta - 86°54')\cos\theta$$

$$= 0.248\sin(2\theta - 86°54') - 0.248$$

Using equation 5*b*, the $i_d$ resulting from the first term of $i_a$ and its series is

$$i_d = -0.248 + 0.248(1 + b)[\sin(2\theta - 86°54') + b\sin(4\theta - 86°54') + b^2\sin(6\theta - 86°54') + \text{etc.}]$$

$$I_{fd} = -\frac{X_{fad}}{X_{ffd}}\,i_d \qquad (3b)$$

$$I_{fd} = -2.59\,i_d$$

As was shown in appendix $B$, the harmonics in $I_{fd}$ are found by using only the bracketed terms of $i_d$.

The first term of the series is in the form

$$\sin[n(\omega t + \theta_0) + \alpha]$$

where

$$n = 2 \qquad \alpha = -86°34' \qquad b = 0.473$$

$$\text{sum} = \frac{-2.59 \times 0.248 \times 1.473[\sin(2\theta - 86°54') - 0.473\sin(-86°54')]}{D(1)} = \frac{-0.946\sin(2\omega t + 201°6') - 0.447}{D(1)}$$

In similar manner the sum of the next series becomes

$$-2.59 \times \frac{1.38}{3} \times 1.473\epsilon^{-0.09\omega t} = \frac{[\sin(2\theta - 86°54') - 0.473\sin(-86°54')]}{D(1)} = \frac{-1.757\epsilon^{-0.09\omega t}\sin(2\omega t + 201°6') - 0.830\epsilon^{-0.09\omega t}}{D(1)}$$

For the third sum

$$n = 2.991 \qquad b = 0.473 \qquad \alpha = 129°42'$$

$$\text{sum} = \frac{-2.59 \times \frac{0.687}{3} \times 1.473\epsilon^{-0.103\omega t}[\sin(2.991\theta + 129°42') - 0.473\sin(0.991\theta - 129°42')]}{D(1)}$$

For the fourth sum

$$n = 1.009 \qquad b = 0.473 \qquad \alpha = 55°16'$$

$$\text{sum} = \frac{-2.59 \times \frac{1.43}{3} \times 1.473\epsilon^{-0.103\omega t}[\sin(1.009\theta + 55°16') - 0.473\sin(-0.991\theta + 55°16')]}{D(1)}$$

$$\text{Third sum} = \frac{[-0.875\sin(2.991\omega t + 18°47')]\epsilon^{-0.103\omega t}}{D(1)} + \frac{[0.413\sin(0.991\omega t + 90°47')]\epsilon^{-0.103\omega t}}{D(1)}$$

$$\text{Fourth sum} = \frac{[-1.82 \sin (1.009\omega t + 22°11')]\epsilon^{-0.103\omega t}}{D(1)} - \frac{[0.861 \sin (0.991\omega t + 265°49')]\epsilon^{-0.103\omega t}}{D(1)}$$

$$0.413 \angle 90°47' - 0.861 \angle 265°49' = 1.271 \angle 87°26'$$

Therefore

$$\text{Third + fourth sums} = \frac{[-0.875 \sin (2.991\omega t + 18°47') - 1.82 \sin (1.009\omega t + 22°11')}{D(1)} + \frac{1.271 \sin (0.991\omega t + 87°26')]\epsilon^{-0.103\omega t}}{D(1)}$$

To these series must be added the 3 terms obtained from the original equations and the total field current becomes

$$I_{fd} = 1 + 1.84\epsilon^{-0.09\omega t} + 1.84\epsilon^{-0.103\omega t} \sin (0.991\omega t + 269°15') - \frac{0.946 \sin (2\omega t + 201°6') + 0.447}{1.224 - 0.946 \cos (2\omega t + 288°)} + \frac{[1.757 \sin (2\omega t + 201°6') + 0.830]\epsilon^{-0.09\omega t}}{1.224 - 0.946 \cos (2\omega t + 288°)} - \frac{[(0.875 \sin (2.991\omega t + 18°47') + 1.82 \sin (1.009\omega t + 22°11')]\epsilon^{-0.103\omega t}}{1.224 - 0.946 \cos (2\omega t + 288°)} + \frac{[1.271 \sin (0.991\omega t + 87°26')]\epsilon^{-0.103\omega t}}{1.224 - 0.946 \cos (2\omega t + 288°)}$$

Figure 1 is an oscillogram of a line-to-ground fault on a small wound-rotor induction motor, the rotor of which was excited by direct current. The calculated curve of armature current is shown as figure 2*a*, the calculated curve of field current is figure 2*b*.

But for a line-to-line fault

$$_1i_b = -j\,1.732\ {}_1i_{a1} = 1.732\ {}_1i_{a1}\ \angle 270°$$

$$_1i_b = 0.494 \sin (\omega t + 338°23') + 1.426\epsilon^{-0.123\omega t} \sin (\omega t + 338°23') + 0.707\epsilon^{0.101\omega t} \sin (1.99\omega t + 158°35') + 1.210\epsilon^{-0.101\omega t} \sin (0.009\,\omega t + 158°\,26')$$

The angle $\theta_0 = 156$ degrees was reckoned on the basis of current in phase $a$ and as the short circuit has been assumed to occur in phases $b$ and $c$ it is necessary to convert $\theta_0$ over to phase $b$ in order to obtain the correct series for $i_b$. Since $i_b$ lags $i_{a1}$ by 90 degrees, it is necessary to subtract 90 degrees from $\theta_0$ to get the correct value to use for $i_b$.

$$\text{correct } \theta_0 = 156° - 90° = 66°$$

Now in a similar manner as was done in the line-to-ground case the summation of each series is found. Thus for the first term

$$0.494 \sin (\omega t + 338°23') = 0.494 \sin [(\omega t + 66°) + 272°23']$$

$$\text{sum} = 0.494 \frac{\sin[(\omega t+66°)+272°23'] - 0.575 \sin [-(\omega t+66°)+272°23']}{1.342 - 1.170 \cos (2\omega t + 132°)} = 0.494 \frac{0.420 \sin [(\omega t+66°)-80°59']}{1.342-1.170 \cos (2\omega t+132°)} = \frac{0.208 \sin (\omega t+345°1')}{1.342-1.170 \cos (2\omega t+132°)}$$

and the total short-circuit current in phase $b$ becomes

$$i_b = \frac{0.208 \sin (\omega t + 345°1') + 0.599\epsilon^{-0.123\omega t} \sin (\omega t + 345°1')}{1.342 - 1.170 \cos (2\omega t + 132°)} + \frac{0.064\epsilon^{-0.101\omega t} \sin (1.991\omega t + 248°22')}{1.342 - 1.170 \cos (2\omega t + 132°)} + \frac{0.798\epsilon^{-0.101\omega t} \sin (0.009\omega t + 161°1')}{1.342 - 1.170 \cos (2\omega t + 132°)}$$

## Appendix D

LINE-TO-LINE SHORT CIRCUIT

$$x_2 = \sqrt{x_d' x_q'} \qquad (4a)$$

$$= \sqrt{2.8 \times 0.21} = 0.75$$

$$x_{qT}' = 2.80 + 0.75 = 3.55$$

$$x_{dT}' = 0.21 + 0.75 = 0.96$$

$$b = \frac{3.55 - 0.96}{3.55 + 0.96} = \frac{2.59}{4.51} = 0.575$$

$$R = R_1 + R_2 = 2 \times 0.073 = 0.146$$

The constants for use in equations 10 are

| | | | |
|---|---|---|---|
| $R_{fd}$ | = 1.0 | $x_{dT} = x_{qT}$ | = 3.55 |
| $X_{afd}$ | = 1.0 | $X_{fad}$ | = 81.7 |
| $R$ | = 0.146 | $X_{ffd}$ | = 31.5 |

The voltage shown on the oscillogram is that of phase $b$ and since the equations require the angle between the direct axis and the axis of phase $a$

$$\theta_0 = (36° + 120°) = 156°$$

The solution obtained in a manner similar to line-to-ground case is

$$I_{fd} = 1.0 + 2.88\epsilon^{-0.123\omega t} + 2.884\epsilon^{-0.101\omega t} \sin (0.991\omega t + 271°26')$$

$$_1i_{a1} = 0.285 \sin (\omega t + 68°23') + 0.824\epsilon^{-0.123\omega t} \sin (\omega t + 68°23') + 0.414\epsilon^{-0.101\omega t} \sin (1.991\omega t + 248°35') + 0.699\epsilon^{-0.101\omega t} \sin (0.009\omega t + 248°26')$$

Care must be taken in calculating the value of $i_d$.

$$i_d = \frac{2}{3} [i_a \cos \theta + i_b \cos (\theta - 120°) + i_c \cos (\theta + 120°)]$$

$$i_a = 0 \quad \text{and} \quad i_c = -i_b$$

$$\cos (\theta - 120°) = \cos (\omega t + \theta_0 - 120°)$$

where the $\theta_0$ here refers to the current in phase $a$, but the $\theta_0$ in the series must be the one with reference to phase $b$.

$$(\omega t + \theta_0 - 120°) = (\omega t + 156° - 120°) = (\omega t + 66° - 30°) = (\omega t + \theta_0 - 30°) = (\theta - 30°)$$

In order to use the value of $\theta_0 = 66$ degrees, the equation for $i_d$ becomes

$$i_d = \frac{2}{3} [i_b \cos (\theta - 30°) - i_b \cos (\theta + 210°)]$$

For the first term of $_1i_b$

$$_1i_d = \frac{2}{3} \times 0.494[\sin(\theta-87°37')\cos(\theta-30°) - \sin(\theta-87°37')\cos(\theta+210°)]$$

$$= 2 \times \frac{0.494}{3} \times \frac{\sqrt{3}}{2} [\sin (2\theta - 87°37') - 1]$$

As was seen in the case of a line-to-ground circuit, only the part containing $(\sin 2\theta)$ goes into making up the series.

Where

$$D(2) = 1.342 - 1.170 \cos (2\omega t + 132°)$$

in a similar manner the sum of the first term's series for the field current is,

$$\text{sum} = -\frac{\frac{0.494}{3}\times\sqrt{3}\times 2.59\times 1.575[\sin(2\theta-87°37')-0.575\sin(-87°37')]}{D(2)}$$

$$= -\frac{1.17\sin(2\omega t+44°23')-0.681}{D(2)}$$

And likewise in a manner simi ar to the line-to-ground case, adding on the part found from the 3-phase solution, the total expression for field current is found.

$$I_{fa} = 1.0 + 2.88\epsilon^{-0.123\omega t} + 2.884\epsilon^{-0.101\omega t}\sin(0.991\omega t + 271°26') -$$

$$\frac{1.17\sin(2\omega t+44°23')+0.681}{1.342-1.170\cos(2\omega t+132°)} +$$

$$\frac{[3.37\sin(2\omega t+44°23')+1.96]\epsilon^{-0.123\omega t}}{1.342-1.170\cos(2\omega t+132°)} -$$

$$\frac{[1.68\sin(2.991\omega t+224°35')+2.87\sin(1.009\omega t+224°26')]\epsilon^{-0.101\omega t}}{1.342-1.170\cos(2\omega t+132°)} +$$

$$\frac{[2.657\sin(0.991\omega t+89°25')]\epsilon^{-0.101\omega t}}{1.342-1.170\cos(2\omega t+132°)}$$

An oscillogram of a line-to-line fault on this same machine is shown in figure 3. The calculated values of armature and field currents are shown in figures 4*a* and 4*b*, respectively.

## Appendix E

### Line-to-Ground Short Circuit With Reactance in Armature

It was shown in appendix *A* that if there is any external reactance in the armature circuit, it must be added to $x_d$, $x_2$, and $x_0$

For an external impedance of 0.96 units the values of $x_{qT}'$ become

$$x_{qT}' = 2.80 + 0.34 + 0.89 + 3(0.96) = 4.03 + 2.88 = 6.91$$
$$x_{dT}' = 0.21 + 0.34 + 0.89 + 3(0.96) = 1.44 + 2.88 = 4.32$$

The ratio $b$ now becomes

$$b = \frac{6.91-4.32}{6.91+4.32} = \frac{2.59}{11.23} = 0.231$$

The resistance of the added reactance was 0.061 units but 3 times this resistance must be added in the same manner as 3 times the reactance was used.

$$R = 0.22 + 3(0.061) = 0.22 + 0.18 = 0.40$$

The constants for use in the equations are then

$R_{fa} = 1.0$ $\quad x_{dT} = x_{qT} = 6.91$
$X_{afa} = 1.0$ $\quad X_{faa} = 81.7$
$R = 0.40$ $\quad X_{ffa} = 31.5$ $\quad \theta_0 = 5°$

The solution obtained is

$$i_a = 0.432\sin(\omega t - 81°41') + 0.261\epsilon^{-0.051\omega t}\sin(\omega t - 81°41') +$$
$$0.129\epsilon^{-0.075\omega t}\sin(1.99\omega t + 102°25') +$$
$$0.564\epsilon^{-0.075\omega t}\sin(0.001\omega t + 97°21')$$

$$I_{fa} = 1.0 + 0.600\epsilon^{-0.051\omega t} + 0.600\epsilon^{-0.075\omega t}\sin(0.999\omega t + 268°37')$$

Using the value of $b$ as found above to calculate the additional harmonics, the complete solution becomes

$$i_a = \frac{0.333\sin(\omega t+280°18')+0.201\epsilon^{-0.051\omega t}\sin(\omega t+280°18')}{1.053-0.462\cos(2\omega t+10°)} +$$

$$\frac{0.022\epsilon^{-0.075\omega t}\sin(1.999\omega t+180°)}{1.053-0.462\cos(2\omega t+10°)} +$$

$$\frac{0.525\epsilon^{-0.075\omega t}\sin(0.001\omega t+98°)}{1.053-0.462\cos(2\omega t+10°)}$$

$$I_{fa} = 1 + 0.60\epsilon^{-0.051\omega t} + 0.60\epsilon^{-0.075\omega t}\sin(0.999\omega t + 268°37') -$$

$$\frac{0.46\sin(2\omega t+283°19')+0.106}{1.053-0.462\cos(2\omega t+10°)} +$$

$$\frac{[0.277\sin(2\omega t+283°19')+0.064]\epsilon^{-0.051\omega t}}{1.053-0.462\cos(2\omega t+10°)} -$$

$$\frac{[0.137\sin(2.999\omega t+107°5')+0.60\sin(1.001\omega t+102°51')]\epsilon^{-0.075\omega t}}{1.053-0.462\cos(2\omega t+10°)} +$$

$$\frac{[0.170\sin(0.999\omega t+89°24')]\epsilon^{-0.075\omega t}}{1.053-0.462\cos(2\omega t+10°)}$$

Figure 5 is an oscillogram of a line-to-ground fault with an external impedance in the armature circuit. Figures 6*a* and 6*b* show the calculated curves of armature and field current.

## Appendix F

### Notation

In general the symbolic notation used in this paper is the same as was used in the previous paper by the authors.

In this paper there is added, however, a sequence and harmonic notation. It seemed advisable to maintain the sequence notation usually used. A subscript letter after a current designates the phase, a number after that designates the sequence. If there is no number after the letter it designates the total current in that phase.

The harmonic notation is quite similar to the sequence notation except that the subscript is placed before the current. The number designates the frequency of the harmonic and if no number is used, it designates the total current including all of the harmonics.

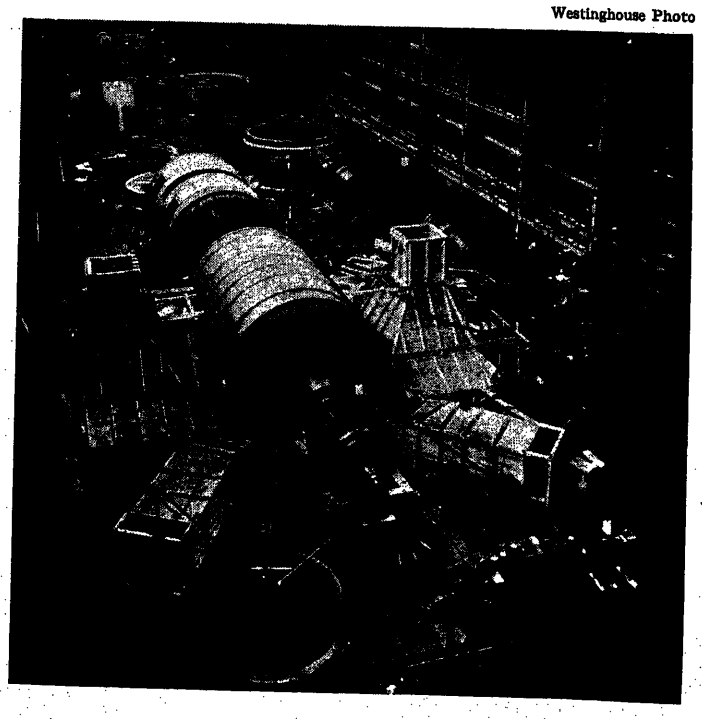
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Westinghouse Photo



# Single-Phase Induction-Motor Performance

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A COMMON procedure in the design of single-phase induction motors involves the determination of a stator winding to yield a desired maximum torque, followed by a check on motor performance. Yet in spite of the importance of the maximum torque value, little can be found in the technical literature concerning methods of predicting its magnitude, outside of those wherein the slip at which maximum torque occurs is substituted in the motor equations and the resulting maximum torque determined.[1] Inspection and trial from motor equations or the circle diagram are possible, but tedious, methods of approach.

A shorter and more direct method is given in this paper, offering the additional advantage of being largely in terms of the ratios of stator and rotor winding resistances to total leakage reactance. As such ratios are independent of the number of conductors used in the winding, analyses based on their use enable the designer to predict the winding necessary to yield a prescribed pull-out torque.

The equation for maximum torque will be derived here and its application and accuracy indicated.

With the winding fixed and the machine constants determined, it is frequently necessary to make a number of checks on the motor performance before it is constructed. Usually these checks involve only the calculation of no-load current and losses. Yet it is sometimes necessary to have performance curves (or several points thereon) while the machine is still in the design stage. Various analyses have been developed whereby the performance can be calculated from the machine constants. These analyses, whether based on the double-revolving-field theory, or the cross-field theory, take the form of circle or vector diagrams, equivalent networks, or analytical solutions. In any case they suffer the disadvantage of requiring tedious calculations, although improvements in simplifying the processes have been made by Branson, West,[6] Veinott[1] and others, with their tabulated procedures.

A process will be shown here which will enable the performance to be predicted readily, without complicated equations and with a precision greater than that of the resistance and reactance calculations. It is believed that a distinct need exists for this type of information.

It is possible to modify the cross-field equations for motor performance obtaining them in terms of ratios of machine constants. By assuming a series of values, the equations can be solved, the results plotted and hence made available for the analysis of any single-phase induction motor whose ratios of constants fall within the range prepared. Then for any speed, the primary current, power factor, watts input, output and efficiency, as well as less important values of counter electromotive force, rotor currents in each axis, and the rotor copper losses, can all be calculated by a comparatively simple process. Two methods of utilizing these curves will be shown, the first, being slightly more involved, requires one complex algebra calculation and is theoretically accurate except for the treatment of iron losses. (These cannot be covered with mathematical accuracy anyway.) The second method is shorter and easier to apply but with less theoretical accuracy. Calculations contrasting the 2 methods with test results and with standard analyses indicate that the shorter method is accurate enough for most routine work.

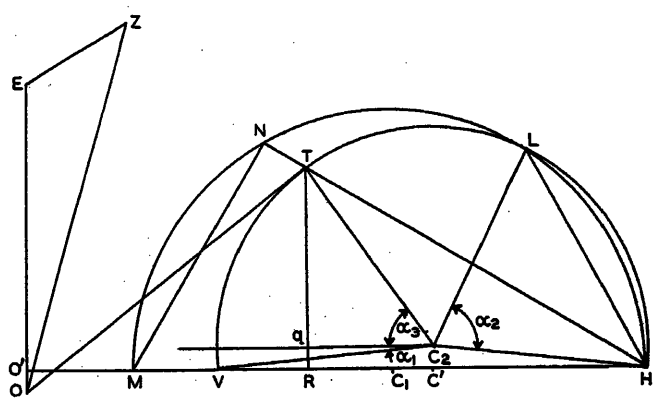



**Figure 1. Circle diagram of the single-phase induction motor, based on the cross-field theory**

Curve sheets will be shown here for 3 per cent slip only. Tabulated values suitable for preparing similar curves are given for other slips.

## Derivation of Maximum Torque Equation

The Branson[2] application of the La Tour type of circle diagram is represented in figure 1. On this diagram it can be shown that the maximum input to the rotor occurs when the point $T$ bisects the arc $VL$, the rotor input being

$$(OE) \times (TR)$$

$(OE)$ represents the voltage $E_c$, less than the applied voltage by the stator-winding resistance drop.

The maximum rotor input is not exactly the point at which the maximum torque occurs, but the difference is negligible in the single-phase induction motor and the equations will be derived on such an assumption.

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A. F. PUCHSTEIN is chief engineer and T. C. LLOYD is development engineer with Robbins & Myers, Inc., Springfield, Ohio.

1. For all numbered references, see list at end of paper.

To derive an expression for $TR$:

$$TR = C_2H \sin \alpha_3 + 0.5\ MV \frac{r_2}{X} \tag{1}$$

Let

$$\frac{r_2}{X} = p$$

The center $C_2$ is above the base by the distance $0.5\ MVr_2/X$

$$MV = O'M \frac{K_r}{2 - K_r} = \frac{E_c(1 - K_r)K_r}{X(2 - K_r)} \tag{2}$$

Then

$$0.5\ MV\frac{r_2}{X} = \frac{p}{2}\frac{E_c}{X}\frac{1 - K_r}{2 - K_r}K_r \tag{3}$$

$$C_2H = \sqrt{(C_2C')^2 + (C'\mathrm{H})^2} \tag{4}$$

$$VH = \frac{E_c}{X}\frac{K_r}{2 - K_r} \tag{5}$$

$$C_2H = \sqrt{\left(\frac{E_c}{2X}\frac{K_r}{2 - K_r}\right)^2 + \left(\frac{p}{2}\frac{E_c}{X}K_r\frac{1 - K_r}{2 - K_r}\right)^2} \tag{6}$$

$$\sin \alpha_3 = \frac{\cos\ \alpha_2}{2} = \sqrt{1 - \sin^2 \frac{\alpha_2}{2}} \tag{7}$$

$$\sin \frac{\alpha_2}{2} = \frac{p}{\sqrt{p^2 + 1}}\frac{2 - K_r}{\sqrt{1 + p^2(1 - K_r)^2}} \tag{8}$$

Then from equations 2, 6, 7, and 8:

$$TR = \frac{E_c}{X} \cdot \frac{K_r}{2(2 - K_r)} \times \left\{\sqrt{\left[1 + p^2(1 - K_r)^2\right]\left[1 - \frac{p^2(2 - K_r)^2}{(p^2 + 1)[1 + p^2(1 - K_r)^2]}\right]} + p(1 - K_r)\right\} \tag{9}$$

Define $tr$ such that $TR = (E_c/X)tr$. Values of $tr$ for various ratios of $r_2/X$ and values of $K_r$ are plotted in figure 2.

In order to apply the correction for the stator resistance drop it is necessary to determine the ratio of $E_c$ to the applied voltage $V$. To do this it is necessary to know the magnitude and position of the current $OT$. This depends obviously upon $O'R$ as well as $TR$ and an expression for $O'R$ will be obtained, applicable when the point $T$ bisects the arc $VL$. Under this condition:

$$O'R = \frac{E_c}{X} \cdot \left[1 - \frac{1}{2}\frac{K_r}{2 - K_r} - \frac{p}{2\sqrt{1 + p^2}}\right] \tag{10}$$

$O'O$ is the current component supplying the core losses; this can be neglected with little error, as it will make but slight modification in the magnitude of the current at the point of maximum torque, and still less modification in the ratio of voltages for which this value is to be used.

Define $o'r$ such that $O'R = (E_c/X)o'r$. Values are plotted in figure 2.

Let $r_1/X = p_1$. Then, accounting for the stator winding resistance drop:

$$V = E_c[1 + p_1(tr - jo'r)]$$

$$\left(\frac{E_c}{V}\right)^2 = \left(\frac{OE}{OZ}\right)^2 = \frac{1}{[(1 + p_1tr)^2 + (p_1o'r)^2]} \tag{11}$$

Let the expression in brackets be $Q'$. Then the final expression for maximum secondary input is

$$V^2\left(\frac{OE}{OZ}\right)^2\frac{tr}{X} = V^2\frac{tr}{Q'X} \tag{12}$$

As the last step it is necessary to fix the relationship between secondary input, secondary output, and torque.

$$\text{Secondary input} = \text{output} + F + Fe\ (C) + \text{Secondary } Cu\ (M) + \text{Secondary } Cu\ (C) \tag{13}$$

Where $(C)$ and $(M)$ represent cross and main axes, respectively.

Let

$$a = \frac{\text{Total secondary copper losses}}{\text{Output} + F + Fe\ (C)} \tag{14}$$

Then

$$\text{Output} = \frac{\text{Secondary input}}{(1 + a)} - [F + Fe\ (C)] \tag{15}$$

It has been shown by Veinott[3] that the ratio $a$ used above is equal to

$$\frac{1 - S^2}{S^2} + \frac{2(r_2/X_0)^2}{[(1 - S^2) - (r_2/X_0)^2]S^2}$$

This can also be written:

$$\frac{1 - S^2}{S^2} + \frac{2[p(1 - K_r)]^2}{[(1 - S^2) - p^2(1 - K_r)^2]S^2} = a$$

Where $S$ is the ratio of actual revolutions per minute to synchronous revolutions per minute. A value for $S$ at the point of maximum torque, as a function of $r_2/X$ is plotted in figure 3. This is slightly modified from Vei-

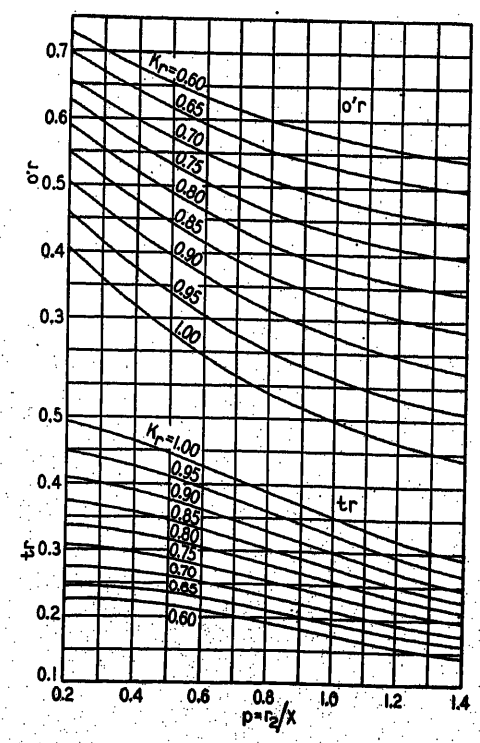



**Figure 2**

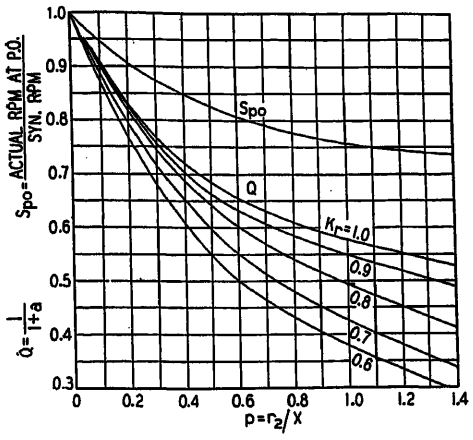



Figure 3

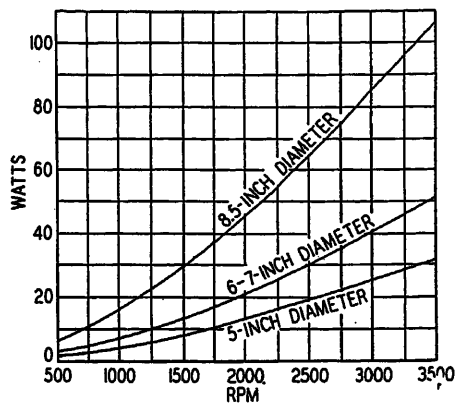



Figure 4. Friction and windage losses classified by outside diameter of stator. Sleeve bearings

nott's curve, which he obtained from the Branson circle diagram. Sumec[4] also gives a formula for this relationship but it applies to greatly restricted conditions.

Values of $1/(1+a)$ (denoted as $Q$) are shown in figure 3. As the final expression for maximum torque in ounce-feet:

$$\text{P. O. T.} = \frac{112.6}{\text{Syn. rpm}} \frac{1}{S_{po}} \left[ \frac{V^2}{X} tr \frac{Q}{Q'} - (F + Fe\,(C)) \right] \qquad (16)$$

The above equation is applicable when the windings are fixed and the constants are known. When the winding is to be determined in order to give a prescribed maximum torque, it should be such as to give the value of total leakage reactance calculated below. Then:

$$X = \frac{V^2\, tr\, Q/Q'}{\left[ \frac{\text{P. O. T.} \times \text{Syn. rpm} \times S_{po}}{112.6} + F + Fe\,(C) \right]} \qquad (17)$$

In using the above equation to design a single-phase motor of the required maximum torque, it is necessary to estimate the friction and windage losses as well as the iron loss of the cross axis. In making such estimates, data on similar machines are useful, but in the absence of such data table I is of value for iron-loss assumptions.

**Table I. Approximate Value of Cross-Axis Iron Losses**

| | | |
|---|---|---|
| 60 cycles: | Below 0.5 horsepower | $Fe\,(C) = 100 \times$ horsepower |
| | 0.5 to 1.5 horsepower | $Fe\,(C) = 50 \times$ horsepower |
| 25 cycles: | Below 0.5 horsepower | $Fe\,(C) = 75 \times$ horsepower |
| | 0.5 to 1.5 horsepower | $Fe\,(C) = 40 \times$ horsepower |

Probable friction and windage losses as a function of speed and outside stator diameter, are shown in figure 4.

It will be noted that $S_{po}$, $tr$, $Q$, and $Q'$ are functions of $r_1/X$, $r_2/X$, and $K_r$, each of which is independent of the actual number of conductors used in the stator winding as long as the saturation factor remains the same. A higher saturation factor reduces $K_r$.

Then since the total leakage reactance $X$ can be calculated from equation 17 in order for the motor to yield the designed pull-out torque, the number of series conductors necessary are:

$$C = \sqrt{\frac{X \cdot 10^8}{2\pi f P_L}} \qquad (18)$$

where $P_L$ = the equivalent permeance of the leakage flux paths (slot, zig-zag and end connection) corrected for winding pitch and distribution. Methods for determining it are well known, but a recent collection of data combining the work of various investigators has been prepared by the present writers,[5] along with processes for calculating $r_1/X$, $r_2/X$ and $K_r$ from machine dimensions.

The development given above involves no approximations aside from (1) those inherent in this type[2] of the circle diagram, (2) the neglect of iron-loss component in locating the position of the stator current, and (3) the slight error in the assumptions from which the speed

**Table II. Contrasted Test and Calculated Values**

Pull-out torque in ounce-feet

| Motor | P.O.T. Test | P.O.T. Calculated |
|---|---|---|
| 3/4-horsepower 4-pole 60-cycle | 107.00 | 104.0 |
| 1/4-horsepower 4-pole 50-cycle | 43.50 | 44.7 |
| 1/4-horsepower 4-pole 60-cycle | 37.75 | 36.8 |
| 1/4-horsepower 4-pole 60-cycle | 37.2 | 35.4 |
| 1/6-horsepower 2-pole 25-cycle | 30.0 | 32.0 |
| 1/10-horsepower 4-pole 40-cycle | 25.5 | 25.9 |
| 1/8-horsepower 2-pole 25-cycle | 23.0 | 23.0 |
| 1/6-horsepower 4-pole 60-cycle | 20.5 | 19.2 |

relationship was obtained.[3] That these errors are not serious can be seen from the contrasted results given in table II. Values were obtained from routine tests and were subject to uncorrected temperature effects and slight errors in constants.

As seen, the test and calculated results agree well within commercial requirements, particularly if $X$ can be calculated to sufficient precision.

An example of calculation is given in appendix I.

## Basis for Performance Calculations: Cross Field Theory

No attempt will be made to give the derivation of the cross-field theory on which the analysis is based, but since some differences exist between the work of different writers it will be necessary to identify the view-point taken.

The reader is referred to a paper by H. R. West,[6] in which he shows 3 fundamental equations for primary and

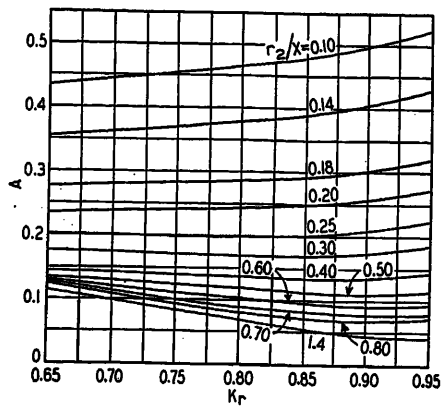



**Figure 5. Current constants for performance**

secondary voltage relationships in the single-phase motor. These are based on the assumptions:

1. Sine-wave distributions of magnetomotive force, and uniform air-gap permeances.

2. Angle of hysteretic lag between flux and magnetomotive force is neglected. (An approximate method of overcoming the small error caused by this assumption will be shown.)

3. The rotor conductors, in generating a speed electromotive force, are considered to cut not only the mutual flux but the rotor leakage flux as well. This assumption follows Arnold as against that of Steinmetz.[3] The evidence available indicates that the former basis is the more accurate, as signified by West.

4. The leakage reactance of stator and rotor will be assumed to be equal when in equivalent terms. The errors due to this are in general negligible.

## Equations

The determination of main and cross-axis rotor currents, as well as the stator current, is always complicated because the necessary simultaneous equations are three in number, and contain constants and variables as complex numbers. As a practical method of attack the local primary drop is neglected and a solution for the rotor values, which depend upon the counter electromotive force, is obtained. This also fixes the primary current, and the stator drop correction is applied later in a manner to be shown.

The 3 equations as given by West (several symbols changed) are:

$$V = I_1 r_1 + jI_1 x_1 + jX_m(I_1 - I_y) \tag{19}$$

$$0 = -jX_m(I_1 - I_y) - S(X_m + x_2)I_x + I_y(r_2 + jx_2) \tag{20}$$

$$0 = j(X_m + x_2)I_x - SX_m(I_1 - I_y) + Sx_2 I_y + r_2 I_x \tag{21}$$

It follows then that:

$I_1 - I_y = I_\phi$

$jI_\phi X_m$ = the counter electromotive force, $E$

Solving equations 20 and 21 for the 2 rotor currents:
Main axis,

$$I_y = E\frac{r_2 + jX_0(1 - S^2)}{r_2^2 - x_2(1 - S^2)X_0 + j(r_2 X_0 + r_2 x_2)} \tag{22}$$

Cross axis,

$$I_x = E\frac{-jr_2 S}{r_2^2 - x_2(1 - S^2)X_0 + j(r_2 X_0 + r_2 x_2)} \tag{23}$$

If the effect of the cross-axis core loss, which is considered as a rotor load (equal to slightly less than half of the total core loss) is taken into account, these equations would become (based on Arnold[8]):

$$I_y = E\frac{[(1 - S^2)(Z_0 + Z_2) + r_2 S^2]}{(Z_0 + Z_2)(Z_2 - jS^2 x_2) + jr_2 x_2 S^2} \tag{22a}$$

$$I_x = E\frac{-jr_2 S}{(Z_0 + Z_2)(Z_2 - jS^2 x_2) + jr_2 x_2 S^2} \tag{23a}$$

Where

$Z_2 = r_2 + jx_2$

$$Z_0 = \frac{1}{\frac{1}{r_f} + \frac{1}{jX_m}}$$

That is, the cross-axis core losses take place in an equivalent resistance, $r_f$; magnetizing reactance and core-loss resistance being represented by a series impedance $Z_0$. The use of these latter equations involving the additional variable $r_f$ would too greatly complicate the set of curves given here and will be neglected. Then $Z_0$ becomes equal to $-jX_m$.

Regardless of the magnitudes of the various constants in these equations, the values of $I_y$ and $I_x$ can always be obtained as functions of $E/X$ for all possible combinations of motor constants. Once such data are plotted they can then be used for practically all designs.

**Table III. Contrasted Calculated and Test Results**

Motor used as example in appendix

| Item | Method I | Method II | Test |
|---|---|---|---|
| Slip | 0.03 | 0.03 | |
| $I_1$ | 3.16 | 3.03 | 3.25 |
| Power factor | 0.595 | 0.619 | 0.585 |
| Input | 207.2 | 205.2 | 209.0 |
| $E$ | 90.5 | 91.0 | |
| $I_y$ | 2.04 | 2.045 | |
| $I_x$ | 1.145 | 1.15 | |
| Output | 0.158 horsepower | 0.159 | 0.1585 |
| Efficiency | 0.566 | 0.578 | 0.565 |
| Revolutions per minute | 1,164 | 1,164 | 1,150 |

## Determination of Curve Data

By substituting the values $r_2 = pX$ and $X_0 = X/(1 - K_r)$ in equations 22 and 23, they become:

$$I_y = \frac{E}{X}\left[\frac{p + j\frac{1 - S^2}{1 - K_r}}{p^2 - \frac{1 - S^2}{2(1 - K_r)} + j\left(\frac{p}{2} + \frac{p}{1 - K_r}\right)}\right] = \frac{E}{X}(A - jB) \tag{24}$$

$$I_x = \frac{E}{X}\left[\frac{-jpS}{p^2 - \frac{1 - S^2}{2(1 - K_r)} + j\left(\frac{p}{2} + \frac{p}{1 - K_r}\right)}\right] = \frac{E}{X}G \tag{25}$$

The values of the "current constants" $A$, $B$, and $G$, are functions of $r_2/X$, $K_r$, and speed. For any value of speed, curves can be drawn as shown in figures 5 and 6. These curves were prepared by assuming values of $p$ and $K_r$ for various slips and plotting the resultant current constants.

## Calculation of Performance, First Method

The fundamental equations neglect the effect of any iron loss in the cross axis. This will be considered here by adding an iron-loss current component to the in-phase part of the stator current.

**Table IV. Calculation Methods Contrasted**

1/4 horsepower, 4-pole, 60-cycle, 110-volts

| | Double Revolving Field | Cross Field Theory | | | |
|---|---|---|---|---|---|
| Item | Equivalent Circuit | Curves* of Method II | Modified[10] Arnold Method | Equivalent Circuit | Branson's Circle[2] Diagram |
| Speed | 1,700 | 1,700 | 1,700 | 1,700 | 1,700 |
| $I_1$ | 3.94 | 3.65 | 3.825 | 3.83 | 4.05 |
| Power factor | 0.734 | 0.762 | 0.737 | 0.722 | 0.745 |
| Input | 318.0 | 306.7 | 310.0 | 305.0 | 320 |
| Output | 197.0 | 203.3 | 199.0 | 203.2 | 198 |
| Efficiency | 0.620 | 0.66 | 0.642 | 0.665 | 0.630 |
| Losses | 121 | 103.4 | 111 | 101.8 | 122 |
| Synchronous watts | 208.4 | 215 | 211 | 215 | 210 |

* $A$, $B$, and $G$ were read for this speed from curves plotted against slip, rather than the set of curves given here, for which this slip is not included.

$$\text{In-phase current} = \frac{E}{X}A + \frac{Fe}{E}$$

$$= \frac{E}{X}(A') \qquad (26)$$

where

$$A' = A + \frac{FeX}{E^2}$$

Similarly the magnetizing current should be added to the out-of-phase component, then:

$$\text{Out-of-phase current} = \frac{E}{X}(B + 1 - K_r) = \frac{E}{X}U$$

Then the primary current is

$$\frac{E}{X}(A' - jU) = I_1 \qquad (27)$$

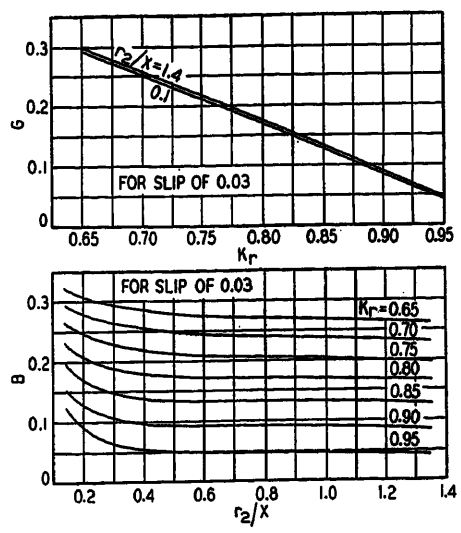
$$\text{Stator impedance} = r_1 + jx_1 = X(p_1 + j\,0.5)$$

$$\text{Applied voltage } V' = E[1 + (A' - jU)(p_1 + j\,0.5)]$$

As this voltage will likely be different from the applied, a ratio $V_{\text{rated}}$ to $V'$ is used to correct the assumed value of counter electromotive force.

With the counter electromotive force known, equations 24, 25, and 27 can be used to obtain the respective currents; input, output, efficiency, and power factor being figured in the usual manner as shown in appendix II. It will be seen that this process has been based simply upon the use of plotted solutions of rotor current.

**Figure 6. Current constants for performance**




## Second Method

In nearly all cases of normal design, it was found that little error is introduced in the vicinity of rated-load values, by assuming that the counter electromotive force differs from the applied voltage by the stator impedance drop considered algebraically. The in-phase component of stator current caused by considering the iron loss, will be neglected (as was done by West). Then:

$$I_1 Z_1 = E\sqrt{(A^2 + U^2)(p_1^2 + 0.25)} \qquad (28)$$

and

$$I_1 = \frac{V}{X}\frac{\sqrt{A^2 + U^2}}{[1 + \sqrt{(p_1^2 + 0.25)(A^2 + U^2)}]} \qquad (29)$$

Procedure: For the motor values of $r_2/X$ and $K_r$, at the slip for which performance is desired, $A$, $B$, and $G$ are calculated or read from the curves.

Calculate

$$U = B + 1 - K_r$$

$$C' = \sqrt{A^2 + U^2}$$

$$D = 1 + C'\sqrt{p_1^2 + 0.25}$$

Then

$$I_1 = \frac{V}{X}\frac{C'}{D}$$

$$\text{Power factor} = \frac{A}{C'} \text{ (See appendix III for correction based on iron loss)}$$

$$\text{Power input} = V \times I_1 \frac{A}{C'} \text{ (See appendix III for correction based on iron loss)}$$

$$\text{Counter electromotive force} = \frac{V}{D} = E$$

$$\text{Rotor input} = E^2\frac{A}{X}$$

$$I_y = \frac{E}{X}\sqrt{A^2 + B^2}$$

$$I_x = \frac{E}{X}G = I_1\frac{G}{C'}$$

Rotor losses $= r_2 (I_y^2 + I_x^2) + (F \& W) + Fe$

The iron loss $Fe$ can be treated differently and need not be included above.

Rotor output = Input − losses

By this process all significant performance items can be obtained at any speed for which curves are prepared. Simple arithmetical ratios are used, complex numbers being completely avoided.

Some comment should be made upon the treatment of core loss. Theoretically the cross-axis core loss (slightly less than half of the total) should appear as rotor load and be subtracted from the output. The subtraction of the total core loss (assumed constant at all loads), from the rotor output is not theoretically justified but produces fair results except in extreme cases. The reduction of core loss with load increase, due to a reduction in counter electromotive force, can be made in either method shown above, inasmuch as the counter electromotive force is known. Then since rotor currents and hence rotor input, were calculated with the assumption of no core loss, the addition of a reduced core loss to the stator input would appear to be a more consistent treatment than subtraction from the rotor output.

The neglect of this core loss results in calculated power factors that are inclined to be low, and more accurate results can be obtained by multiplying power factor, as calculated, by the ratio.

$$\frac{\text{Stator input with core loss}}{\text{Stator input without core loss}}$$

Illustrative examples and comparative results are given in appendix III.

## Conclusion

Calculations shown in tables III and IV are taken from design-sheet data in which later tests indicated a fair, but not exact, agreement between predicted motor constants and the values as measured. Under these conditions discrepancies between final test performance and predicted performance include the results of small design-sheet errors. Examples are available in which better agreement exists between predictions and tests but those included here were selected as about representative.

Designers are well aware that in dealing with small single-phase induction motors, predictions of performance cannot be made with the consistent accuracy possible, say, with large polyphase machines. This is true regardless of the theoretical accuracy of the method employed; the discrepancies arise largely from the nonconstant nature of the so-called constants. For this reason the accuracy of the calculation methods given here can best be investigated by comparison with other established analysis. Such data are given in table IV.

**Table V. Calculated Values of $A^2$**

| $r_2/X$ = | 0.2 | 0.25 | 0.30 | 0.40 | 0.50 | 0.60 | 0.80 | 1.00 | 1.40 |
|---|---|---|---|---|---|---|---|---|---|
| **Slip = 0.02** | | | | | | | | | |
| $K_r$ = 0.95 | 0.190 | 0.154 | 0.128 | 0.096 | 0.076 | 0.065 | 0.049 | 0.041 | 0.030 |
| 0.90 | 0.182 | 0.148 | 0.123 | 0.095 | 0.077 | 0.067 | 0.053 | 0.044 | 0.038 |
| 0.85 | 0.177 | 0.144 | 0.122 | 0.095 | 0.080 | 0.071 | 0.060 | 0.053 | 0.050 |
| 0.80 | 0.173 | 0.141 | 0.122 | 0.096 | 0.084 | 0.077 | 0.070 | 0.065 | 0.065 |
| 0.75 | 0.169 | 0.141 | 0.122 | 0.099 | 0.089 | 0.084 | 0.080 | 0.079 | 0.084 |
| 0.70 | 0.167 | 0.141 | 0.123 | 0.103 | 0.094 | 0.091 | 0.091 | 0.094 | 0.104 |
| **Slip = 0.04** | | | | | | | | | |
| $K_r$ = 0.95 | 0.370 | 0.296 | 0.255 | 0.193 | 0.150 | 0.129 | 0.100 | 0.080 | 0.059 |
| 0.90 | 0.349 | 0.278 | 0.238 | 0.180 | 0.143 | 0.121 | 0.097 | 0.078 | 0.061 |
| 0.85 | 0.335 | 0.270 | 0.230 | 0.177 | 0.145 | 0.125 | 0.102 | 0.085 | 0.073 |
| 0.80 | 0.327 | 0.265 | 0.229 | 0.178 | 0.149 | 0.130 | 0.112 | 0.100 | 0.090 |
| 0.75 | 0.320 | 0.262 | 0.228 | 0.179 | 0.153 | 0.135 | 0.124 | 0.114 | 0.108 |
| 0.70 | 0.310 | 0.257 | 0.225 | 0.179 | 0.158 | 0.140 | 0.133 | 0.127 | 0.124 |
| **Slip = 0.05** | | | | | | | | | |
| $K_r$ = 0.95 | 0.454 | 0.375 | 0.314 | 0.234 | 0.190 | 0.160 | 0.122 | 0.097 | 0.066 |
| 0.90 | 0.435 | 0.359 | 0.301 | 0.228 | 0.183 | 0.155 | 0.122 | 0.100 | 0.076 |
| 0.85 | 0.420 | 0.345 | 0.292 | 0.221 | 0.180 | 0.157 | 0.125 | 0.105 | 0.088 |
| 0.80 | 0.405 | 0.335 | 0.285 | 0.216 | 0.181 | 0.160 | 0.132 | 0.114 | 0.100 |
| 0.75 | 0.392 | 0.330 | 0.283 | 0.217 | 0.181 | 0.161 | 0.140 | 0.125 | 0.116 |
| 0.70 | 0.383 | 0.326 | 0.283 | 0.220 | 0.183 | 0.165 | 0.149 | 0.137 | 0.135 |

**Table VI. Calculated Values of B**

| $r_2/X$ = | 0.2 | 0.3 | 0.4 | 0.6 | 0.8 | 1.0 | 1.2 | 1.4 |
|---|---|---|---|---|---|---|---|---|
| **Slip = 0.02** | | | | | | | | |
| $K_r$ = 0.95 | 0.066 | 0.058 | 0.051 | 0.048 | 0.047 | 0.046 | 0.046 | 0.046 |
| 0.90 | 0.109 | 0.101 | 0.096 | 0.092 | 0.090 | 0.090 | 0.089 | 0.088 |
| 0.85 | 0.150 | 0.144 | 0.141 | 0.137 | 0.133 | 0.132 | 0.131 | 0.130 |
| 0.80 | 0.191 | 0.184 | 0.180 | 0.176 | 0.174 | 0.171 | 0.170 | 0.167 |
| 0.75 | 0.233 | 0.226 | 0.220 | 0.214 | 0.210 | 0.207 | 0.203 | 0.199 |
| 0.70 | 0.270 | 0.261 | 0.255 | 0.248 | 0.244 | 0.240 | 0.233 | 0.225 |
| **Slip = 0.04** | | | | | | | | |
| $K_r$ = 0.95 | 0.113 | 0.080 | 0.060 | 0.048 | 0.048 | 0.047 | 0.047 | 0.046 |
| 0.90 | 0.160 | 0.120 | 0.105 | 0.094 | 0.092 | 0.091 | 0.090 | 0.089 |
| 0.85 | 0.190 | 0.155 | 0.145 | 0.135 | 0.132 | 0.130 | 0.129 | 0.127 |
| 0.80 | 0.225 | 0.195 | 0.185 | 0.175 | 0.171 | 0.170 | 0.170 | 0.164 |
| 0.75 | 0.255 | 0.235 | 0.222 | 0.213 | 0.210 | 0.209 | 0.205 | 0.197 |
| 0.70 | 0.295 | 0.273 | 0.260 | 0.249 | 0.245 | 0.243 | 0.238 | 0.225 |
| **Slip = 0.05** | | | | | | | | |
| $K_r$ = 0.95 | 0.145 | 0.097 | 0.076 | 0.058 | 0.051 | 0.048 | 0.047 | 0.045 |
| 0.90 | 0.188 | 0.135 | 0.114 | 0.098 | 0.094 | 0.092 | 0.090 | 0.088 |
| 0.85 | 0.224 | 0.175 | 0.155 | 0.138 | 0.133 | 0.131 | 0.130 | 0.129 |
| 0.80 | 0.257 | 0.207 | 0.186 | 0.177 | 0.173 | 0.170 | 0.167 | 0.163 |
| 0.75 | 0.286 | 0.245 | 0.224 | 0.210 | 0.207 | 0.200 | 0.198 | 0.193 |
| 0.70 | 0.323 | 0.281 | 0.263 | 0.245 | 0.239 | 0.232 | 0.227 | 0.217 |

## Symbols and Factors

$V$ = applied voltage
$r_1$ = stator-winding resistance
$r_2$ = rotor resistance in stator terms
$x_1$ = stator-winding leakage reactance
$x_2$ = rotor leakage reactance in stator terms
$X_m$ = mutual or magnetizing reactance in stator terms
$X_0 = X_m + x_1$
= magnetizing reactance for air gap and primary leakage fluxes
$K_r = \dfrac{X_0 - X}{X_0}$
$X \cong x_1 + x_2$
$= x_1 + \sqrt{K_r}\, x_2$
$F$ = watts, friction and windage
$Fe$ = watts, core loss
$E_c = V - I_1 r_1$ (as vectors)
$E$ = counter electromotive force
$I_1$ = primary current
$I_y$ = rotor current of the main axis in stator terms
$I_x$ = cross-axis rotor current in stator terms
$S$ = per cent of synchronous speed

$S_{po}$ = per cent of synchronous speed at which maximum torque occurs

$p = r_2/X$

$p_1 = r_1/X$

$$tr = \frac{K_r}{2(2-K_r)} \times \left\{ \sqrt{\left[1 + p^2(1-K_r)^2\right]\left[1 - \frac{p^2(2-K_r)^2}{(p^2+1)[1+p^2(1-K_r)^2]}\right]} + p(1-K_r) \right\}$$

This is plotted in figure 2.

$$o'r = \left\{1 - 0.5 \cdot \frac{K_r}{2-K_r} - \frac{p}{2\sqrt{1+p^2}}\right\}$$

This is plotted in figure 2.

$$Q' = [(1 + p_1\, tr)^2 + (p_1\, o'r)^2]$$

$$Q = \frac{1}{1+a}$$

$$a = \frac{\text{Total secondary copper losses}}{\text{output} + F + Fe\,(C)}$$

This is plotted in figure 3.

$C$ = series conductors of the stator winding

$P_L$ = equivalent permeance of the leakage flux paths

$A$ = in-phase portion of the "current constant"

$$A - jB = \left\{ \frac{p + j\left(\frac{1-S^2}{1-K_r}\right)}{p^2 - \frac{1-S^2}{2(1-K_r)} + j\left(\frac{p}{2} + \frac{p}{1-K_r}\right)} \right\}$$

This is plotted in figures 5 and 6.

$$G = \left\{ \frac{-jpS}{p^2 - \frac{1-S^2}{2(1-K_r)} + j\left(\frac{p}{2} + \frac{p}{1-K_r}\right)} \right\}$$

This is plotted in figure 6.

$$A' = A + \frac{Fe\,X}{E^2}$$

$$U = (B + 1 - K_r)$$

$$C' = \sqrt{A^2 + U^2}$$

$$D = 1 + C'\sqrt{p_1^2 + 0.25}$$

## Appendix

*I. Example of Maximum Torque Calculations.* Machine data are taken from the example given by Veinott[1] for a single-phase induction motor, 110 volts, 4 poles, 60 cycles.

$r_1 = 3.8$ $\quad r_2 = 4.65$ $\quad X = 8.3$ $\quad K_r = K_p^2 = 0.929$

$F + Fe\,(C) = 19$ watts

$r_1/X = p_1 = 0.458$ $\quad r_2/X = p = 0.56$

From curves:

$tr = 0.392$, $o'r = 0.342$, $Q = 0.65$, $S_{po} = 0.817$, $(1 + p_1\, tr)^2 = 1.387$ $\quad (p_1\, or)^2 = 0.0246$ $\quad Q' = 1.387 + 0.0246$ or 1.4116

**Table VII. Approximate Values of G**

| Slip = | 0.02 | 0.04 | 0.05 |
|---|---|---|---|
| $K_r$ = 0.95 | 0.049 | 0.049 | 0.047 |
| 0.90 | 0.093 | 0.091 | 0.090 |
| 0.85 | 0.135 | 0.131 | 0.130 |
| 0.80 | 0.175 | 0.171 | 0.168 |
| 0.75 | 0.215 | 0.210 | 0.205 |
| 0.70 | 0.250 | 0.245 | 0.240 |

$$\text{P. O. T.} = \frac{112.6}{1800 \times 0.817}\left[\frac{110^2 \times 0.392 \times 0.65}{8.3 \times 1.411} - 19\right]$$

= 18.6 ounce-feet. This result is the same as that of Veinott.

*II. Performance Calculations, First Method.* Single-phase induction motor, 1/6-horsepower, 110 volts, 6 poles, 60 cycles.

$r_1 = 3.95$ ohms $\quad X = 9.72$ ohms $\quad r_1/X = p_1 = 0.406$

$r_2 = 3.07$ ohms $\quad K_r = 0.862$ $\quad r_2/X = p = 0.315$

Friction and windage ($F$ and $W$) = 9 watts; iron loss ($Fe$) = 29.4 watts; from curves, for a slip of 0.03, $A = 0.170$, $B = 0.138$, $G = 0.123$

$B + 1 - K_r = U = 0.276$

$\sqrt{A^2 + B^2} = 0.219$

Assume a counter electromotive force of 100 volts.

$\frac{Fe\,X}{E^2} = 0.026$ $\quad A' = 0.196$

$V' = 100[1 + (0.196 - j\,0.276)(0.406 + j\,0.5)] = 121.78 - j\,1.68 = 121.8$

$\text{Correction} = \frac{110}{121.8}$ or 0.905

$I_1 = \frac{90.5}{9.72}(0.196 - j\,0.276) = 1.82 - j\,2.58$ or 3.16

$I_y = \frac{90.5}{9.72}\,0.219 = 2.04$ $\quad I_y^2 r_2 = 12.72$ watts

$I_x = \frac{90.5}{9.72}\,0.123 = 1.145$ $\quad I_x^2 r_2 = 4.02$ watts

$\text{Rotor input} = EI_y \cos\theta_2 = 90.5 \times 2.04 \times \frac{0.17}{0.219}$ or 143.5 watts.

Rotor output = 143.5 − rotor losses = 143.5 − (12.72 + 4.02 + 9.0)
= 117.8 watts or 0.158 horsepower

$\text{Core loss} = \frac{\text{counter electromotive force}}{\text{applied voltage}}\,(Fe)$

$= \frac{90.5}{110} \times 29.4$ or 24.3 watts.

Stator input = Rotor input + Core loss + Stator copper loss
= 143.5 + 24.3 + 39.4 or 207.2 watts.

$\text{Power factor} = \frac{207.2}{3.16 \times 110}$ or 0.595

Alternate method, neglecting small angle between applied volts and counter electromotive force

$\text{Power factor} = \frac{1.82}{3.16}$ or 0.575

$\text{Efficiency} = \frac{117.8}{207.2}$ or 0.566

*III. Performance Calculations, Second Method.* Same motor used in II with a slip of 0.03.

$A = 0.17 \qquad B = 0.138 \qquad G = 0.123 \qquad U = 0.276$

$$C' = \sqrt{A^2 + U^2} = 0.324$$

$$D = 1 + C'\sqrt{p_1^2 + 0.25} = 1.209$$

$$I_1 = \frac{V}{X}\frac{C'}{D} = 3.03$$

$$\text{Counter electromotive force} = \frac{V}{D} = 91.0$$

$$\text{Rotor input} = E^2\frac{A}{X} = 144.7 \text{ watts}$$

$$I_y = \frac{E}{X}\sqrt{A^2 + B^2} = 2.045 \qquad I_y^2 r_2 = 12.85 \text{ watts}$$

$$I_x = \frac{E}{X}G = 1.15 \qquad I_x^2 r_2 = 4.05 \text{ watts}$$

$$\begin{aligned}\text{Rotor output} &= \text{Input} - \text{rotor losses} \\ &= 144.7 - (12.85 + 4.05 + 9.0) \\ &= 118.8 \text{ watts or } 0.159 \text{ horsepower}\end{aligned}$$

Core loss, corrected as before = 24.3 watts

$$\begin{aligned}\text{Stator input} &= \text{Rotor input} + \text{Core loss} + \text{Stator copper loss} \\ &= 205.2 \text{ watts}\end{aligned}$$

$$\text{Efficiency} = \frac{118.8}{205.2} \text{ or } 0.578$$

$$\text{Power factor} = \frac{205.2}{3.03 \times 110} \text{ or } 0.619$$

Alternate calculation method for input and power factor:

$$\text{Input, neglecting core loss} = VI_1\frac{A}{C'} \text{ or } 175 \text{ watts}$$

Corrected by adding core loss = 199.3 watts

$$\text{Power factor, core loss neglected} = \frac{A}{C'} = 0.526$$

$$\text{Power factor corrected for core loss} = \frac{A}{C'}\frac{\text{Input with core loss}}{\text{Input without core loss}}$$

$$= 0.526\,\frac{199.3}{175} \text{ or } 0.60$$

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# The Engineer's English

IN AN ARTICLE entitled "The Importance of English to an Engineer," appearing in *The Electric Journal* for February 1937, pages 81–2, W. W. Palmer challenged engineers to assume as an obligation to themselves and to society, in which they are playing a rôle of increasing importance, the aim of becoming fluent speakers, more convincing writers, to the end of becoming better salesmen of the ideas constantly being created by their inventive minds.

Mr. Palmer believes that the engineer's inability to express himself forcefully is not an inherent characteristic, but a product of the environment and tradition in which he has received his professional training; and to strengthen that contention he traces the various stages in the evolution of an engineer, showing the factors at each stage contributing to the inarticulateness of the technical man. Quoting from the article, ". . . there is no objection to an engineer being given a cultural education, but the old idea that he must learn to write and speak a couple of dead languages and study the lives, characteristics, and vaporing of poets and writers of all ages has been overstressed."

Continuing, the author execrates the manner in which the engineering graduate attempts to obtain employment: "The employment manager, knowing engineers, expects their written applications to be evasive on their weak points and exaggerated on what they consider their strong ones. The general attempt is to prove that they can fill any position. . . . . No specific and sound reasons are given as to why the writer's services will pay dividends. The writer does not intentionally evade, but he is simply incapable of properly presenting his case in writing. . . . . Few engineers sell their services. They are hired. The distinction is reflected in their salaries."

After the young engineer has been hired "lack of practical experience necessitates that at first he work among those whose educational advantages have been inferior to his own. From them he frequently acquires the use of profanity for emphasis and superlatives for impressiveness. Enunciation and precision are forgotten. This loss is reflected in his work."

"Years later we find this engineer writing important purchase specifications that will be misinterpreted; dictating letters in which the ideas to be conveyed are smothered beneath an avalanche of words. To him punctuation is a stenographic function. At this age the engineer's work has become so specialized that few in, or outside of, his group of associates are capable of correcting or criticizing. . . . He speaks a highly technical language that normally isolates him from general conversations. He becomes a lone thinker but at the same time he must be able to interpret the results of his thoughts to less technical thinkers, such as his executives."

"We like to feel that engineers have been, and always will be, true pioneers in the advance of civilization. On the other hand, we know that those who lead best are often misunderstood, inadequately appreciated, and poorly compensated. The blame is our own when we do not make ourselves understood."

# D-C Machine Stray-Load-Loss Tests

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## Synopsis

Two test methods for the determination of stray load losses in d-c machines are described. Application of the loading-back principle permits measurements to a high degree of accuracy. A technique is developed for stabilizing no-load losses so that consistency of results is improved. Results of tests of several machines are presented, together with an analysis of the relation of loss to operating conditions of the machine.

IN THE MEASUREMENT of efficiency of d-c machinery, stray load loss is generally receiving insufficient consideration. Its omission from conventional efficiency tests has resulted principally from the difficulty experienced in measuring it accurately. Variability in performance of the commutator apparently is the factor which has caused failure to obtain consistent results in previous attempts to measure stray load loss.[1-5] Consequently the accurate determination of d-c machine losses and efficiency has lagged behind that of other types of machinery.

Methods of controlling the performance were devised and applied to d-c machines in the course of work on stray load loss of induction machines,[6] in which it was found possible to repeat conditions and measurements almost at will. The present investigation was undertaken to extend this experience and information to the testing of other machines, and to demonstrate the applicability of the loading-back type of test to d-c machines.

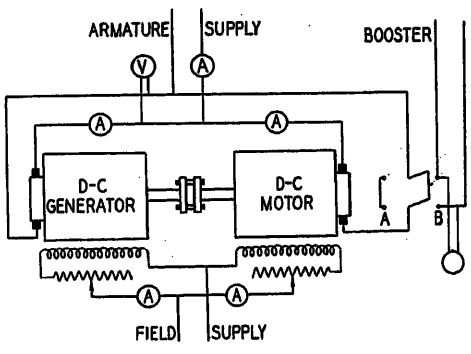



**Figure 1. Diagram of connections for load-back tests**

The load-back test is a familiar tool used extensively for loading machines and conducting heat runs. Two machines are direct-connected and operated from a common source with current circulating between them, one machine acting as a motor to drive the other as a generator. Slight adaptations which are necessary for applying it to the measurement of stray load loss are discussed. Two types of load-back test which are most practicable and easily performed commercially are described, together with the technique which should permit obtaining consistent results. The variation of stray load loss with some of the operating conditions is investigated, and curves are presented to show these effects graphically.

## Summary

This investigation of stray load loss in d-c machines outlines methods whereby that loss may be measured, and presents the results of application of some of those methods to several groups of machines as described in table I. Several definite conclusions may be drawn from this work:

1. Stray load loss is not a negligible factor in d-c machine performance and efficiency. It is in the order of magnitude of other losses and must receive due consideration.

2. Stray load loss can be measured, and should be measured in preference to the assignment of a value from an empirical formula.[4,5]

3. Stray load loss was found by test to range from 0.8 to 1.8 per cent of full-load input in several groups of machines.

4. Controlling factors of the amount of stray load loss are armature current, magnetic field strength, and machine speed.

5. The familiar load-back test can be adapted to the measurement of stray load losses in d-c machines. It can be made with the assurance of reasonably consistent results if proper technique be employed to eliminate variations in no-load losses during the test.

6. Two methods of loading-back appear to be the most practicable for commercial tests, from the standpoint of accuracy, convenience, and amount of equipment involved. The choice of test to be used will depend upon the equipment available to the tester.

7. The "electrical loss supply" method with a booster (Hutchinson method[7]) has the desirable feature of keeping armature currents nearly equal in both machines and of permitting loading of machines under the same conditions of excitation. It has the disadvantage of requiring an additional generator to serve as a booster. It involves input to the system from 2 electrical sources, thus doubling the chance for error in measurements.

8. The "electrical loss supply" (Kapp[7]) method has the simplest circuit available for the measurement of stray load loss. It can be performed with a minimum of equipment, although greater convenience may be achieved with 2 independent sources of voltage for armature and field circuits respectively.

9. Having only one source of supply for the losses, the Kapp method has the advantage of high accuracy and sensitivity.

10. Load-back methods usually require identical machines, but if one machine is available which has been calibrated previously for its stray load loss, any other machine of similar rating may be loaded-back upon it.

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The author is indebted to Professor Theodore H. Morgan for his advice and encouragement and for the opportunity to do this work, and to the manufacturers who donated machines for the tests.

1. For all numbered references, see list at end of paper.

## Nature of Stray Load Loss

By definition, stray load loss is a residual loss that cannot be determined from "conventional performance" data taken at no load. It is the increase in loss that results from loading of the machine by increase in armature current. The flux distortion accompanying increases in armature current gives rise to this loss through far-reaching effects. The iron loss is changed; eddy currents occur in the conductors due to transverse fluxes and to tooth saturations; tooth-frequency losses are changed to some extent; and short-circuit loss in the coils undergoing commutation is changed. These effects are dependent in turn upon the amount of armature current; the frequency of flux pulsations and hence the speed of the machine; and upon the saturation of the iron at no load.

**Table I. Machines Tested for Stray Load Loss**

| Machines | Rating | Voltage | Current (Amperes) | Speed (RPM) | Stray Load Loss (Per Cent of Full-Load Input) |
|---|---|---|---|---|---|
| 1 and 2 | 15 hp | 230 | 55.6 | 1,750 | 1.2 |
| 3 and 4 | 10 hp | 110 | 79 | 1,700 | 1.6 |
| 5 and 6 | 10 hp | 220 | 38.2 | 1,750 | 0.95 |
| 7 | 10 hp | 230 | 38 | 1,750 | 0.85 |
| 8 and 9 | 7.5 kw | 160 | 47 | 1,800 | 1.8 |

Information as to the manner in which these factors influence the loss is helpful in devising test methods. It is desirable and usually necessary to include measurements of the loss at other than only normal operating speed, armature current, or excitation. This investigation therefore attempts to determine some of these relationships in order to bring out the significance of certain procedures required in some of the tests available.

## Load-Back Tests

The load-back test has long been used for loading machines in heat runs and to a certain extent for efficiency measurements. It was originated as early as 1886,[8] and several variations have been proposed since then. A brief discussion will serve to identify some of the methods and their salient features. More complete descriptions are to be found in the engineering literature.[7]

### Kapp Method

In their simplest form, load-back tests are made with rotors of 2 machines coupled or belted together. Both armatures are connected to a common source of power, the machines being loaded-back upon each other by means of current circulating between them. The loading is controlled by adjustment of the internal generated voltage of either or both machines, the one with the lower excitation becoming the motor. Assuming for purposes of this discussion that the field circuits are separately excited, the entire loss in this combination of machines is supplied electrically from the line, and includes the no-load losses of both machines plus the additional losses occasioned by the assumption of load. The machine acting as a motor thus supplies all of the losses through its circuit, and hence has the larger armature current. The difference between machine currents, however, decreases as the size of the units increases.

This method, attributed to Kapp and also called the "electrical loss supply" method uses the circuit shown in figure 1 when the switch in the motor circuit is in the *A* position. The total losses are determined from readings of the line ammeter, which indicates automatically the difference in machine currents. This test provides for measurements of high accuracy and considerable sensitivity to small changes in loss. Its principal disadvantage is that the 2 machines cannot be operated at the same magnetic saturation.

### Hutchinson Method

If a booster generator be placed in series with the armature of one machine, the loading-back of the system may be accomplished through adjustment of the booster voltage in such a way as to cause different voltages to exist at the terminals of the 2 machines. The connection for this is shown in figure 1 with the switch at *B*. Current thus will circulate without the necessity for adjustment of the internal generated voltage of either machine. The power input to the system from the booster will be approximately equal to the copper losses in the 2 machines. Mechanical losses will be supplied substantially as in the Kapp test, from the common voltage source. Thus the armature currents under load conditions will be nearly equal, and the field excitations will be exactly the same in both machines. Only one additional instrument is needed, a voltmeter indicating the booster voltage where it is impressed on the load-back system.

This type of test is known as the Hutchinson method. It operates the machines under quite desirable conditions, but does require an additional generator in the testing equipment. The total loss input from which stray load loss is calculated comes from 2 sources, however, which necessitates additional care in the reading of all instruments.

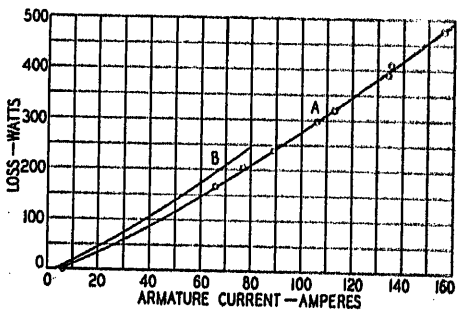



**Figure 2. Stray load loss of machines 1 and 2**

*A*—Loss as measured by load-back tests

*B*—Loss for one machine

Excitation normal

Speed—1,800 rpm

### Other Methods

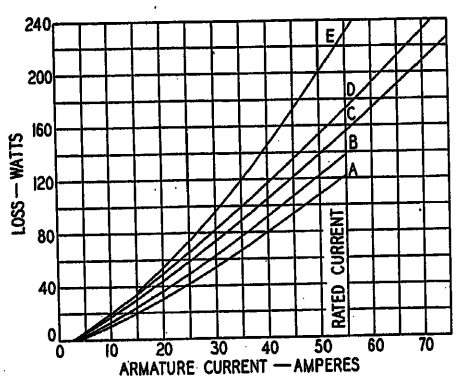
There are other types of load-back test which could be used, if the greater complication of circuits and possible loss of accuracy did not make them unsatisfactory for

commercial stray-load-loss measurements. The Blondel opposition method, in which an auxiliary motor connected to the set is used to supply the rotation losses and a booster to supply the electrical losses, does operate both machines under identical conditions. It is better suited to laboratory use than to commercial tests. Another method, called the "mechanical loss supply" method, uses the auxiliary motor coupled to the machines to supply all losses, the machines being operated independently of any common source. The adjustment of loading must be made entirely by manipulation of field current, thus making it undesirable as a test for stray load loss. The same objection applied to the Potier method, in which all the losses are supplied by a booster generator in series with both machines.

## Load-Back Test Procedure

In order to adapt the load-back test to the measurements of stray load loss, certain simplifications can be made in the usual test procedure employed. The requirements as to conditions to be maintained are different. Values of the loss are desired over the ordinary working range of armature current, speed, and excitation. It is therefore unnecessary to operate the machine with rated terminal voltage. Thus speed control may be had by variation of the armature voltage, and independently of field current adjustments. As loss in the field circuit is not included in the calculations for stray load loss, it is possible for it to be supplied from an independent source at constant voltage.

**Figure 3. Variation of stray load loss with excitation, machines 1 and 2**

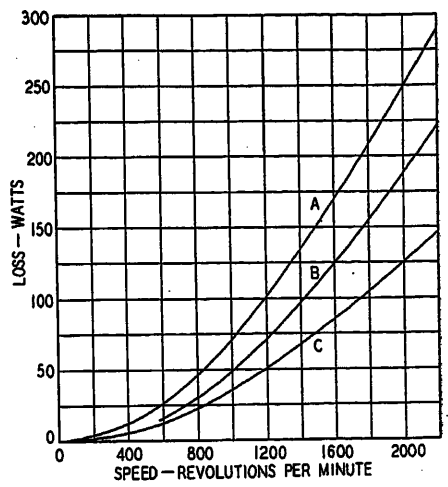



Speed—1,800 rpm
Excitation:
*A*—129 per cent normal
*B*—114 per cent normal
*C*—Normal
*D*—86 per cent normal
*E*—28 per cent normal

The control of all losses during a load-back test is very important to the success of the test. Since the stray load loss results from the difference between total measured loss and the known losses, variation of any of these during a run may cause considerable error in the final result.

The most important item requiring control is the brush-friction loss. This loss ordinarily is quite erratic, and causes the no-load loss of which it is a part to be unstable. In these tests it is not necessary that no-load losses duplicate those for ordinary working conditions, but merely that they be held constant during measurements of other quantities. Control of this brush-friction loss may be had by stabilizing surface conditions of the commutator. This is done through a judicious application of paraffin to the commutator to form a thin lubricating film. Paraffin is applied in quantities only sufficient to reduce the friction loss and consequently the no-load loss to a minimum, as indicated by input to the machines for a particular speed and excitation. For short periods of time, the no-load loss will then remain practically constant, but will gradually increase as the film of paraffin wears off. Frequent checks of the no-load loss are quite essential to consistent results in all tests. Where curves of no-load losses with various field currents and speed will be necessary as in tests conducted according to the Kapp method, they will be useful only so long as the original conditions are repeated.

**Figure 4. Variation of stray load loss with speed, machines 1 and 2**




Excitation—Normal
Armature current:
*A*—70 amperes
*B*—55 amperes (rated)
*C*—40 amperes

The use of paraffin on the commutator is practically indispensable for stray load loss testing. It is doubtful whether this treatment should be recommended for general practice, however. As to the effect on brush-contact resistance, paraffining does not make it abnormally large. Apparently carbon particles become imbedded in the thin film and assist in maintaining good commutation.

Accurate determination of copper loss in the machines is also very important to the stray-load-loss test. Actual values of terminal-to-terminal drop must be measured instead of being calculated on the basis of assumed constant values of brush-contact drop. Care must be taken to include the drops in all parts of the machine circuits back to the junction where applied voltage is measured.

Proper specification of the magnetic saturation also is necessary, particularly where machines have compound field windings. Total ampere-turns determine the field strength; so it is better for purposes of this test to omit the series windings and retain only the shunt and commutating windings. More stable operation of machines is obtained as a result of this procedure. Brushes must be set carefully in the neutral position to eliminate undue loss in the commutated coils.

## Test of Machines

Measurements were made for the stray load loss of several sets of machines as described in table I. All machines are stock models of their type. Machines 3, 4, and 7 are of the same type as 5 and 6 except older and of different voltage ratings. Number 7 was loaded back on number 5. All machines were mounted on a solid base, carefully aligned and direct-connected through flexible couplings.

Electrical connections were made as shown in figure 1. A variable voltage supply was provided for the armatures, and a fixed voltage supply for the shunt fields. The booster, used in all tests except on machines 8 and 9, was a variable voltage machine of suitable capacity. Instruments were calibrated against primary standards. Speeds were measured by stroboscope where feasible, otherwise by tachometer, so that it was convenient to consider 1,800 rpm as the normal speed of all machines.

As a preliminary to the testing of each pair of machines, the brushes were set in the neutral position as found by running the machines successively under full load in opposite directions at the same speed. The brushes were worn in and the commutator was lubricated with paraffin until a stable value of no-load loss was reached. Curves of no-load loss were then taken for various speeds and excitations.

The sequence of operations in the Hutchinson test was first to warm the machines by running them under load. Then both were motored and a setting made so that currents were equal in both machines with excitation adjusted to a specified value. The value of the no-load loss was read, the switch in figure 1 thrown to the $B$ position, and the booster voltage increased in gradual steps to increase the loading, speed being maintained at a desired value by adjustment of the supply voltage. A final reading was then taken of the no-load loss and the machines were shut down quickly to obtain the terminal-to-terminal drop. On some sets of machines, other data were taken for loading the machines by the Kapp method, with the motor switch always in the $A$ position.

## Results of Tests

The data obtained in these tests were reduced to stray load loss by subtracting all of the known losses from the power input of the line, and of the booster when used. Curves shown in figures 2–4 are for the test of machines 1 and 2 by the booster (Hutchinson) method and are typical of results of tests on all machines. Figure 2 shows the loss under normal conditions of speed and excitation. Curve $A$ shows the experimental points, which give the loss for both machines acting together, plotted as a function of the arithmetical sum of armature currents. The curve $B$, for one machine by itself, is obtained by a graphical separation method.[9] Briefly, the first approximation of curve $B$ is found by plotting one-half of the ordinate of $A$ against half of its abscissa. Using the actual ratio of machine currents, this approximation is used to reconstruct a curve similar to $A$. One-fourth of the difference between the reconstruction and the experimental curve is used as a correction by which to find the true curve of $B$. Actually, in all of the tests performed the armature currents were sufficiently close in value, and such was the nature of the variation of the loss that very little correction was necessary.

The change of stray load loss with armature current, other conditions being constant, follows a smooth progression, with the loss increasing at a greater rate for larger currents. This is what might be expected, but it is interesting to note that it does not increase with the square of the current, as might first be supposed.

### Variation With Excitation

In figure 3 are shown curves for the loss of one machine alone with various field currents. These curves are similar to curve $B$ of figure 2, and are those derived from experimental points by graphical separation. From them, it is apparent that stray load loss increases as the excitation or magnetic saturation is reduced. This effect was observed to differing degrees in all machines tested. The explanation is probably that flux distortion has farther-reaching effects in producing stray load loss as the initial saturation of the iron is reduced. For small variations in excitation around normal conditions, the changes in loss seem to be nearly proportional. Curves $A$–$D$ show results typical of all machines.

This relationship makes it advisable to manipulate field currents, when required in the conduct of the stray-load-loss test by the Kapp method, in such a way that as the excitation of one machine is reduced to make it assume load as a motor, that of the other is increased in like proportion. In this way, the error introduced by changing the saturation as machines are loaded is minimized.

Attempts were made in tests of machines 1 and 2 to measure the loss for extremely low excitations, in the order of 25 per cent of normal field current. Under such conditions, however, one factor which affects the measurement becomes more apparent, and machines are operating so low on the saturation curve that an exact specification of the degree of excitation is not possible. The loss itself can be measured with the same accuracy as at normal conditions, but the initial total magnetization conditions are dependent not alone upon field ampere-turns but also upon the residual magnetism or hysteresis of the iron as a result of changing armature flux. Thus, for the same values of shunt field current, different curves will be obtained depending upon whether armature currents are being increased or decreased. This effect is present at all saturations to some extent, but becomes of smaller importance as the excitation approaches normal. It does contribute to the difficulty of manipulation in the tests, and may account for inconsistencies in results which have not been explainable heretofore. Curve $E$ in figure 3 shows the loss for approximately 30 per cent of normal excitation.

### Variation With Speed

The variation of stray load loss with speed is shown in figure 4 for several values of machine current, excitation being held constant for all cases. The loss is seen to in-

crease rapidly with speed. This is to be expected from the fact that the frequency at which the stray load losses occur is proportional to speed, and that the loss should therefore be a function of speed to some power between 1 and 2. For the curves shown in figure 4, the exponent is approximately 1.9. Other machines showed exponents from 1.2 to 1.6.

### Summary of Results

To sum up the results of the tests, values are given in table I of the stray load loss for each machine under normal conditions of load, excitation, and speed, expressed in per cent of input at full load. These figures show that stray load loss differs with the type of machine.

For some of the machines, tests for stray load losses were conducted by both the Kapp and Hutchinson methods. Good agreement was shown in the results, and final figures are given as an average value of the 2 tests. The methods are fundamentally the same, although by means of the booster it is possible to keep field currents constant at all times. In the Kapp test, manipulation of the field current is necessary to make the machines take load, with the result that the 2 machines will be operating under somewhat different saturation conditions. The error caused by this effect can be minimized by following the procedure suggested above. This offers no serious handicap to the measurement of stray load loss by this method and results will be well within any tolerance for accuracy in the final value of stray load loss.

Emphasis should be made here that it is not always necessary to have 2 identical machines for a load-back test if one machine has previously been subjected to a test for its stray load losses. The requirement of 2 identical machines is only necessary for the purpose of making proper division of the stray load loss between them.

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# Central-Station Voltages for Lighting

OF THE POPULATION in the United States receiving central-station service, 98 per cent is now supplied at a nominal standard voltage of 115 or 120, according to an article by G. S. Merrill (A'08, M'12) head of the section of lighting economics of the incandescent lamp department, General Electric Company, Cleveland, Ohio, appearing in the August 1937 issue of the Edison Electric Institute *Bulletin*, pages 327–8. The trend has been slowly toward the adoption of the higher voltages. In 1923, 36.3 per cent of the population using central-station service obtained power at 110 volts, 40.9 per cent used 115 volts, and 19.4 per cent used 120 volts. In 1937 only 1.8 per cent of this population is supplied by 110-volt circuits, but 52.1 per cent of the users obtain power at 115 volts, and 46.0 per cent at 120 volts. From 1923 until 1933 the use of 115-volt service increased, but since 1933 its use has declined and 120-volt service has gained in favor at the expense of both of the other standard voltages. This trend is attributed to the increasing use of light, heat, and power on residential circuits and the use of 3-phase 4-wire 120/208-volt networks in commercial areas.

In the interest of good lighting service, public utility companies and lamp manufacturers in general are trying to encourage the use of lamps of which the labeled voltage corresponds to the average voltage at which they are operated. Although the amount spent by customers for electric energy and for lamps decreases if the lamps are operated at lower voltage, the light output diminishes more rapidly than the operating expense, and the customer pays more per unit of light.

In areas where part or all of the business section is supplied at 120 volts and the residential section at 115, the problem of keeping properly rated lamps in use throughout the community is very difficult, and the re-establishment of a single standard voltage for the whole community is presumed to be best accomplished by increasing the voltage on the existing 115-volt circuits to 120. Poor voltage regulation throughout an area also contributes to undervoltage operation of lamps, because lamps properly rated for operation along the high-voltage branches of the network must be provided, and experience has indicated that these high-voltage lamps find their way into many low-voltage sockets. The same difficulty is experienced along the boundary line between systems operating at different voltages.

The author suggests that the establishment of a single standard utilization voltage of 120 throughout the United States not only would remove a great obstacle to the operation of lamps at correct voltage, but also would contribute to improvements in the design, production, distribution, and use of appliances on central-station circuits. The article contains a comprehensive statistical survey of the utilization voltages employed in various states in convenient tabular form, and one figure delineating the upward trend of these voltages during the last 14 years.

# Discussions

## Of AIEE Papers—as Recommended for Publication by Technical Committees

ON THIS and the following 29 pages appear discussions submitted for publication, and approved by the technical committees, on papers presented at the sessions on communication and research, insulation co-ordination, general power applications, power generation and electrical machinery, power transmission, and vibration and balance at the 1937 AIEE summer convention, Milwaukee, Wis., June 21–25. Authors' closures, where they have been submitted, will be found at the end of the discussion on their respective papers. Other discussion of summer convention papers will be published as it is made available.

Members anywhere are encouraged to submit written discussion of any paper published in ELECTRICAL ENGINEERING, which discussion will be reviewed by the proper committee and considered for possible publication in a subsequent issue. Discussions of papers scheduled for presentation at any AIEE meeting or convention will be closed 2 weeks after presentation. Discussions should be (1) concise; (2) restricted to the subject of the paper or papers under consideration; and (3) typewritten and submitted in triplicate to AIEE headquarters 33 West 39th Street, New York, N. Y.

### Application of Spill Gaps and Selection of Insulation Levels

**Discussion of a paper by H. L. Melvin and R. E. Pierce published in the June 1937 issue, pages 689–94, and presented for oral discussion at the insulation co-ordination session of the summer convention, Milwaukee, Wis., June 25, 1937.**

**J. H. Foote and J. R. North** (Commonwealth & Southern Corporation, Jackson, Mich.): This paper gives an excellent presentation of the application of gaps as protective devices co-ordinated with insulation levels.

The authors point out that the protected level varies with the time of incidence of the surge, the protected level or surge voltage allowed on apparatus being higher with decrease in time, i.e., with increased steepness of wave front, higher voltages are impressed. With this in mind, the statement of page 689 that, "A spill gap provides a definite voltage discharge level . . ." may be misleading. Should not the word "curve" or "characteristic" be substituted for the word "level" which ordinarily brings to mind one numerical value remaining uniform under varying conditions.

Figure 1 is clear and should be widely studied by the users of gapped equipment. Much misunderstanding might thereby be eliminated relative to the protection afforded by gaps.

We cannot agree with item 1 under conclusions, "Spill gaps . . . afford dependable protection to equipment and insulation against failure from lightning" unless qualified. Gaps are particularly adapted for the protection of insulation in air, such as bushings and insulators, rather than for solid or laminated forms of insulation. The authors point out the necessity of extremely close gap spacing when used for the protection of solid insulation against fast waves.

Data as to allowable spacings from the operating standpoint are interesting and valuable. Evaluation of service interruptions occasioned by the operation of gaps must be made by each operator to suit existing conditions. In view of the wide range of gap settings used at the same operating voltage in different locations, we would like to ask the authors to give correlating data regarding apparatus insulation strengths and neutral grounding conditions in order that these gap settings may be further studied. It would be very helpful if this explanatory data could include the following information for each of the locations cited:

Original insulation tests specified for apparatus protected.

System neutral effectively grounded or ungrounded.

Ratio of zero sequence impedance to positive sequence impedance under maximum fault conditions.

**M. H. Lovelady** (Central Power and Light Company, San Antonio, Texas): Melvin and Pierce are to be commended for the abundance of information contained in their paper "Application of Spill Gaps and Selection of Insulation Levels."

The table I in the paper tabulates the operating record of spill gaps in Texas. Although not stated, these apparently are mostly straight grounded gaps without fuses or expulsion tubes. The table shows a remarkably small percentage of gap operations and it would be of interest to know whether means were used definitely to determine whether or not the gaps operated.

A south Texas company has perhaps more repeater type fused gaps in operation than any of those companies to which the authors had access to operating records and a condensed report covering the operating record of these gaps is of interest.

A total of 185 repeater-type fused gaps have been installed to date and 200 more will be installed this year, however only 103 single-phase installations were in operation during the entire lightning season of 1936 and the tabulation is confined to these 103 installations.

The authors conclusions with respect to minimum permissible gap settings are of interest and bear out operating experience of the south Texas company. Excessive operations due to switching surges have not been experienced with gap settings of a lower ratio than those mentioned in the paper. The settings at all installations have a ratio of normal line to neutral voltage approximately as follows; for 69-kv systems 1.35, for 38-kv systems 1.87, for 22-kv systems 2.2, and for 12-kv systems 2.85. All of the installations are on solidly grounded-neutral systems.

More information regarding the frequency of operation of close-set gaps would be of interest. The table in this discussion shows the number of operations that took place between inspections. All installations were inspected after each lightning disturbance.

Thirty of the installations are at attended stations and it is of interest to note that operators have on several occasions reported that the gaps spilled over without system follow up current, indicating that the surge was dissipated during the instant of very low or zero system voltage.

| Line Voltage (Kilovolts) | Gap Setting (Inches) | Number of Installations | Operations Between Inspections — No. of Tubes 1 | 2 | 3 | 4 | Total Operations |
|---|---|---|---|---|---|---|---|
| 66 | 6 | 60 | 80 | 23 | 8 | 8 | 182 |
| 38 | 4 | 16 | 30 | 15 | 2 | 2 | 89 |
| 22 | 2 | 9 | 10 | 4 | 2 | 0 | 33 |
| 12 | 1.25 | 18 | 17 | 7 | 2 | 0 | 37 |
| Total | | 103 | 146 | 49 | 14 | 10 | 341 |

All of the fused gaps except 9, are installed on transformers directly at the bushing and in series with the transformer fuse. The other 9 are installed on the line side of the oil circuit breakers at the bushing, at a station where 3 69-kv lines enter the station. The station being located at a point where lightning is particularly severe. This station also has fused gaps located at the transformer bushings. The station is protected by overhead ground wires over the the station and extending one mile out on each of the 69-kv circuits.

It is interesting to note that on 2 occasions the gaps at the transformers operated when none of the line gaps operated and that there were 10 operations of the line gaps when the transformer gaps did not operate. On no occasion did both sets of gaps operate simultaneously and on no occasion did more than one gap operate on the same phase. Of the 10 line gap operations, 8 were on the same line, the remaining 2 operations taking place one on each line.

Only 2 of the 341 operations were accompanied by blowing of transformer fuses and those were probably due to faulty fuses as a number of operations have taken place at the same locations without fuse failures.

During the entire period there were no tube failures on the fuse gaps and no tube flashovers. There were several failures of devices to trip the next tube into operating position. These failures however were due to mechanical difficulties and the trouble has now been remedied.

Nine of the operations were caused by birds shorting out the gaps, a condition not considered serious as the operations caused no system disturbance and the loss of one tube out of 4 is not serious.

Only 2 of the operations occured during periods when there was no visible lightning and these are the only 2 operations that may be attributed to switching surges.

It is of interest to note from the tabulation that of the 10 reports of all 4 fuses operating between inspections, 9 of these occurred at end of the line stations. It is also interesting to note that average operations per unit per year for the system is 3.4, while average operations per unit per year for end of the line installations is 6.5.

Based upon the above record, the company now plans to change all of the end of the line installations to 8 fuse repeaters instead of 4.

Although the repeater-type fuse gaps have only been in operation on the Texas system for a little more than a year, single-shop fuse gaps have been used for several years. The transformer failure record at points where the single-shop fuse gaps had been installed lead to the installation of the repeater type. A comparison of transformer failure records at some of these points is of interest.

At one 38-kv station 3 transformers failed in 1930 and one more in 1931. Fused gaps were installed in 1932 and there have been no more failures.

At a 69-kv station, 2 transformers failed in 1931 and 2 more in 1932. Fused gaps were installed after the 1932 failure and there have been no more failures.

At another 69-kv station, 2 transformers failed in 1932, 2 in 1935, and 2 more in the early part of 1936. After the 1936 failure, fused gaps were installed and there have been no more failures.

**H. L. Rorden** (Ohio Brass Company, Barberton, Ohio): It is unfortunate that the volt-time characteristics of insulation failures are not susceptible to mathematical analysis. The problem of insulation co-ordination depends upon volt-time characteristics, which must be determined empirically. Because of this and the vast amount of data that has been accumulated from a great number of sources, it is difficult to draw reasonable conclusions. Differences of opinion also complicate the problem, so that the absolute performance of dielectrics under high-voltage surges is still not completely understood. Since volt-time performance plays such a prominent part in the general scheme of co-ordination, it seems timely to point out some characteristics which may not be generally understood and which may lead to erroneous conclusions if overlooked.

It should be of interest to all working in this field to know that the volt-time characteristics of insulation failures in general, are not as definite or precise as we may like to have them. As an illustration, it is frequently possible to obtain time lags at minimum impulse flashovers which differ by 100 per cent or more in time without a measurable difference in voltage. In flashover tests of a simple rod gap for instance, successive flashovers may range from about 8 microseconds to more than 20 microseconds with identically the same voltage applied. It is apparent that the phenomenon that produces such flashovers is very unstable and cannot be measured as an exact time. It would seem more logical that these data be plotted as a band. This band becomes narrow rapidly with increasing overvoltages, but is still measurable in the very short time range. In this short time range the curve may be very steep with respect to voltage, so that in spite of the narrow band a considerable range of voltage may obtain at exactly the same time to flashover. The band, therefore, is broad as a function of time at minimum flashovers and is broad as a function of voltage at the high overvoltages. In some instances it is found that a variation of 100 per cent in voltage may obtain at identically the same time to flashover. This range is not common, but in some tests it does obtain. It is apparent that to assume an average and plot a line to represent such volt-time characteristics, may be misleading and result in the adoption of margins which may be insufficient.

Another point of interest is in connection with so-called "flat" volt-time characteristics such as are illustrated in figure 1 of the transformer subcommittee report, figure 3 of the arrester levels paper by Messrs. Foote and North, and figure 1 of the spill gap paper by Messrs. Melvin and Pierce. Flashovers which are not dependent upon the formation of corona to complete the breakdown, are usually said to have a flat volt-time characteristic. An example of this is the sphere gap. In nonuniform dielectric fields such as in the rod gap where long times to flashover may obtain, the curve is said to be sloping. A little further clarification on these phenomena is in order. It would seem probable that the conception of a flat curve originated from the fact that analytically no flashover may be considered as a flashover at infinity. Therefore, once a minimum voltage was reached, the curve was continued without change in voltage to infinity. This is a misnomer, since it is impossible to obtain long time lags in sphere-gap flashovers. The flashover of spheres, being almost independent of corona, will occur very quickly or not at all. Thus the volt-time curve of a sphere-gap tested with the $1^1/_2 \times 40$ wave ceases to exist as soon as it becomes flat. Ordinarily it is not possible to obtain flashovers of a sphere-gap with this test wave in more than 3 microseconds. Therefore, the entire curve is that part which curves upward in times less than 3 microseconds. This point is of interest because it has been assumed in some instances that lower flashovers of gaps, irrespective of time, indicates better protection. It is apparent that if a gap or insulation having a "flat" characteristic is to be protected by another gap, it would be useless to provide protection that might flashover in 10 or 15 microseconds when a failure would occur in less than 3 microseconds or not at all. Thus the minimum flashover alone not only may offer no protection, but may be a definite hazard to the system, since it may result in an outage which would offer no protection in any event.

If the curves in the 3 papers mentioned are intended to illustrate general characteristics of surge tests irrespective of wave shape, then it might be said that the flat part of the curves exist as illustrated. The flat portion may be true for slow waves where flashover occurs on the wave front or at the crest. In that event, the flat part of the curves exist and the short time to flashover does not. Therefore, while the curves may illustrate a general principle, they must be used with care, since the complete curves as illustrated do not represent all possible wave shapes and must be limited when one wave only is considered. A complete family of curves would be necessary to represent relative volt-time curves for all waves.

It is significant that the authors of all 3 papers (excepting the committee reports) in this group, have expressed some unfavorable comment on bushing gaps. Laboratory tests indicate that bushing gaps have several undesirable features, which makes them a hazard rather than a help. The one point in favor of bushing gaps is, that it is possible with these gaps in general to obtain the same flashover for both polarities at minimum voltages. Power arcs frequently whip in any direction and the use of bushing gaps encourages an arc to form near the surface of porcelain where it can do considerable damage. The impulse characteristics of bushing gaps are very similar to rod gaps and, therefore, their usefulness for surge voltages is limited to minimum flashovers with slow waves. They are useless for fast waves, as previously mentioned in the discussion of "flat" curves. They are also useless at the high overvoltages where they are most needed, unless an unusually low gap spacing is adopted. If a parallel rod gap is desirable to protect the bushing, a spacing considerably less than the usually recommended gap spacings for bushings must be adopted if overvoltage protection of the bushing is expected. This low gap spacing is necessary because an overvoltage arc tends to follow a surface, where at minimum voltage an arc may strike clear. This phenomenon is observed also in strings of suspension insulators. For example, in an insulator string equipped with arcing horns, the horns may be so adjusted that the arc will strike clear between the horns at minimum flashover, but unless an unusually low spacing between the arcing electrodes is adopted the arc may cascade the insulators on high overvoltages exactly as though the horns were not present. Bushing gaps and rod gaps are parallel cases to the insulator string.

These gaps adjusted to the so-called test gap spacing, may flashover at minimum impulses, and at the high overvoltages, the arc may follow the surface of a parallel bushing exactly as though the gap were not present.

I should like to ask the authors of the 3 papers, if their experience indicates whether most insulation failures are associated with a single severe surge such as direct strokes or if there are a fair percentage of failures that occur with strokes of lesser magnitude and

current, such as traveling waves. Recent publications have shown that a large percentage of direct strokes are above 10,000 amperes, and up to 50,000 amperes. It would seem probable that if many failures are due to surges of low current such as arresters are capable of dissipating, that there must be some breakdowns which occur during surges of low magnitude on systems not equipped with arresters. That is, if progressive deterioration weakens insulation, so that failure becomes imminent, such failures would not necessarily be assoicated with direct strokes. However, if most failures are associated with direct strokes, it would seem that more attention should be given to the higher current and energy surges than to those of lesser magnitude.

**K. B. McEachron** (General Electric Company, Pittsfield, Mass.): The proper solution of the problem of insulation co-ordination depends upon a knowledge of the flashover or failure characteristics of the apparatus to be protected, as compared with the protective level allowed by the protective devices used. If all apparatus had the same shape volt-time curves of failure or performance, the problem would be relatively simple. Thus, if the volt-time flashover characteristics of the line insulator, bus and switch support, bushing, and the puncture of solid insulation as used in the transformer, were all similar in shape, and if the rod gap or lightning arrester were entirely independent of the effects of wave front and current magnitude, it would be possible to maintain any desired levels without knowledge of what sort of impulses must be considered when lightning strikes the line or station.

Actually, however, although the volt-time curves for the lightning arrester and transformer insulation are similar in shape, the bushing, line and bus insulators, and the rod gap, all have volt-time curves which increase very rapidly as the time to flashover becomes short. This characteristic does no harm, and in fact, is an advantage in a device being protected, but is not a desirable characteristic for a protective device. This is especially true when the frequency of occurrence of any particular wave of lightning front is not known. The variation in the rod-gap spark potential from 60 cycles wet to flashover on a 1,000 kv per microsecond front will be of the order of 6 to 1, while the same ratio for the lightning arrester will not in general be more than 2 to 1, the arrester being unaffected by weather conditions.

These considerations lead to the conclusion that, if close and dependable protection is to be expected, one should make use of the lightning arrester installed close to the transformer, with adequate direct stroke protection over the station and for a short distance out, so that waves of known magnitude and steepness can arrive only through the surge impedance of the line, giving rise to voltages across the arrester which can be predicted reasonably well in advance. This allows one to operate with a known margin between the arrester potential and the tested strength of the transformer.

The ideal arrester protection, which has been long recognized as such, would be to have the arrester potential unaffected by either the rate of voltage rise or the amount of current in the discharge. It is true that considerable progress has been made in this direction in the last few years, which provides more definite protective levels than possible heretofore, and yet for the best results and to maintain dependable margins, a knowledge of the maximum magnitudes of the incoming waves is essential, both as to rate of rise and magnitude of current.

These considerations indicate that the greatest lack of knowledge concerning lightning is in relation to the wave shapes and magnitudes which may result from direct strokes at the point where the stroke occurs. This is especially important in connection with distribution systems where direct stroke protection cannot be readily installed at transformers. Knowledge of such wave shapes is very difficult to secure at reasonable expense, and although some data are available much still remains to be done.

Fortunately, waves which travel over conductors, even relatively short distances, are subject to calculation, and are so modified that an exact knowledge of the original lightning stroke is not necessary. This method is conservative, but until more is known of the wave shapes of lightning and the frequency of occurrence of those wave shapes, it appears to be the safest policy to pursue.

Messrs. Sporn and Gross are to be complimented, particularly on the co-ordination chart, which I am sure will be very useful.

With reference to the Melvin-Pierce paper, what was the ampere rating of the fuses used on the 110-kv system discussed on page 691? With the type of repeator fuse used, how quickly does another fuse become available, and is protection lost in the interval? Multiple strokes involve time intervals as short as 0.0005 seconds and successive discharges may be as far apart in time as 0.5 seconds, which makes the answers to these questions of interest.

**J. T. Lusignan, Jr.** (Ohio Brass Company, Mansfield, Ohio): All 3 papers on insulation co-ordination or selection of insulation levels bring out quite well the factors involved and the advantages to be gained. Messrs. Sporn and Gross very aptly summarize the advantages when they term them "economy." In other words it is merely a case of saving equipment cost and watching the weakest link of the chain. That is, all equipment should be reasonably high enough so as to have small chance of failing, but none should be abnormally higher than others as this usually involves high costs with no particular gain in the net performance of the system.

All of the papers have to do with choosing protective levels and arranging the equipment above them. The question that probably arises in the minds of most readers is how the individual equipment pieces should be arranged relative to one another. Messrs. Foote and North seem to feel that the only care necessary is that all equipment be above the protective level, making no recommendations as to which should be highest or lowest. Messrs. Sporn and Gross seem to favor having the bus insulation the highest in the station.

Whatever procedure is used, care must be taken not to choose insulation levels on too close hair lines. In this regard I would like to emphasize a few points as to the porcelain members involved, that is the bushings and bus insulators. Besides the atmospheric factors which cause the flashover voltages of such insulation to vary, each of these devices has individual characteristics which affect flashover.

Bushings seem to be the most variable in this respect, probably because they have the more involved electrostatic field. This field is that of a rod and torus, with a mass of solid and/or liquid insulation as a principal dielectric between them. It is this mass of insulation which is supposed to support all applied potentials, any relief from high overvoltages being gained by flashover of the air along the outer porcelain shell. The inside insulation has an appreciable effect upon the outside flux of the air, and therefore the flashover characteristics of the bushing. Since some bushings nowadays are made entirely of porcelain or paper, some of porcelain and oil and some of paper and oil, it can be appreciated that each will have the outside air paths affected differently. Also the temperature and condition of the inside insulation has some affect upon the outside electrostatic field. All of these factors combine to make very difficult the problem of standardizing bushing flashover values within narrow bands. There is also the question of using the flashover values secured in a laboratory on a smooth testing tank, with those which will occur when the bushings are mounted on breaker or transformer tanks having protruding metal parts in different arrangements around the base of the bushings.

The question of standardizing bus insulator flashover values is a little less complicated, since the dimensions, materials, and shapes of many of these insulators are rather well standardized today. However, tolerances must be allowed on each side of the flashover values, established under standard conditions in laboratories, since these insulators are not always mounted alike in stations. In other words, some are base-mounted and some cap-mounted, while others are arranged in double as well as single stacks, and with widely different hardware fittings at the line ends.

In those cases where suspension insulators are used in stations, it must be remembered that the established suspension flashover values are based on simple hanging strings in laboratories, and not the horizontal tension strings, with and without jumpers, as is frequently used in some bus structures.

In all of the above papers the need is recognized for putting the "protective level" above the expected switching surge level. The question that I would like to raise is as to what should constitute the switching surge level. Messrs. Melvin and Pierce introduce new data which I feel should change the idea of many of us as to the proper switching surge level. In their conclusions they state:

"The minimum permissible spill-gap settings, for transmission voltages, without adverse effects on service, are less than those previously considered possible.

*a.* The lower limit generally applicable is the equivalent of approximately 3.0 times the normal phase-to-netural voltage, in terms of 60-cycle flashover.

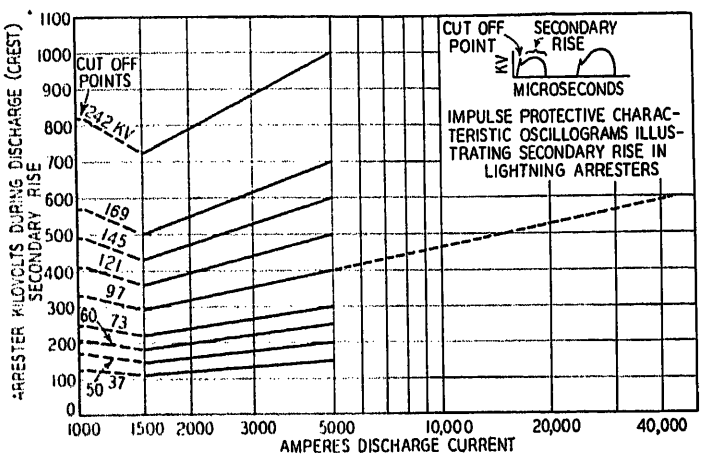



**Figure 1. Performance of station-type arresters**

Data from table I of paper by Foote and North

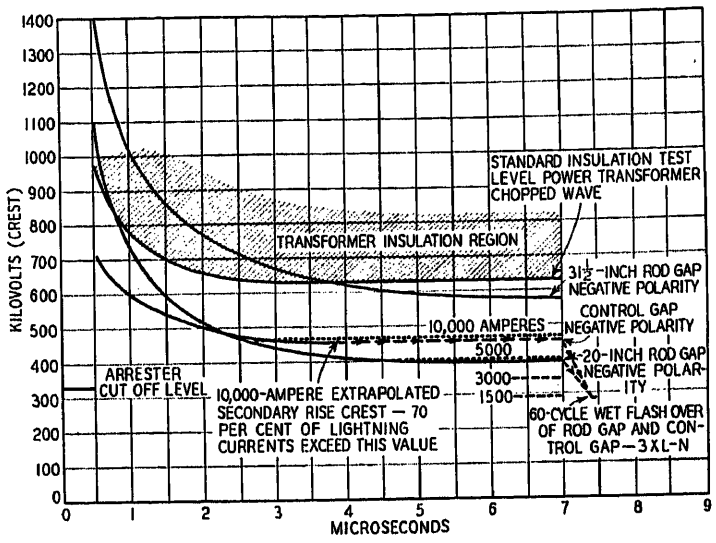



**Figure 2. Typical insulation co-ordination showing relative effects of arrester secondary rise and back-up protection of rod gaps and control gap**

*b.* When extremely low protective levels are necessary or desirable and preferably where fused gaps may be applied, the minimum permissible limit may be approximately 2.0 times normal."

Up to now I believe that most of us have felt that a switching surge had the same flashover characteristics as the power frequency wave. Recent work in our laboratory has led us to believe that a switching surge, with its short duration and rapid attenuation, compared to a long 60-cycle wave, might have flashover characteristics higher than the latter and closer to those of impulse surges than originally supposed.

Accordingly, our engineers feel that it is wiser to design a protective device to handle expected lightning surges, overlooking pure 60-cycle overvoltages, on the assumption that the latter is the result of generator overspeeding but not switching. Appreciable data have been gathered showing the crest values of switching surges. We believe that it would be most helpful if more were gathered telling of the wave shapes of switching surges. We feel that this might reveal wave shapes which will permit devices being set appreciably lower than is felt to be safe on the present power frequency basis.

**P. M. Ross** (Ohio Brass Company, Barberton, Ohio): The operating experience of Messrs. Melvin and Pierce is of valuable assistance in arriving at protective gap levels which are sufficiently low to protect expensive insulation, yet of such magnitude that they can be "lived with" on the system under operating conditions.

The authors mention various switching surge tests conducted to determine the minimum spill-gap settings which are permissible from an outage standpoint. I should like to ask the authors if they can give any information relative to the switching surge wave shapes.

Emphasis has been placed on establishing basic protection levels by means of spill gaps. Such gaps are not subject to deterioration, and remain unchanged by time. There still remains the important problem of determining the time deterioration of major insulation so that a change in basic insulation levels may be adopted to compensate for such reduced levels. I would like to inquire if the experience of the authors of all 3 papers indicates a relative destruction effect of switching surges, induced surges, and direct strokes.

Table I of Messrs. Foote and North's paper illustrates arrester characteristics up to 5,000 amperes. Thus it is shown that for the usual surge or traveling waves arresters are capable of maintaining the surge potential to a safe value.

The authors state in a footnote under table I that station-type arresters can withstand 10,000-ampere crest surge currents. In recent publications statistical data indicate that approximately 70 per cent of stroke crest currents will be in the neighborhood of 26,000 amperes ("The Lightning-Stroke Mechanism of Discharge," McEachron and McMorris, October 1936, *General Electric Review*). The data as presented by the authors in table I have been plotted on a semilogarithmic basis, figure 1. Since the data plotted in this manner are found to lie on a straight line, extrapolation into the regions in which the greater percentage of direct strokes actually obtain seems reasonable. It is thereby found that the secondary rise crest kilovolts across the arrester at 10,000 amperes has risen to 460 kv and to approximately 600 kv at 50,000 amperes (if the arrester will thermally withstand these currents).

It is interesting to consider these figures when they are plotted with typical transformer insulation in view of the authors' statement that "Arresters generally have the following characteristics which are of value in this connection: . . . . (*c*) The performance characteristics are such as to approximate the volt-time characteristics of transformer insulation." In figure 2 is plotted a typical transformer insulation band with a 20-inch negative-impulse rod-gap characteristic (95 per cent lightning strokes on transmission lines are negative polarity), negative-impulse characteristics of a 115-kv control gap set with wet switching surge flashover of 3 times line to neutral voltage and a 97-kv arrester as recommended by the authors for an effectively grounded neutral 3-phase system. The arrester gap breakdown or cut-off point is shown at 330-kv at the ordinate.

The secondary rise crest kilovolts are plotted horizontally. They have been terminated at the 20-inch rod gap, the 60-cycle flashover of which is also 3 times line to neutral voltage. It is to be noted that if surge currents exceed approximately 5,000 amperes the 20-inch back-up gap having a negative minimum flashover of 395 kv will flashover due to the secondary rise across the arrester. Carrying this analysis still farther it is to be seen that the extrapolated value for 10,000 amperes falls at approximately 5 times line to neutral voltage. Currents as high as 50,000 amperes would cause a secondary rise voltage approaching the breakdown of new transformer insulation. I would like to ask the authors if they have any additional data to extend the secondary rise kilovolts crest into the region from 5,000 amperes to 50,000 amperes, also if they have available the total time to crest of the secondary rises for the various discharge currents? Such an analysis as shown in figure 2 indicates that the cut-off point is of minor importance when surge currents of 3,000 amperes and up are encountered as insulation failures are caused by crest voltages, the values of which are determined or permitted by the secondary rise crest of the arrester.

## Application of Arresters and the Selection of Insulation Levels

**Discussion of a paper by J. H. Foote and J. R. North published in the June 1937 issue, pages 677–82, and presented for oral discussion at the insulation co-ordination session of the summer convention, Milwaukee, Wis., June 25, 1937.**

**H. L. Rorden:** See discussion, page 1291.

**P. M. Ross:** See discussion, this page.

**J. T. Lusignan, Jr.:** See discussion, page 1292.

**Herman Halperin** (Commonwealth Edison Company, Chicago, Ill.): The authors state on page 680 that "The arrester voltage

rating must be at least 10 per cent above the calculated maximum sound phase voltage to ground." As we have not followed this practice in Chicago, I should like to discuss it.

The manufacturers state that for modern arresters the 60-cycle breakdown is at least 150 per cent of the arrester rating. This factor alone usually provides a safe margin to justify the use of an arrester rated equal or less than the maximum phase-to-ground voltage during abnormal conditions.

We have been using 3-kv arresters on the 4,000-volt distribution system, which is grounded at the substations through 3/4-ohm reactors. During unusually heavy fault currents, the fuse that normally short-circuits the reactor blows. In general, the ratio $Z_0/Z_1$ is over 2 when the fuse has blown, and is less than 2 when it has not blown. For faults near the substations our information shows definitely that the maximum line to neutral voltage may reach 3,500 to 3,800 volts, and this condition applies when the fuse across the reactor blows. The fuse blows in about 15 cases a year, or about once every 3 years for each substation. For most faults, the maximum voltage is 3,000 volts or less.

Arresters rated at 3 kv have been used for 25 years on this system with satisfactory results. The rate of arrester failures due to all causes is about 0.3 per cent per year and the rate for the modern type of arrester but a small fraction of this percentage. These failures include, of course, those due to corrosion of the gaps and other deterioration.

For the year 1936, 69 arresters failed in service incidental to lightning. The average distance to these arresters from the substation bus was 7,500 feet. There were also 40 failures of arresters due to unknown causes, and for these cases the average distance from the arresters to the substations was 6,300 feet. The average distance for all arresters on the system from the substation busses was 6,000 feet. The voltages during faults are highest on the line wires nearest substations, and yet this characteristic did not cause a large proportion of the arresters near substations to fail.

Table III of the paper shows a margin of arrester performance in the basic insulation level which includes a circuit gradient of one kv per foot. This value may not be sufficiently high to insure an adequate safety factor under severe conditions. Hodnette and Ludwig reported in their June 1937 paper voltage drops in arrester leads as high as 10 kv per foot in laboratory tests. Lightning investigations on the Chicago distribution system as reported by Halperin and Grosser in the January 1936 issue of ELECTRICAL ENGINEERING indicated values of circuit gradient as high as 1.0 to 1.7 kv per foot. In our measurements no cases of transformer failure and only one fuse blowing occurred, although a large number of measurements were made. It appears quite possible that, with lightning conditions severe enough to cause actual equipment damage, higher values of circuit gradient might have been encountered. At least until more definite data are available, particularly for transmission systems, values higher than one kv per foot should in some cases be used in designing and in analyzing equipment performance.

The use of higher gradients reduces or eliminates the selectivity margins given in the paper. Some compensation, however, exists in the 5 per cent or greater differential between the basic impulse level and the transformer bushing flashover. Perhaps the selectivity margin could properly be determined on the basis of actual flashover voltage of the equipment to be protected rather than on the basic impulse insulation level.

These remarks emphasize the authors' recommendation to place arresters as close as possible to transformers or other equipment to be protected.

**E. Piepho** (Detroit Edison Company, Detroit, Mich.): Foote and North have condensed the great body of available material relating to lightning protection of electrical apparatus, and presented it in a form immediately usable to the operating engineer. Data which they give have passed through the controversial stage and are now widely accepted. Interpretation and use of this material, however, may warrant some comment.

To the section on marginal requirements, the authors might have added a statement concerning the effect of deteriorated lightning arresters, or arresters of earlier manufacture than the more improved types whose performance is shown in table I. Such arresters would give higher voltage drops during discharge than the values shown in the paper. The surge impedance of ground connections is also of great importance since the voltage drop across this impedance adds to the voltage across the arrester during discharge, giving proportionally higher impressed voltages on the protected equipment. For example, on distribution systems ground-connection impedance has so much effect that considerable improvement in protection of transformers has been realized by interconnection at the transformer of the secondary neutral wire and the arrester ground lead.

The selectivity margins shown in table III appear to be comfortable for all voltage classes, yet the operating engineer using these data should bear in mind that these margins can easily be wiped out by any one or more of the marginal requirements having greater weight than assigned by the authors. This has the effect of making each arrester installation almost an individual matter. It also suggests that operating companies using a great number of lightning arresters will find it profitable to undertake a program of testing a certain percentage of new, and all reclaimed, arresters before placing them in service. Furthermore, now that basic insulation levels are being established, operating companies can proceed to test the various kinds of old equipment in service to determine their fitness to operate in their voltage class.

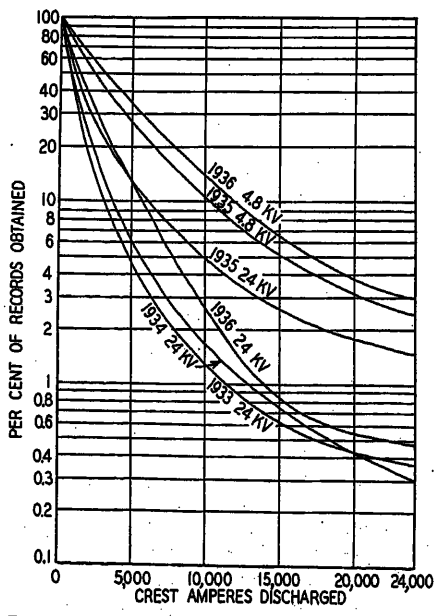



**Figure 1. Magnitude of lightning current through arresters on 4,800- and 24,000-volt lines**

It is regrettable that the authors were unable to present data on lightning arrester performance beyond 5,000 amperes. The majority of lightning surges passed by arresters appear to be less than 5,000 amperes, nevertheless surges of greater magnitude are not uncommon. Records of surge currents through arresters have been obtained on the Detroit Edison system for several years, using surge recorders in the ground connections of various 24,000-volt arresters, and surge-crest ammeters in the ground leads of arresters on 4,800-volt distribution transformers. H. W. Collins reported the first year results of this investigation on 24,000-volt lines in the May 12, 1934, issue of *Electrical World*. This work has been continued and considerable additional data obtained. The accompanying curves show the per cent discharges at different current values obtained from these records. About 9 per cent of the surges recorded on 24,000-volt lines were over 5,000 amperes, and about 30 per cent were over 5,000 amperes on the 4,800-volt lines. The greater percentage of high current surges on the distribution lines in probably due to greater exposure, since all the 4,800-volt line recorders are located on farm lines, whereas many of the 24,000-volt recorders are in the urban area. These records have also demonstrated that lightning arresters of present manufacture can pass surge currents in excess of 20,000 amperes without damage. Consequently, it seems the time has come for manufacturers to extend the data on voltage across arresters during discharge considerably beyond the present 5,000-ampere limit.

This paper should focus attention of all operating men on co-ordination of equipment insulation which is important because better protection can thereby be secured at less cost. It should also enable manufacturers to standardize somewhat on lightning-arrester characteristics, which should lead to lower costs and consequent broader application of arresters.

**Hollis K. Sels** (Public Service Electric & Gas Company, Newark, N. J.): Messrs. Foote and North, in their paper on "Application of Arresters and the Selection of Insulation Levels" and Messrs. Sporn and Gross in their paper on "Insulation Coordination" bring out valuable comparisons between the protection afforded by lightning arresters and the basic insulation levels of other equipment. While a great deal of information has been gathered on the characteristics of insulated equipment and protective devices, a great deal of informa-

tion is still needed on the impulse strength of equipment in service and on new equipment being manufactured by those who are not equipped with complete testing facilities or, if equipped, may not have complete information on equipment being built.

The opinion expressed in both these papers seems to be to rate the bus insulation strongest, with bushings, transformer insulation, and lightning arresters following with suitable margin requirements provided in each step. There are 2 major factors which appear to us to need further consideration before they can be standardized on as a general policy. First, while it is theoretically possible to maintain a marginal requirement between steps of only 10 per cent, we believe that in practice it will be impossible to maintain less than 20 per cent between barrier-type insulation level inside transformers and circuit breakers and the protection level because of the deterioration which is bound to take place in insulation and the variation in protective ability of equipment. The company with which I am associated has purchased plenty of equipment which, at the time of purchase was properly co-ordinated, but now, because of its depreciation, is almost as uncoordinated as if no co-ordination had been made originally. Messrs. Melvin and Pierce have made some allowances for deterioration in their application of spillway gaps. Second, every station design naturally falls into at least 4 levels, that is, line entrance insulation, the disconnecting switch and bus insulation, which are usually the same, the circuit breaker and transformer bushings, which are usually interchangeable but may be gapped differently, and the internal transformer and breaker insulation levels.

Considering the relative cost to repair, and the fact that most busses are sectionalized if not properly protected, it would appear that bus and disconnect supports should not necessarily be the strongest insulation in the station. In our own designs we have tried to adopt the following order of strength:

1. Transformer and circuit-breaker internal insulation.
2. Transformer and circuit-breaker bushings and bus insulation.
3. Co-ordination gap and line insulation.
4. Lightning arresters.

We feel that a minimum margin of 10 per cent between each of these groups, allowing 30 per cent between the transformers and the arrester and 10 per cent between porcelain insulation and the arrester, should give a reasonable degree of protection, both in service and dollars.

We note that Messrs. Foote and North, in setting up their marginal requirements to take care of the distance and potential gradient between the equipment and protective device, have based their calculations on an allowance of a potential gradient of only one kv per foot, which is equivalent to an incoming wave having a 500-kv-per-microsecond front. In our calculations we have used corresponding values of 1.7 kv per foot, which is equivalent to 1,000 kv per microsecond wave front.

While the values assigned in some of our basic assumptions may be debatable, I am presenting this discussion to show that there is considerable need for a further discussion and standardization on the various factors involved. We cannot simply say that here is a basic insulation level which is adequately protected by the protective characteristics of lightning arresters which you can buy today.

**L. G. Smith** (Consolidated Gas, Electric Light & Power Company of Baltimore, Md.): This paper is an excellent step in the placing of the co-ordination of arresters and station insulation on an arithmetical basis. Until it is possible to accomplish this we are only guessing when lightning arresters are applied. Unfortunately even now we cannot place insulation co-ordination and arrester application on a basis of ready calculation since the data concerning actual lightning discharges are quite meager. However, we do know that

1. Some wave fronts are very steep and apparently the closer the stroke to the substation the steeper the wave front.
2. Stroke currents vary from small values to very high ones and these current values can be expressed on a probability basis.

The data presented by the method followed by the authors are predicated upon wave fronts sufficiently low to permit the arrester gaps to break down before the solid insulation fails and upon surge currents of 5,000 amperes or less. With the present information this is the nearest approach that can be made to an arithmetical solution. However, whether or not this solution represents the majority of the cases is questionable. With lines of the completely shielded or "lightning-proof" type connected to a station, the margin of safety given by the authors can probably be applied with some assurance of being adequate.

However, in the case of stations connected to unshielded lines other factors must be considered. Direct strokes near the station may result in very steep wave fronts being imposed upon the station insulation. As a matter of fact there are no published data giving volt-time characteristics of lightning arrester gaps. If such curves approach those of sphere gaps better assurance of co-ordination is obtained. From published data the probability is that 85 per cent of the strokes will be greater than 5,000 amperes. On unshielded lines the limit of the surge currents carried to the stations will be the insulation level of the lines themselves. However, there will be strokes sufficiently close to the station so that lightning arresters will function before the line insulation has time to flashover, thus probably requiring the arresters to discharge more than 5,000 amperes. Records of lightning arrester and equipment failures justify this point.

In cases where the stroke occurs sufficiently far from the station to permit the line insulation to flashover before imposing a high-voltage surge on the substation the 5,000 amperes assumed by the authors should be ample for practically all operating voltages. However, in order adequately to handle steep-wave-front surges or surges originating close to the station, the ideal arrester is one which has a gap with a volt-time characteristic co-ordinated with the transformer insulation and has an impedance drop for currents up to the point where the arrester element flashes over lower than the impulse strength of the equipment protected.

Therefore, it is believed that, until further data are available, the safest practice in application of lightning arresters is the use of arresters with the lowest possible rating consistent with the dynamic potentials that exist on a given system.

**F. J. Vogel** (Westinghouse Electric & Manufacturing Company, Sharon, Pa.): The report on "Basic Impulse Insulation Levels" gives a tabulation of voltage classes and impulse insulation levels in terms of crest kilovolts. This basic impulse insulation level is presumed to be the minimum insulation level of any apparatus in a station. It is supposed that transformers should have at least this impulse strength or higher and that protective devices would limit the voltages to a lower value to provide a factor of safety in service.

I note that this is the beginning of a program to standardize the level of all the individual parts of a station. I believe this will lead to satisfactory results if it is recognized that considerable latitude must still be given to the designers of equipment. For example, the level of protective equipment should be the determining value for transformers and other equipment, and there exists at the present time no standardization of these devices. Therefore, the basic impulse insulation level given is purely arbitrary since the foundation, which is the voltage level which can be maintained by protective equipment, is lacking.

There is also a trend toward the use of unit equipment, that is to say transformers with either deion gaps or arresters built into the equipment. Since such devices are self-protecting and are a unit, there is little or no point in setting arbitrarily the impulse levels of any of the parts of such devices. The designer must know the performance of each part and provide sufficient factor of safety so that it is a serviceable piece of equipment. Such equipment might or might not adhere to present standards in so far as the performance of the individual parts is concerned.

These points are also brought out in the paper by Messrs. Foote and North. They point out that it is essential, before designing any structure, to determine the stresses which will be placed upon the structure. In this paper the insulation stresses on transformers and equipment are assumed to be limited by the performance of arresters only, and the limits in the application of arresters are important in considering the insulation co-ordination problem from this angle. The authors have made a very thorough study of the problem, and have arrived at sound conclusions.

Arresters are often applied where, due to overhead ground wires and favorable conditions, it is considered that there is little chance of direct strokes. On the other hand, there are few, if any, locations where it can be stated that there is absolutely no possibility of direct strokes, and many where it is not considered economically possible to guard against direct strokes. Therefore, the performance of arresters when subjected to extremely steep wave fronts and heavy surge currents are the important limits.

In design work, where the stresses are known, it is common to apply a "factor of safety." In the paper, this has been done by the use of a "tolerance factor," and a "selectivity margin." The "gradient factor" is really a factor not dependent on the arrester, but on the application. Let us briefly consider what these factors involve. The "tolerance factor" tells us that the arrester is a manufactured product, and as such is subject to variations when new, and

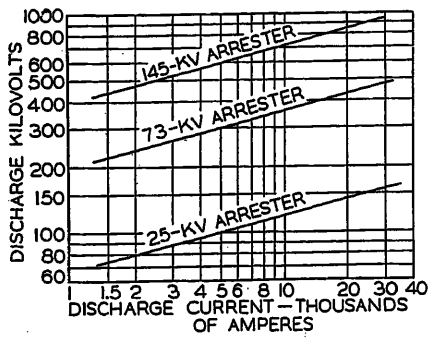



**Figure 2. Discharge kilovolt-ampere curve for lightning arresters from table I of paper by Foote and North**

in service. The tolerance and selectivity factors also tell us that there are unknown factors, such as steepness of the front of the surge. The breakdown voltage of any gap is subject to increase when the wave front is steep enough. The question then is, what steepness may be expected, and in turn what will be the voltage and what effect will this voltage have on the insulation? The answer to these questions is not entirely available, and differs for low- and high-voltage classes. It is possibly safe to say that protection, regardless of wave-front steepness, can be guaranteed for the low-voltage classes, but not necessarily so for the high-voltage classes. Further data and discussion of this subject will undoubtedly follow in the next few months.

The very existence of a distance or gradient factor indicates the necessity of placing the arrester immediately adjacent to the transformer in so far as the transformer only is concerned. The use of a value of one kv per foot may be a fair assumption, but it may be exceeded. In the laboratory, while making steep-wave-front tests on actual apparatus, values 2 or 3 times this high have been seen. There is no guarantee that natural lightning might not occasionally furnish similar results. The practice of locating the protective device, whether gap or arrester immediately adjacent to the transformer appears very desirable from the standpoint of transformer protection.

The question of "surge current" is an important one. Again, surge currents have been assumed at the very nominal value of 5,000 amperes, but there are definite possibilities of currents as high as 10,000 or 15,000 amperes in many cases, to say nothing of the rare cases when there may be from 60,000 to 200,000 amperes. The factors of "thermal ability" to discharge heavy currents, as well as the resultant discharge voltage have not been completely disposed of, as little data are published. A possible extrapolation of the author's data from table I is shown on figure 2 of this discussion for 3 voltage classes. If this extrapolation be correct, the arrester might conceivably cease to protect transformers beyond the following limits: The full wave transformer strengths are 645 kv, 345 kv, and 153 kv for the 138-, 69-, and 25-kv classes, respectively. These voltages will be exceeded when arrester currents in excess of 7,000, 9,000, and 25,000 amperes are encountered. The lack of standardization of arresters is shown by the fact that there are arresters available which will protect these same transformers with discharge currents up to 40,000 amperes or more.

It is interesting to note that the use of the deion gap has been omitted for the low-voltage distribution transformers, in which case there is little or no increase in voltage due to discharge current and no "thermal limitations." This application in certain transformers has had a nearly 100 per cent service record.

The above discussion leads to the same general conclusions as drawn by the authors, and places additional emphasis on the desirability of recommending protective gaps in the station, located as described by the authors, since they provide a limited amount of free insurance against failure of the arrester, and might prevent the failure of a transformer when the surge current is beyond the discharge capacity of the arrester, resulting in too high a discharge voltage.

# Insulation Co-ordination

**Discussion of a paper by Philip Sporn and I. W. Gross published in the June 1937 issue, pages 715–20, and presented for oral discussion at the insulation co-ordination session of the summer convention, Milwaukee, Wis., June 25, 1937.**

**K. B. McEachron:** See discussion, page 1292.

**J. T. Lusignan, Jr.:** See discussion, page 1292.

**P. M. Ross:** See discussion, page 1293.

**J. H. Foote** (Commonwealth & Southern Corporation, Jackson, Mich.): The authors in this paper have presented a most excellent recapitulation of the important considerations involved in insulation co-ordination. They have pointed out that co-ordination has 2 main objectives, (1) protection of service and equipment, (2) economy, and to these we heartily subscribe.

Your attention is particularly called to their "insulation co-ordination chart." This presents, in graph form, for ready use, a vast amount of data pertaining to the insulation strength of apparatus, performance of protective devices, etc. At first, it may appear complicated, but a little study will clearly demonstrate its value in solving insulation co-ordination problems.

**L. G. Smith** (Consolidated Gas, Electric Light & Power Company of Baltimore, Md.): The authors' classification of the 3 types of overvoltage is quite complete. The first 2 types readily lend themselves either to calculation or to estimation, based upon operating data. However, the third classification, that is overvoltage due to lightning, is still a somewhat indefinite factor and at the same time is the one which is most likely to cause damage to equipment. The practice of the authors' company to install transformers with reduced insulation is a very intriguing one in view of the economic savings resulting. The natural question is whether or not the present-day transformer insulation is too safe from an economic point of view.

In setting a level for transformer insulation, if sufficient information were available, it should be possible to place it on an economic basis, that is, obtaining a balance between capital cost and cost of transformer failures and depreciation. However, to do this it would be necessary to have:

1. Complete information as to probability of strokes of various magnitudes and wave front that could enter stations, in which transformer equipment is installed.
2. Complete volt-time curves of lightning-arrester gaps would be necessary.
3. Volt-ampere characteristics of arresters would be required up to very high surge currents.
4. Volt-time curves of transformer insulation.
5. The effect of repeated voltage strains on transformer insulation, upon the volt-time breakdown characteristics, and upon the characteristics of transformer insulation would be necessary, in order to determine the deteriorating effects of repeated surges.

The lower the margin of safety between the transformer insulation and the voltages to which the lightning arresters will limit the incoming surges, the broader must be the knowledge of the probable types of surges that will be encountered. If the margins are too low, steep wave front surges may damage the transformer insulation before the arrester gap can discharge. Likewise, with low margins, the higher values of surge currents may cause impedance drop in arresters sufficiently high to cause transformer failure.

In reference to the practice cited by the authors of installing the arresters, as close as possible, if not mounted directly on the transformers protected: This is unquestionably an ideal location from the standpoint of lightning protection to the transformers. It is the practice which our company is following. However, it must be remembered that when arresters are installed at the transformers in a large outdoor substation, there may be oil circuit breakers or air-break switches, installed at locations remote from the arresters which might need some supplementary protection. Likewise, air-break switches in incoming lines may be open. As this would constitute a point of reflection, frequent flashovers may occur when such switches are open. With the object of preventing such troubles it has been the practice of our company in 13.2-kv substations to install station-type arresters as close as possible to the transformers, and to install line-type arresters at the terminals of the incoming or outgoing lines. For the protection of such air-break switches, lightning arresters may not be necessary, in that an expulsion protective

gap may be used, due to the fact that the volt-time curves of the expulsion protective gap and the post insulator both have about the same shape.

**V. M. Montsinger** (General Electric Company, Pittsfield, Mass.): In connection with the general problem of insulation co-ordination I wish to point out that so far as I am aware the insulation co-ordination movement was started in the transformer subcommittee in 1927, although nothing was published until the 1930 summer convention at Toronto.

This activity was initiated as the result of the failure in August 1926 of some 220-kv transformers having reduced insulation levels (that is, transformers given an induced voltage test of 2.73 times line to neutral voltage) operating on a highly insulated line and without any form of lightning protection. This was the first 220-kv circuit built in the East where lightning was severe and the failure of the transformers brought home the fact that consideration must be given not only to protection against lightning but to the possibility of designs more highly resistant to lightning impulses.

Under item 7 of the minutes of the May 27, 1927, meeting of the AIEE transformer subcommittee, there appears the following heading: "Relation Between Impulse Strength of Transformer Windings, High Voltage Bushings and Line Insulators Near the Transformer Bank." Under this item appears in part the following:

"The question of whether it was best to use the bushing or some external arcing device as a protection to the transformer was discussed and it was the consensus of opinion that it would be poor engineering to use the bushing as a protective device for the windings. It was agreed, therefore, that the committee draw up recommendations on the length of insulators or number of discs which should be used next to the transformer banks of different standard voltages. . ."

The question of co-ordination of transformers was discussed at each subsequent meeting and at the May 9, 1928, meeting the following table for co-ordination was recommended:

| System Voltage (Kilovolts) | Maximum Value of Line Insulation Adjacent to Station in Terms of 60-Cycle Root-Mean-Square Dry Flashover Kilovolts |
|---|---|
| 66 | 250 |
| 88 | 360 |
| 110 | 400 |
| 132 | 450 |
| 154 | 550 |
| 187 | 650 |
| 220 | 750 |

The 60-cycle flashover given in the above table corresponds to the number of line insulators given in the second column of table I of the report of the transformer subcommittee on "Insulation Strength of Transformers" being presented at this session.

The method of establishing protective levels by means of insulator disks was, of course, quite crude and was soon superseded by the use of the more flexible rod gap or "co-ordination gap." As soon as it was realized that the co-ordination gap did not necessarily co-ordinate, the spacings were increased 10 per cent and its name was changed to "test gap."

This early consideration of transformer insulation co-ordination by the transformer subcommittee stirred up interest in the general problem of co-ordination and, as pointed out in the article on "Basic Impulse Insulation Levels," other committees became interested and this finally led to the formation of the EEI-NEMA joint committee to act upon the broad subject of co-ordination.

It is interesting to note that the test gap spacings given in the EEI-NEMA report and from which the basic impulse kilovolt levels were obtained are the same as those recommended by the transformer subcommittee in 1933. This shows that even though the method of selecting the insulation level was quite crude we arrived at the level eventually selected by the EEI-NEMA committee on a more rational basis; namely, the protective level that is available.

The fact recognized in 1927, as mentioned before, that it would be poor engineering to depend on the transformer bushing as a protective device has been fully justified by later developments. In fact, the latest proposal of expressing the insulation level by kilovolts instead of by test gap eliminates the bushing entirely as the yard stick for even impulse testing of transformers, much less using the bushing as a protective device.

While the industry has been feeling its way for the past 10 years on the problem of co-ordination, making use of the best information available, I think we have finally reached the stage where a logical and practical basis has been reached both for impulse testing of transformers and for protecting transformers in service. This, of course, does not mean that further progress will not be made as many groups are still working along these lines.

## Insulation Strength of Transformers

**Discussion of a paper by the transformer subcommittee of the AIEE committee on electrical machinery published in the June 1937 issue, pages 749–54, and presented for oral discussion at the insulation co-ordination session of the summer convention, Milwaukee, Wis., June 25, 1937.**

**H. L. Rorden:** See discussion, page 1291.

**V. M. Montsinger** (General Electric Company, Pittsfield, Mass.): I wish to comment on 2 points which apparently are not clear in connection with this report. One of the points is the "minimum time to flashover" given in column 8, table II.

The reason why a minimum time to flashover is specified is to prevent the use of a short rod-gap spacing for the chopped wave tests resulting in flashover in, say, 0.5 or 1.0 microsecond, where the impulse strength of insulation is considerably in excess of the strength for longer periods of time to flashover. This increase in strength of insulation is shown in a general way in the volt-time curve for transformer insulation given in figure 1.

The volt-time curve of insulation based on single shots has been fairly well established* and the values are as follows:

| Time to Breakdown (Microseconds) | Single-Shot Impulse Strength in Per Cent of Full-Wave Strength |
|---|---|
| 3 and longer | 100 |
| 2 | 105 |
| 1.5 | 112 |
| 1.0 | 125 |
| 0.5 | 150 |
| 0.25 | 190 |

The shape of the volt-time curve of insulation based on repeated shots (i.e., 100 shots or more at various time intervals) has not yet been definitely established. Some data are available and tests are now in progress. It is planned to give the results of the tests in a future paper.

The question of how the chopped wave test (110 per cent of the basic level) and the full wave test (95 per cent of the basic level) were arrived at has been asked since this report was published, indicating that their derivation is not clear. As pointed out in the report, the standard bushing level for distribution transformers is 5 per cent above the test gap level which has been in use for some time. Also, the level of power-transformer bushings above 69 kv is approximately 5 per cent above the test gap level. The present impulse test code specifies that in test (*b*) the bushing be flashed over at 5 per cent overvoltage. The maximum impulse voltage applied is, therefore, 10 per cent above the minimum full-wave flashover of the test gap.

Since the basic insulation level given in the EEI-NEMA report corresponds to the minimum full-wave flashover of the test gaps, the chopped-wave test should be 110 per cent of the basic insulation level.

The present test code specifies that the full wave must be not less than 90 per cent of the standard minimum flashover voltage of the standard bushings. Since the basic insulation level or test-gap level is 5 per cent over the standard-bushing level, the new full-wave test should be 95 per cent of the basic level.

To agree with the recommendations made by the subcommittee since this report was written, the 100 kv and 115 kv given in columns 3 and 4 of table II should be changed to 95 kv and 110 kv, respectively. The 110 kv given in column 3 of table III should be changed to 105 kv. The reason for this change is that the EEI-NEMA report has a footnote to table I, page 711 of the June issue of ELECTRICAL ENGINEERING, to the effect that consideration should be given to increasing by approximately 10 per cent, the basic level of 100 kv.

The 100-, 115-, and 110-kv values given in tables II and III, respectively (mentioned above) were based on a basic

*Figure 1, page 480, April 1937 issue of ELECTRICAL ENGINEERING, discussion of paper entitled "Dielectric Strength of Transformer Insulation," by P. L. Bellaschi and W. L. Teague.

impulse level of 105 kv instead of 100 kv in anticipating that the basic level would be increased later. It appears rather doubtful now that the 100-kv basic level will be changed.

In connection with the question of gapping bushings on which the report requests comments, now that the impulse test level will soon be expressed in kilovolts and the bushing will no longer be used as a voltmeter during the impulse test, there is no need for gaps on bushings.

However, as a protection to the bushing in those cases where other protective equipment is not provided, a gap may be used in the station to prevent flashover of the bushing and damage to the porcelain by follow current.

Since the volt-time curves of gaps and bushings are similar in shape the spacing of the gap should be at least 10 to 15 per cent below the ungapped-bushing positive-wave flashover, but not low enough to cause undue outages by flashover of the gap. The gap will provide protection to the bushing over quite a wide range of impulse waves. It should be understood, however, that a gap of this spacing will serve only as a protection to the bushing and cannot be depended upon to protect the winding from steep waves because the volt-time curve of insulation is relatively flat.

**J. R. North** (Commonwealth & Southern Corporation, Jackson, Mich.): This report presents a most excellent summary, both historical and factual, of the insulation strength of transformers and will be highly appreciated by the industry. It will serve not only as a valuable reference report, but will also eliminate confusion in the minds of those who have not been able to follow closely the developments which have taken place during recent years.

Discussion is invited regarding gaps on bushings. In our opinion, based upon experience and analytical studies, the manufacturers' practice of furnishing short rod gaps mounted directly on bushings is very undesirable and should be discontinued for the following reasons:

(*a*) These gaps tend to lead the arc directly along the porcelain and thus they represent a distinct hazard because of the possibility of damage to the porcelain and serious interruption in case of arc-over.

(*b*) These gaps give a false sense of security against lightning surges since the protection is limited to the gap flashover voltage and the volt-time characteristic of the gap may be widely different from that of the insulation to be protected.

(*c*) It is not always realized that care must be taken to insure that the low gap setting required to give some degree of protection does not cause unnecessary service interruptions during switching surges.

We agree, of course, with the thought that suitable lightning protective devices should be installed at stations to protect apparatus from lightning surges. However, these devices should be installed in such a manner as to give proper protection without jeopardizing service or equipment.

An interesting definition of a "directly grounded circuit" appears in the note at the bottom of page 749. We would like to inquire as to the derivation of this statement and how it relates to the values of sequence impedances and sound phase voltages to ground.

Referring to table II, it is believed that the test levels for distribution transformers should correctly be limited to ratings of 69 kv and below.

## Basic Impulse Insulation Levels

**Discussion of a paper by the EEI-NEMA Joint Committee on System Insulation Co-ordination, published in the June 1937 issue, pages 711–12, and presented for oral discussion at the insulation co-ordination session of the summer convention, Milwaukee, Wis., June 25, 1937.**

**V. M. Montsinger:** See discussion, page 1297.

**F. J. Vogel:** See discussion, page 1295.

**J. H. Foote** (Commonwealth & Southern Corporation, Jackson, Mich.): This report presents the basic insulation levels expressed in terms of voltage which were agreed upon as the result of a thorough study by the joint EEI-NEMA committee of apparatus performance records, operating conditions, and the characteristics of available lightning protective devices. The next step in the work of the committee is, as stated in the report, "specification of insulation strengths of all classes of equipment in the established insulation levels." It will be noted that a change is necessary in the wording of the scope of the committee, item 2, on page 711.

In presenting table I, "Basic Impulse Insulation Levels," an important note has been omitted. The basic levels are intended to be reference levels. A statement should therefore be included with the table to the effect that apparatus to be suitable for operation in the voltage classifications must have insulation which has an impulse strength at least equal to and presumably greater than the levels as expressed in kilovolts. Insulation strengths in excess of the levels are satisfactory.

In our opinion, the basic insulation level of 100 kv for the 15-kv classification should be raised approximately 10 per cent to a value of 110 kv to line up with the other levels and to properly fit with available lightning protective devices. The basic level of the 34.5-kv classification should also be raised from 190 to 200 kv, to be consistent with the immediately adjacent levels.

The first column of table I is entitled "Maximum Rated Voltage Classification." These named voltage classes are intended chiefly as indexes and the column should better be labeled "Present Standard Voltage Class" or some similar title.

The voltage classifications are those at present generally associated with these values. Basic insulation levels a step higher or lower than shown as associated with the voltage classifications may often be used. For example, where lightning arresters of less than full voltage rating can be utilized on systems having the neutral effectively grounded, insulation levels one step below the basic levels can generally be protected.

## Tests on Oil-Impregnated Paper—II

**Discussion and author's closure of a paper by Hubert H. Race published in the July 1937 issue, pages 845–9, and presented for oral discussion at the communication and research session of the summer convention, Milwaukee, Wis., June 25, 1937.**

**Herman Halperin** (Commonwealth Edison Company, Chicago, Ill.): It was of considerable interest to learn that high power-factor oil does not seem to mean correspondingly high power factor for the impregnated-paper insulation. We have found some increases in the power factor of core oil in the oil-filled cables in service in Chicago. The typical value of power factor of the core oil in new cable was about 2 per cent at 100 degrees centigrade. Since the lines have been in service, it has been found that typical values are about 0.8 and 5 per cent at 60 and 100 degrees centigrade, respectively. In some cases the power factors are higher; for example 15 per cent at 100 degrees centigrade. So far these power factors do not seem to be increasing after the changes occurring in the first few years of service, and there have been no indications of changes in the insulation from what tests have been made on short lines or from temperature measurements on other cable on longer lines.

It is hoped that the author is correct in his deduction that oxidized oil does not appreciably affect the life of samples which are gas-free. In tests on experimental oil-filled 132-kv cables, we have found in one case that changes did not occur until after 3 years of deterioration. Conclusions from this experience as well as from the observations of others, especially the English cable makers on their tests of one year and more, are that unusual phenomena may take a matter of several months or more to develop and give evidence of their presence by means of power-factor tests.

However, the quality of insulation should not be judged on the basis of life on voltage only. Doctor Race found that there is no apparent correlation between life and increase in power factor due to oxidation. In the practical operation of oil-filled cable, such excessive increases in dielectric losses and resultant decreases in carrying capacity can terminate the useful life of the cable without failures occurring.

The conclusion of the author about the longer life of gas-free oil-impregnated paper at one atmosphere as compared to similar cable with gas at pressures up to 200 pounds per square inch is of vital interest in connection with the discussions and tests during the past several years on the various gas-pressure types of cable to operate at 180 or 200 pounds per square inch. The implication of the author's conclusion is that oil-filled cables installed in the regular manner are preferable to these other types of cables

In interpreting these results, it should be kept in mind, however, that the miniature samples do not represent truly pressure-type cables. In the Hochstadter-Bowden-Vogel pressure cable and the Henley gas-cushion cable, and in some other types, the insulation is impregnated with a heavy, degasified compound, and the insulation is not in direct

contact with the gas. In Doctor Race's samples the oil is thin and gas-saturated and is in contact with the gas space. Most of the samples tested under gas pressure were surrounded by a gas space while the degasified samples were surrounded by a large oil volume. It appears that the difference in heat conductivity of the surrounding media might have influenced the test results. It should also be kept in mind that gaseous ionization is depending on both pressure and stress. While 200 pounds per square inch might not be sufficient at the stresses used in the accelerated life tests to prevent ionization, it might be quite sufficient at the lower stresses occurring in normal cable operation.

**G. M. L. Sommerman** (American Steel & Wire Company, Worcester, Mass.): In connection with the results for specimen 225, for which the saturant was a used oil from an oil-filled cable in service, Doctor Race states that high power factor of oil does not mean correspondingly high power factor of oil-impregnated paper. From figure 2 it is seen that the oil power factor when first measured at 100 degrees centigrade was 0.15, but after heating to 115 degrees centigrade the power factor at 100 degrees centigrade was 0.12. This suggests that part of the high measured power factor of the used oil was due to the presence of moisture or other impurities which could be volatilized, and that the power factor of the oil was much less than that indicated, probably less than 0.05 at 100 degrees centigrade, after the vacuum treatment in the impregnation process. The writer reported (ELECTRICAL ENGINEERING, 1937, page 572) a relationship between power factor of oil and power factor of impregnated paper, but it is necessary to consider the power factors of the vacuum-treated oils in order to obtain this correlation.

The conclusion that high power factor of oil-impregnated paper does not necessarily mean short life as long as temperature equilibrium is maintained confirms a similar conclusion reached by Professor Whitehead (AIEE TRANSACTIONS, 1933, page 1011). Also, in a previous discussion (ELECTRICAL ENGINEERING, 1936, page 1141), the writer pointed out that dielectric loss has no bearing on cable insulation life, unless the insulation loss is comparable with the maximum allowable conductor loss.

The comparison between the life of gas-free, oil-filled cables and the life of compressed gas-filled impregnated cables is dependent on the test conditions, because the life of gas-filled cables is very markedly dependent on the electric stress for stresses in excess of that necessary to initiate gaseous ionization. For the test specimens used by Doctor Race and a test voltage of 22 kv, the stress on a gas film at the conductor surface would be about 1,100 volts per mil if the conductor were smooth; it is actually even greater due to the fact that the conductors are threaded. The breakdown strength of thin films of carbon dioxide or nitrogen under 200 pounds per square inch pressure is about 800 volts per mil. It is therefore indicated that considerable gaseous ionization occurred in testing the specimens which were drained and saturated with compressed gas. If these specimens were prepared with smooth conductors and tested at a voltage of 13 kv (average stress of 200 volts per mil), they probably would last indefinitely.

**Hubert H. Race:** The first sentence of the second paragraph of Mr. Halperin's discussion is a misstatement of the conclusions drawn from the data presented. While the oil used to impregnate specimen number 202 had high power factor we have no evidence that it was oxidized, and precautions were taken using an evacuated reservoir so that the oil was not in contact with air at any time. Its high power factor was probably caused by asphaltic varnish dissolved from the tape used in making the joint from which it was drawn. The interesting points learned from this specimen are that the power factor of the impregnated paper was much lower than that of the oil alone (see figure 2), and that its stability was good and its life relatively long (150 days at 22 kv and 123 days at 30 kv. See figure 1).

On the other hand, specimens numbers 201 and 202, which were gas free but were impregnated with preoxidized oil, showed less stable life histories and very much shorter life than any other specimens in this group (see figure 1). Also, table VIII shows that upon post-mortem examination, the oil-impregnated paper from specimen number 202, containing preoxidized oil, was much more nonuniform and had from 2 to 10 times the dielectric loss of specimen number 225, containing used oil. It seems to me that these data contradict Mr. Halperin's statement.

I agree with the first and last sentences of the third paragraph of Mr. Halperin's comments—that, from the point of view of the operator, high power factor with its attendant power losses and decrease in current carrying capacity is important. However, for our miniature tests the second sentence of this paragraph is misleading in that as far as is experimentally possible all specimens in the third group were oxygen free, being completely sealed after drying and evacuation to 0.1 micron pressure. Therefore, deterioration during life was not comparable to conditions which might exist in a cable in service if air is accidentally entrapped during installation.

Regarding the last paragraphs of both Mr. Halperin's and Mr. Sommerman's comments, I doubt whether small differences in thermal conductivity had any appreciable effect on life since we have found little difference between tests on gas-free specimens at 60 degrees centigrade and 100 degrees centigrade. Gaseous ionization is certainly a function of both pressure and stresses and it is probable that for any pressure there is a gradient below which little ionization will occur. To say the least, it seems to me that our tests show that the gas-free, oil-filled systems have a higher factor of safety than any gas saturated system up to 200 pounds per square inch pressure, which is the limit of our experimental experience.

Regarding the first paragraph of Mr. Sommerman's comments, I agree that the difference between heating and cooling points in figure 2 was probably caused by the removal of moisture. The point illustrated by this specimen is that the power factor of impregnated paper may be much lower than that of the oil with which it is impregnated. This depends upon the physical properties of the paper and upon the nature of the material in solution or in suspension in the oil causing its high conductivity. In this case I believe the solute was asphaltic varnish, as already mentioned.

# The Dielectric Strength of Noninflammable Synthetic Insulating Oils

**Discussion and author's closure of a paper by F. M. Clark published in the June 1937 issue, pages 671–6, and presented for oral discussion at the communication and research session of the summer convention, Milwaukee, Wis., June 25, 1937.**

**E. J. Rutan** (Consolidated Edison Company of New York, Inc., New York, N. Y.): It may be desirable to present data from an investigation being carried on as part of committee work in the ASTM on the breakdown voltage test method for synthetic insulating liquids. The present procedure requires 5 breakdowns on each cup filling. For synthetic liquids this may lead to reporting reduced values as seen from the accompanying figure.

The author does not state the details of his test procedure. It might be well if he did so as regards the number of shots and number of fillings in arriving at values of dielectric strength.

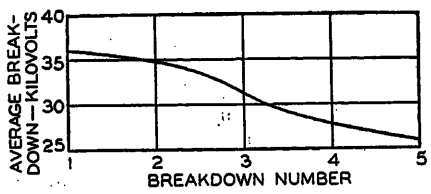



**Figure 1. Dielectric-strength tests on 80 fillings of new and used Pyranol, 1934–35**

Relative breakdown voltage of each of 5 succeeding breakdowns on the same filling of the test cup

**Herman Halperin** (Commonwealth Edison Company, Chicago, Ill.): While this paper presents very interesting information, it leaves unanswered important questions regarding power factor, thermal properties, and chemical characteristics. It is true that these properties are not within the scope of the paper, but in connection with oil-impregnated paper insulation these properties may be of greater practical importance in some instances than dielectric strength.

It is stated that the Pyranol compounds are mixtures prepared to give the desired physical characteristics for various purposes. No data are presented to show that the results of the one mixture covered in the paper are representative for the various Pyranol compounds, or to show the effect of composition on dielectric strength.

Since the dielectric strength of mineral oil is largely dependent on treatment, the differences in dielectric strength shown between Pyranol and transformer oil might for some types of oil with proper treatment be

reduced to practically zero. The author's information, however, does indicate that the Pyranol will retain its dielectric strength better than mineral oil.

The oxidation stability of Pyranol is emphasized, however, on the basis of figure 2. It is known that, for at least mineral oils, dielectric strength is not a reliable criterion of oxidation, and more information on this matter for Pyranol would be of interest. For impregnated-paper insulation, it has been found that the short-time breakdown tests are not a reliable criterion of the performance of the insulation in service. Long-time data would be of interest and value.

**V. M. Montsinger** (General Electric Company, Pittsfield, Mass.): I wish to discuss this paper from the standpoint of using noninflammable synthetic liquid in power transformers.

While up to the present time this synthetic liquid has been used mostly in distribution transformers, 500 kva and less, there is an increasing demand and application in power transformers. Up to the present time the General Electric Company has built a total of approximately 60,000 kva of power transformers using the noninflammable synthetic liquid. Approximately 80,000 kva more are under construction.

One particularly suitable case is where transformers are used in electric cars and locomotives where light weight and small dimensions are essential and noninflammability is important. In the past, locomotive transformers of the air-blast type have been used but they were not entirely successful, as it is difficult to keep dirt and moisture out of the coils. Space limitations prevent using factors of safety high enough to take care of these impurities that get into air-cooled coils, and as a result these transformers have not been immune from failure. Since, for a given spacing, a synthetic liquid (or oil) gives from 3 to 4 times the dielectric strength of air it can readily be appreciated what a noninflammable liquid means in the way of improvement in the design of locomotive transformers. It not only enables one to build a transformer with greatly increased dielectric strength, but makes it possible to maintain this high strength during its entire life. Several such transformers are already in service and the indications are that their use will rapidly increase.

There are also some other cases where a synthetic noninflammable liquid can be used to advantage in power transformers, namely, where the use of an inflammable oil is impractical or forbidden and the voltage is too high for transformers of the air-blast type. In such cases on account of the high cost of the liquid, great pains are taken in the design to reduce the amount of liquid required to a minimum. This minimum liquid space is obtained by the use of a design of tank which reduces the amount of liquid to a minimum. The additional cost of the tank is more than offset by the saving in the amount of the noninflammable liquid.

There are, of course, means of using nonabsorbent high-dielectric-strength materials to displace some of the expensive liquid, provided sufficient clearance is left to allow the necessary flow of oil to carry the heat from the core and coils to the cooling tank surface. Laboratory investigations have shown that the amount of liquid necessary to dissipate the heat is very much less than the amount ordinarily required to fill the transformer.

The broad use of this noninflammable liquid in power transformers for general purposes depends largely upon 2 important factors.

1. Lower cost resulting from improved technique and skill in manufacture of the liquid and from its use in larger quantities.
2. Means for making further reductions in the amount of liquid required in a given transformer.

Both of these developments are being pushed aggressively.

There is no question but that the time is coming when all power transformers will be built with a noninflammable synthetic liquid.

**L. J. N. Mothersill** (Philco Products, Ltd., Toronto, Ont., Canada): Mr. Clark publishes a comparison of 40 capacitor sections with mineral oil and with chlorinated hydrocarbon impregnant subjected to a stress of 733 volts per mil. What percentage of the conservative working stress is this value in the application of these liquids to (*a*) transformers, (*b*) cable, (*c*) capacitors? In computing probable life of capacitors from accelerated life test at higher than rated voltage it is customary to employ an inverse power relation which has been stated at anywhere from the inverse of the fourth to eighth power of the applied voltage. What exponent is suitable with these liquids and does the author favor direct current or alternating current for such life testing? I would be interested in the drying and impregnation times of the samples.

In a paper published by Jackson, *Proceedings* of the Royal Society, volume 153, the temperature power-factor characteristic of chlorinated diphenyls is reviewed and the power factor shows a decided hump near the solidifying point of the compound and also a decrease in the dielectric constant. Is this general with this type of liquid dielectric? This would appear to affect operation of capacitors in cold climates considerably. It would be of interest in the corona test procedure to know if the foils protrude from the ends of the section (i.e., if they are staggered to give the so-called noninductive winding)? Is the capacitor tissue employed of standard or of special quality and what is the relative value of super calendered and more porous papers? The writer has had some experience with the application of solid chlorinated compounds as capacitor impregnants and would be interested in comparison of the newer liquid impregnants with, say, chlorinated naphthalene. In matching paper and impregnant dielectric constants is it advisable to utilize a paper with high constant but also with accompanying high power factor? These points of discussion apply to cable and to capacitors as well as to transformers in a lesser extent but in the capacitor the stress effect is more easily segregated from temperature effects and that is the reason for approaching the discussion from this angle.

In connection with the chemical stability, the writer has noticed that chlorinated naphthalene gives rise to serious erythema on skin exposed to vapor or solutions of the wax. Is this experienced with the Pyranol type of compound?

**E. W. Greenfield** (Anaconda Wire and Cable Company, Hastings-on-Hudson, N. Y.): The dielectric properties of these chlorinated derivatives of cyclic organic hydrocarbons as reported by Mr. Clark are exceedingly interesting. Three characteristics are outstanding, namely, high initial dielectric strength, high chemical stability (as based on dielectric strength measurements), and high dielectric constant.

Although we have occasionally noted dielectric strength of clean dry mineral transformer oil as high as 40 kv (ASTM), there appears to be little doubt from the figures reported by Mr. Clark that the synthetic dielectric liquid possesses a consistently greater electrical strength. It is suggested that the basis of this difference lies in the relatively greater specific gravity and thermal conductivity of the synthetic liquid rather than in a greater ionization potential of the molecule. The conventional dielectric strength tests on oils involve both electric and thermal effects so that impulse dielectric strength testing would be highly desirable in determining the cause of the observed phenomena.

Of the 2 synthetic dielectric liquids studied, Mr. Clark describes a "viscous" type which is indicated as being commercially available for use as a cable saturant. It is assumed from the nature of the data that this synthetic cable saturant is offered as a possible substitute for unsynthesized oils in high-voltage impregnated-paper cables and as such may present certain advantages. Several remarks concerning this use of the new liquids are pertinent.

Table I giving certain physical properties of the viscous synthetic liquid shows a viscosity at 210 degrees Fahrenheit of only 48 seconds (S.U.). This would indicate that the liquid is much less viscous than those saturants normally associated with solid type cable which have viscosities in the neighborhood of 100 to 150 seconds (S.U.) at the same temperature. From the same table I, the pour point of the synthetic liquid is given as +10 degrees centigrade (50 degrees Fahrenheit) which would immediately exclude its use from the field of oil-filled cables, the saturant of which must be limpid at all service temperatures. However, the situation is not as incompatible as at first apparent. From the standpoint of the solid-type cable and its own particular problems, the flow characteristics of the synthetic liquid may be such as to provide a low impregnating viscosity and a high viscosity over the operating temperature of the cable. These features might be desirable, particularly in the so-called "nonmigrating compound" cable applications. However, there is no indication from table I what the flow characteristics are and it is to be hoped that Mr. Clark, in his closure, will present a viscosity-temperature curve of the synthetic liquid under discussion. Data on surface tension and wetting characteristics would also be valuable.

Oxidation stability of cable saturants is normally evaluated on the basis of accelerated aging in the presence of air at high temperature. Of all the dielectric properties studied, dielectric strength is the

least sensitive to the chemical changes taking place during aging whereas power factor is perhaps the most sensitive. This is also apparent from figure 1 for transformer-type oils at least over a period of the first 20 days. It is to be regretted that power factor measurements were not made during this same period since any difference in induction phenomena would have been easily apparent.

By increasing the dielectric constant of the saturant, the synthetic-liquid-impregnated papers present a more equitable distribution of stress. The increase in dielectric strength of the laboratory samples when impregnated with the synthetic liquid is probably a result of this more uniform stress distribution in combination with the higher dielectric strength of the saturant. However, it must be pointed out that, in the absence of any description of the test cell or test conditions, no comparisons can be drawn from these results with actual thick-wall cable conditions. In long-life tests of cable samples, dielectric energy loss and gaseous ionization are most important factors. In cases where gaseous ionization may be present, the increased dielectric constant of the saturant may place a heavier stress burden on the vacuous or gas phases, thus lowering the initiating ionizing potential of the entire cable. This, in combination with a high over-all dielectric constant (and generally accompanying high power factor), may place the synthetic liquid saturated cable in a disadvantageous position. Although high dielectric strength of the impregnated paper material as such is desirable, it by no means can serve as a criterion for the quality and stability of the power cable.

**F. M. Clark:** In considering the characteristics and industrial application of new types of dielectric compounds, the attempt is frequently made to evaluate the new materials from the standpoint of the experience accumulated in applying the older type of compounds which are to be replaced. This frequently leads to confusion and error since many of the ideas developed from experience with the older compounds apply only to such compounds but are often accepted as generalizations of fundamental value. Such an evaluation is to be particularly avoided when the chemical type of compound is so radically changed as in the subject matter of the present paper, wherein the oxidizable hydrocarbon molecules of mineral oil are considered in comparison with the nonoxidizable molecules of chlorinated aromatic hydrocarbons. It is particularly unfortunate that space would not allow me to discuss the dielectric loss characteristics of the compounds presented in this paper. To discuss adequately the dielectric properties of these compounds other than the dielectric strength is also impossible in my closure. I prefer rather to present the data concerning the dielectric loss and dielectric constant characteristics of these materials in a separate paper at some future date.

Mr. Rutan asks whether the dielectric strength data represent single-shot values or the average of a series of tests. All dielectric strength data presented in the paper are the average of a series of 5 tests for each filling of the dielectric-strength test cup. In each case, 3 distinct samples of the dielectric liquid were tested and the total of 15 dielectric test "shots" was averaged. The testing procedure is in accordance with the usual commercial and ASTM practice. In testing the dielectric strength of any liquid carbonization results with each arc-over, the amount of carbonization depending upon the period during which the electric arc is allowed to play. In the test setup used in the present paper, the arc duration is reduced sufficiently in time such that the tendency of a single sample to drop in dielectric strength from the first to the fifth "shot" has been eliminated. With longer time of arc duration, the tendency described by Mr. Rutan is recognized to exist. This drop, however, involves atmospheric conditions of humidity and is most pronounced with increasing water content in the air in contact with the liquid under test.

I appreciate the comments of Mr. V. M. Montsinger. His enthusiasm concerning the commercial possibilities in these liquids strengthens my own. Materials such as described, characterized by a high and permanent dielectric strength, nonoxidizable and of high dielectric constant, possess highly desirable dielectric characteristics.

The 733 volts per mil used in the long-time tests referred to by Mr. Mothersill represent approximately twice the normal working stress of capacitors and a considerably higher ratio to the average working stress of oil-filled cables. In the case of transformers, the usual working stress is considerably lower because of design differences. It is probably possible to predict more reliably the relationship between commercial life and higher-than-rated-voltage short-time life test results under laboratory conditions, using the chlorinated-hydrocarbon-impregnated insulation, than with mineral-oil-treated insulation. This follows because of the chemical stability of the chlorinated hydrocarbon as compared to the susceptibility of mineral oil to change. However, the value of such a relationship, especially for mineral-oil-treated insulation, may well be doubted. Sufficient data are not available in the case of the chlorinated-hydrocarbon-treated insulation to warrant a statement at this time. Furthermore, it is to be observed as stated in the publication that the dielectric failures with the chlorinated-hydrocarbon-treated insulation are so infrequent that no attempt is warranted to establish an empirical relationship between the 733 volts per mil and commercial ratings. The dielectric assemblies referred to were dried at 100–105 degrees centigrade under a pressure of less than 300 microns over a period of 48 hours, after which they were impregnated with the insulating liquid over a period of 24 hours, during which the whole assembly was kept under heat and vacuum after which the assemblies were cooled to room temperature under vacuum while immersed in the treating liquid.

Mr. Mothersill refers to a publication by Jackson in which it is described that the power factor had "a decided hump near the solidifying point." This change is not peculiar for the chlorinated hydrocarbons but occurs with all liquids undergoing a change in state. The actual temperature at which it occurs with mineral oil depends upon the physical characteristics of the oil. We have never found that the changes as described by Jackson are at all effective in determining the dielectric strength and permanency of the chlorinated-hydrocarbon-treated insulation.

All tests for corona formation were made with electrode arrangements in which the edges of the electrodes were practically superimposed. The dielectrics in all cases were of standard commercial quality with no special preparation. It is impossible to compare the dielectric characteristics of chlorinated naphthalene with those of the newer liquid impregnants as requested by Mr. Mothersill. The chlorinated naphthalenes of best dielectric characteristics are high-melting solids limited in their voltage application because of crystalline tendencies. The liquids have the advantage of being able to be operated at higher voltage stresses because of the absence of void formation, the usual accompanying feature of crystalline formation in solids.

Mr. Mothersill requests information concerning the relative toxicity of chlorinated naphthalenes and the chlorinated hydrocarbons described in the paper under discussion. Conclusions concerning this point must be postponed until investigations now in progress have been completed. In the work with which I am familiar, no serious erythema has been encountered.

The present paper describes the dielectric characteristics of blends of chlorinated hydrocarbons and single component mixtures. It has been found that blends in general show the same dielectric-strength characteristics as exhibited by the individual components.

In the dielectric-strength data of the paper, no special treatment has been given either the mineral oil or the chlorinated hydrocarbon aside from the usual commercial preparation. Mr. Halperin's speculation that the differences in dielectric strength between the chlorinated hydrocarbons and the transformer oil mixtures "might be reduced to zero with proper treatment" does not appear to be substantiated in fact.

Figure 2 referred to by Mr. Halperin was in no sense given as an indication that dielectric strength was a criterion of oxidation. Figure 2 was given to demonstrate the ability of the chlorinated hydrocarbon to retain its dielectric strength even under the most severe water-contaminating conditions. It is recognized that low dielectric-strength values are the inevitable result of water contamination in mineral oil.

In answer to many of the comments of Mr. E. W. Greenfield, I refer him to an article entitled "Nonflammable Dielectric Organic Compounds," published in *Industrial and Engineering Chemistry* for June 1937, pages 698–702. The accumulated evidence tends to indicate that the dangers arising from the ionization of trapped gas pockets are materially reduced by the use of chlorinated-hydrocarbon liquids. Whether or not a gas pocket will form in insulation depends upon many factors involving the physical characteristics of the impregnating liquid and the solubility of gases therein. The characteristics of the chlorinated hydrocarbon liquids described in the present paper on the basis of experience seem particularly well adapted to eliminate or reduce the ionization dangers which have been the subject of so much investigation and concern in oil-treated dielectrics.

# Properties of Saturants for Paper-Insulated Cables

**Discussion and author's closure of a paper by G. M. L. Sommerman published in the May 1937 issue, pages 566–76, and presented for oral discussion at the communication and research session of the summer convention, Milwaukee, Wis., June 25, 1937.**

**Herman Halperin** (Commonwealth Edison Company, Chicago, Ill.): This paper gives some excellent information on the properties of cable saturants with and without resin added. The data show that the addition of suitable resin to some oils improves the aging properties considerably without deleterious effects on other properties. I was particularly interested in noting that the resultant impregnated-paper insulation had low dielectric losses.

The author's work has in general been carried up to the temperature of 85 degrees centigrade. We have established emergency ratings for cables operating at 4 kv to 33 kv in Chicago based on maximum allowable temperatures ranging from 90 degrees to 105 degrees centigrade, depending on the cable. Although such operation is not expected to occur in more than one day every year or every few years for a given line, yet it seems that the author's work would have been of a little more interest if his temperatures had been carried above 85 degrees centigrade.

Mr. Sommerman found that the stability of naphthenic oils might be improved if better methods of refining them were used. Interest in insulating oils on the part of oil refiners has increased recently and data of this kind should expedite the procurement of better oils. It is indicated that naphthenic oils are more stable to gaseous ionization than paraffinic oils but are less stable to oxidation. In cable insulation of the ordinary or solid type, some void spaces are certain to occur incidental to manufacture and to installation and operation, and stability to gaseous ionization in high-voltage cable is of great importance. The initial losses in cables now being manufactured are low and slight increases due to oxidation, although not desirable, are less important than increases in losses due to ionization because the small amount of available oxygen can be consumed, but the changes due to ionization may be cumulative. At present, it appears, therefore, that long life and best over-all economy will be gained by emphasis on immunity to effects of ionization at the expense, if necessary, of some loss in oxidation stability.

**Wm. A. Del Mar** (Habirshaw Cable & Wire Corporation, Yonkers, N. Y.): Two types of saturants are now in use in American paper-insulated cables one a naphthenic base oil of tacky consistency and the other a paraffin base oil mixed with rosin.

Cable users naturally wish to know which is the better saturant and why some manufacturers use the pure mineral oil, while others use the rosin blend.

I do not think that the time has come to make a final decision between the 2 types as there is not enough difference to permit a completely logical choice to be made. The prospects of improvement are brighter while the 2 types are both available, as this condition leaves open 2 avenues of development, rather than one.

The case, as I see it, may be summarized as follows:

ARGUMENTS FOR NAPHTHENE-BASE OIL

1. It does not leave deposits in the tanks and pipes and thus saves expensive and time-consuming cleanings, which are necessary with rosin blends. However important this may be to the manufacturer, it does not affect the cable user.

2. It gives somewhat lower initial dielectric loss at high temperatures, i.e., above 60 degrees centigrade.

ARGUMENTS FOR PARAFFIN-BASE OIL BLEND

1. Ability to maintain a constant initial quality by blending oils from several sources of supply. This is not practicable with the tacky naphthene-base oil.

2. Less susceptibility to oxidation, as shown by Doctor Sommerman.

3. Less migration of saturant, due to greater viscosity.

4. Somewhat greater stability when subjected to electrical discharge in vacuo.

Our research laboratory has made a series of load-cycle life tests to compare cables made with the 2 types of saturants and found little difference, such difference as

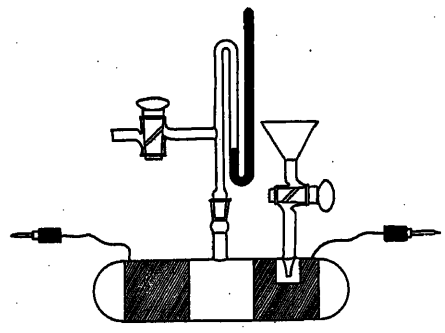


**Figure 1. Oil stability tester**

there was being consistently in favor of the rosin type. This finding is substantiated by data given by Halperin and Betzer, ELECTRICAL ENGINEERING, October 1936.

The laboratory also made tests of electrical stability in the presence of electrical discharges in vacuo, taking as starting point the work of Z. W. Nederbragt, referred to as number 10 in Doctor Sommerman's bibliography.

This test is based on the well-known fact that insulating oils may give off gas, chiefly hydrogen, under the influence of electric discharge. To determine how various compounds compare with each other in this respect, we have arranged a test set wherein a sample of a given oil is degassed to a constant pressure (1.0 millimeter mercury absolute) in a discharge tube, and then subjected to a glow discharge. The amount of gassing is then measured by the pressure rise in the tube, as indicated by a mercury manometer. The sample is tested for power factor and resistivity before and after exposure to the electrical discharge.

Figure 1 shows the oil stability tester or discharge tube. It is similar to Nederbragt's discharge tube but has added the funnel, stop-cock, and nozzle, shown to the right. These make possible a closer control in the preparation of the oil sample to be tested, it having been found that the rate of gas evolution is greatly affected by the degree of degassification of the oil, as well as by the initial vacuum. The electrodes consist of tin foil wrapped around the outside of tube at each end. Quoting Nederbragt:

"On its way from one tin-foil coating to the other, the current passes through the glass as a displacement current, then as an electron, and ion current through the gas space, and finally again through the glass. A small portion of the current passes through the glass where this is covered with oil and therefore also passes through the oil as a displacement current."

The electrical circuit is shown in figure 2.

A current of slightly under a milliampere is passed through the apparatus with a voltage of about 15,000. We used 60-cycle voltage as being nearer to practical conditions than Nederbragt's 7,500 cycles. The oil becomes agitated and foams, evolving gas and depositing a filmy residue of cable wax.

Typical results are shown by figure 3 in which curve *A* represents a paraffin base oil with 15 per cent rosin. Curve *C* represents the same oil without rosin. Naphthene base oil, as used in solid type cables, gave curves that coincided substantially with curve *C* except that there was less downward tendency at the right-hand side. In other words, the 2 pure oils were substantially equal. The addition of rosin improved the paraffin oil.

Oil-filled-cable oil shows less than half the gas evolution of oil *A*. The oil now used by all the oil-filled-cable makers is the same and has proved to be the best, from the standpoint of gas evolution, of any oil so far tested. There are, however, prospects of improvement.

The different types of failure which occur on load-cycle life test have been puzzling, as have the irregularity of results on apparently identical cables. It is hoped that these oil tests will throw some light on this problem. The apparent irregularities may turn out to be the results of a race between gas evolution and rising power factor. The stability of power factor and resistivity promises to be as significant as gas evolution but we are not yet prepared to make any report on it.

This work is in active progress and it is impossible to predict what will come out of it. We hope, however, to be able to publish more details in the course of a few months.

**L. J. Berberich** (Westinghouse Electric & Manufacturing Company, East Pittsburgh, Pa.): In the last 10 years there has been

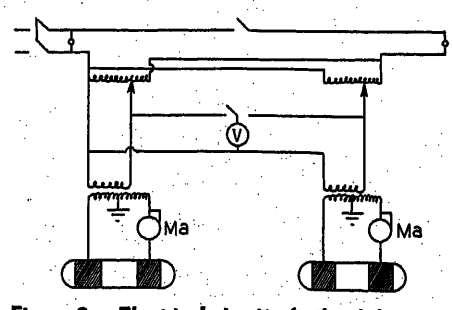



**Figure 2. Electrical circuit of oil stability test set**

considerable controversy over the use of rosin in cable saturants. The proponents and opponents of rosin are about equally divided. The reason for this division of opinion is perhaps twofold: (1) Whatever investigations of the effects of rosin that have been made were sketchy and did not cover the action of various types of rosins in various types of oils, and (2) the effects of rosin in terms of cable life have not been conclusively shown. Thus, it is encouraging to see Doctor Sommerman's paper,

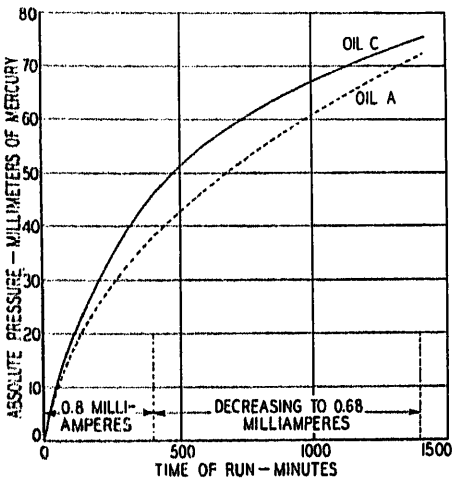



**Figure 3. Oil stability tests**

Temperature 35 degrees centigrade
Initial pressure = 1.0 millimeter of air

which reports for the first time the results of a careful, wide-range investigation covering various types of oils and rosins. Although the results indicate that a purified rosin compounded with the proper type of oil should result in better cable performance, yet definite proof of this is still lacking.

The addition of rosin to cable oils in the past by some manufacturers was encouraged perhaps because it was found that rosin increased the viscosity of the saturant and thus reduced migration, and that it showed some oxidation inhibition. This was done, however, at the expense of increasing the saturant power factor. More recently, however, purified forms of rosin have become available and, as Doctor Sommerman shows, these can be added to mineral oils with little or no increase in saturant power factor

Rosin is believed to be active as an oxidation inhibitor because it itself is easily oxidized, that is, it consumes the oxygen dissolved in the saturant through the phenomenon of antoxidation. Apparently, however, its oxidation products have less effect on the cable power factor than those of mineral oil. The results of Piper, Thomas, and Smith[1] may provide an explanation for this. These investigators have shown that only low molecular weight oxidation products increase the power factor of impregnated paper to a significant extent, apparently because such products are selectively sorbed by the paper. Mineral oil appears to form more low molecular weight oxidation products than rosin does. Rosin itself is a mono-carboxylic acid and because of the peculiar nature of the compound and its high molecular weight, it does not contribute to the saturant power factor when freed of impurities.

Doctor Sommerman also shows that rosin decreases the wax formation for all types of oils studied when they were subjected to gaseous ionization. The writer has found in studying the gas evolution from oils in a low-pressure gaseous discharge that rosin actually increased the gas evolution from low-viscosity-index oils, while for oils of higher viscosity index, the gas evolution was decreased. It was also found that oils of low viscosity index formed considerable quantities of wax and very small amounts of gas and the reverse was true of oils of high viscosity index. This is corroborated by the work of Linder[2] who showed that for pure organic compounds the wax formed decreased as the hydrogen to carbon ratio of the compound increased. In other words, he found that the aromatic type of compound tended to polymerize to a waxy solid with little gas evolution while the paraffins formed little wax and considerable amounts of gas. This does not agree with figure 13 of Doctor Sommerman's paper. Thus it is suggested that in evaluating stability to gaseous ionization, both gas evolution and wax formation should be determined. In the writer's opinion, gas evolution is perhaps more dangerous than wax formation. The wax formed is a fair insulator and results in no serious harm, but the gas may spread throughout the cable and initiate more gaseous ionization which may become cumulative.

In analyzing the oils studied, Doctor Sommerman has listed 3 basic constituents; namely, "paraffinic," "naphthenic," and "residual." Although used in petroleum technology, the term "paraffinic" as related to molecular structure is a misnomer. All oils in the lubricating oil range which have been freed of wax contain no straight chain paraffins. Paraffins having molecular weights equivalent to those of cable oils or even transformer oils, would be solid at room temperature. Petroleum chemists now have evidence that the major portion of the heavier petroleum fractions are polycyclic naphthenes or cycoparaffins with varying lengths and numbers of paraffin side chains. In oils of high viscosity index, the side chains are numerous and long enough to dominate and in the low-viscosity-index oils, the naphthenic nucleus dominates since the side chains are probably small. Oils of very low viscosity index (below 0) contain considerable percentages of aromatic or benzenoid type of hydrocarbons again modified by side chains. This accounts for the steep slope of the viscosity-temperature curve of such oils. The problem of determining the structure of petroleum is exceedingly difficult because the various constituents lie so close to each other in physical and chemical properties that even the most refined methods of separation have failed to result in the isolation of individual compounds.

The data given by Doctor Sommerman should be of assistance to both the refiner and to the cable manufacturer.


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2. E. G. Linder and A. P. Davis, *Jour. Phys. Chem.*, volume 35, 1931, page 3649.


**G. M. L. Sommerman:** Mr. Halperin raises the question of the relative importance of oxidation stability and stability to gaseous ionization for cable saturants. The importance attached to oxidation stability varies greatly among different cable engineers and it has also fluctuated up and down, during the past 10 years. Only 2 or 3 years ago, the importance attached to oxidation stability was very high as evidenced by the number of researches started, and patents applied for on this subject. Just recently it has dropped to a rather low value. The true value is probably somewhere in between, especially when the cable manufacturing requirements are included in the consideration. Some oils possessing excellent stability to gaseous ionization are so poor in oxidation stability that it is impracticable for a cable manufacturer to use them as straight oils. The addition of 15 per cent improved resin to these oils increases the oxidation stability to a value exceeding that of the oils most stable to oxidation; at the same time the stability to gaseous ionization is increased to a value exceeding that of the oils most stable to gaseous ionization.

It may be noted that the increased oxidation stability imparted by resin additions which was observed in the tests of saturants alone is also evident in aging tests of impregnated paper.

Mr. Halperin states that for reasons involving emergency loadings on cables he is interested in power factor values at temperatures as high as 90 to 105 degrees centigrade (these temperatures are 20 degrees centigrade higher than maximum cable operating temperatures). Data at these higher temperatures were obtained on a number of samples, and these indicate that the power factor-temperature curves in figures 4, 5, and 6 may be extrapolated reliably to 105 degrees centigrade. If a measuring temperature somewhat above 85 degrees centigrade had been employed in the aging tests reported in figures 8 to 11, all the power factors would have been larger in nearly the same proportion, and the same comparisons and conclusions would have been obtained.

The writer is glad to note Mr. Del Mar's confirmatory evidence that the addition of rosin to a paraffin base oil reduces the gas evolution in gaseous ionization tests. The publication of his results on power factor stability in such tests will be awaited with interest.

Relative to the importance of wax formation of saturants exposed to gaseous ionization, mentioned by Doctor Berberich, it may be said that excessive wax formation must be avoided because the wax would interfere with the free radial movement of the saturant in the cable caused by load cycles. This radial movement is necessary for proper operation of cables.

Concerning the form of the wax formation versus viscosity index curve of oils (figure 13), it was recognized in the paper that the wax test results were not conclusive for the 2 oils of lowest viscosity index, and that the wax formation for these oils might actually be higher than that for oils of intermediate viscosity index. For oils in the lower viscosity index range, the behavior would be in accordance with Berberich's suggestion. For oils in the higher viscosity index range, however, the writer

observed that the wax formation as well as the gas evolution increased with increasing viscosity index. For these oils, the percentage of aromatic constituents is small in all cases, and the observed behavior may be due to a dependence on the degree of predominance of open chain groups or ring groups in the oil molecules, as suggested in the paper at the beginning of page 575.

## Oxidation in Insulating Oil

**Discussion and authors' closure of a paper by J. B. Whitehead and F. E. Mauritz published in the April 1937 issue, pages 465–74, and presented for oral discussion at the communication and research session of the summer convention, Milwaukee, Wis., June 25, 1937.**

**E. J. Rutan** (Consolidated Edison Company of New York, Inc., New York, N. Y.): In this paper the authors have attacked a problem which it seems has waited too long for definite data. Particularly interesting are the frequent straight-line relationships which their results develop. Examination of the data on acidity and saponification and its relation to power factor does disclose that the results depend on but a limited range. This is noticeable on figure 11 where one point seems to be used to determine a flattening of the curve. In figures 8 and 10 data are given for acidity number at 0.8 and 1.1 which when computed gives 2 additional points for figure 11 showing the curve to be flat when extended to higher acidity numbers.

In view of the fact that the authors state a change in the ratio of the type of acids is shown by figure 11 it is unfortunate that they did not measure power factor on samples having 0.8 and 1.1 acid number. This would have extended the curves in figures 12 and 13 and made the results more conclusive.

The writer would also like to inquire regarding the reliability of the electrometric acidity determinations. The authors discuss the method in considerable detail giving data on sensitivity and blank determinations but they do not state the limit of accuracy based on several checks of the same oxidation condition. This point is raised because in the ASTM a section has been working for several years on electrometric acidity methods but has been unable to recommend any method as yet as reliable although many methods have been investigated. It would be desirable to discuss this method because this paper will no doubt be referred to by many and the acidity method may be accepted without the necessary investigations.

To this writer the authors' conclusion number 5 does not seem reasonable. Usual experience with dielectric strength measurements on insulating oil in accordance with ASTM methods shows variations between samples of 3 kv which might be 10 per cent of the average. It does not seem reasonable therefore, to attempt to draw a curve through points of less than 1 per cent difference. In my opinion the authors should have plotted the measured values of breakdown voltage giving due consideration to the accuracy of the method. Thus their conclusion would have been that there is no noticeable effect of oxidation on breakdown voltage over the range investigated. It would also have been desirable if data for figure 16 had been carried to the higher acidity numbers. Comparison might be made between figure 16 and the mineral transformer oil results in figure 1 of the paper by F. M. Clark on "The Dielectric Strength of Noninflammable Synthetic Insulating Oils" (ELECTRICAL ENGINEERING, June 1937), which seem also to contradict the authors' conclusion number 5.

**Herman Halperin** (Commonwealth Edison Company, Chicago, Ill.): This paper is another stimulating addition to our knowledge of insulation as developed by Whitehead and his assistants.

It is remarkable and interesting to find that in most cases the authors show practically straight-line relations between the electrical and chemical properties. Several other investigators have failed to get such good agreement. It was especially remarkable that the power factor is proportional as well to the acid number as to the saponification number. It would be of interest to learn whether or not this proportionality still holds if the oil is allowed to form soaps. Our data and the data of some others indicate that the various oxidation products are quite different in their effect on the power factor.

Conclusion 2 is based on an inhibition period during which no carbon dioxide is formed and on figure 11. This inhibition period is in accord with some test results of R. W. Dornte (*Industrial and Engineering Chemistry*, volume 28, page 26, January 1936). Probably the high ratio of saponification number to acid number shown in figure 11 at low acid numbers is due to lack of sensitivity of the test for low acid numbers. This is suggested by the data shown in figure 10 indicating zero acid number initially. A slight change in the position of the line in figure 10 could flatten the curve of figure 11 toward a horizontal line.

**W. M. Goodhue** (Harvard University, Cambridge, Mass.): The paper raised a question in my mind concerning the comparison of oils from different sources. In the paper, a correlation between chemical and electrical properties is given for one oil and, as suggested by the authors, a similar correlation would probably be found if another oil were substituted. But this is not the same as saying that 2 oils from different sources can be directly compared electrically *if the independent variable is not time* but a chemical variable such as oxygen absorbed. The difficulty is that oil is not a chemical individual or even a single series of chemical compounds. The correlation between specific chemical and electrical properties would certainly depend on the proportion of compounds present among the different chemical series, and on the proportion of compounds present within a given series, as well as catalytic impurities. Therefore we have the likelihood of 2 dissimilar oils behaving with stability in reverse order compared to their electrical characteristics if a chemical independent variable such as oxygen absorption is used instead of time.

For example, in equation form, if

$$\text{oxygen absorption} = \alpha_1 t \text{ for oil number 1}$$
$$= \alpha_2 t \text{ for oil number 2}$$

where

$$t = \text{time}$$
$$\text{power factor} = \beta_1 t \text{ for oil number 1}$$
$$= \beta_2 t \text{ for oil number 2}$$

Then, on combining equations,

$$\text{power factor} = \frac{\beta_1}{\alpha_1} \times \text{oxygen absorption, for oil number 1}$$
$$= \frac{\beta_2}{\alpha_2} \times \text{oxygen absorption, for oil number 2}$$

Now with 2 dissimilar oils there is no assurance that $\beta_1/\alpha_1$ and $\beta_2/\alpha_2$ are in the same order as $\beta_1$ and $\beta_2$; therefore the change of variable in the power factor from time to oxygen absorption is unsafe, for the purpose of comparing the 2 oils concerning stability, that is in this case the increase of power factor with time.

Therefore I wish to insist that the chemical variables be used only for studying the performance of a single oil throughout its history. When comparing 2 oils, the fundamental variable of time must be used. The excellent curves employing time obtained by the authors themselves show that accuracy can be obtained in an oxidizing apparatus of specified surface areas and other dimensions. This is less empirical than employing a chemical variable instead of time, since with a chemical variable dissimilar oils are not even comparable.

The authors' contributions, however, are valuable, namely (1) a reliable test method for studying electrical properties versus time, under *standardized conditions* of exposure to oxidization and (2) methods of studying the chemical variables. Contribution 1 is suitable for comparing 2 dissimilar oils and contribution 2 is suitable for studying the improvement in manufacture of a single oil. Therefore what has been said in this discussion does not detract in any way from the value of the authors' work and, furthermore, may supplement it when applied to the question of standard testing methods for oils of unspecified origin.

**F. M. Clark** (General Electric Company, Pittsfield, Mass.): The paper by Whitehead and Mauritz describes a series of oxidation test results obtained with what is described as a "highly refined insulating oil as used in oil-filled cables." Data such as these suffer from the difficulty of interpretation and practical application. However, the continued accumulation of such data may eventually lead to the recognition of worthwhile relationships between the chemistry and the dielectric properties of mineral oils.

There is, however, an underlying thought in the paper which from my own experience demands further consideration because of the attempts which may be made to extend the idea beyond that specifically stated by the authors. This is the thought which is summarized in conclusion number 7.

Experiments in my own laboratory extending over a period of years tend to show that, when on oil of the type used in cables

and transformers is oxidized in the manner similar to that described by the authors, substantially the same results are obtained with regard to the linear relationships described. However, there are distinct exceptions to the linear relationship which appear unexpectedly as different oils are investigated or as the oxidation conditions are changed. Furthermore, even when the linear relations obtained by the authors are observed in a variety of oils, they are not of the same character. Although a linear relation between power factor and acid number or saponification may be obtained for 2 oils, the slope angle of the linear relation is rarely the same, indicating a different chemical value for the same power factor. It is because of such variations, which trace back to chemical differences in the oils tested, that but slow progress has been made in attempts to correlate chemical and electrical oil characteristics.

The usual method of estimating the suitability of consecutive shipments of impregnating oil from a definite source of supply is to study the physical and chemical properties of the oil, including an oxidation test and the effect of oxidation on the electrical properties of the oil. In such work, data such as that presented by the authors have been recognized as being of value in the detection of variations from the normal. Too often, however, such laboratory control-of-oil-shipment tests have assumed an importance out of all proportion to their original significance. Instead of being considered as tests to determine continuity of properties from one shipment to the next, they have come to be considered as of fundamental importance. This has led to widespread discussion of oxidation tests of all sorts. While it is true that no oil with abnormally low oxidation resistance would be looked upon favorably by a cable engineer, still the mere fact that an oil may have excellent resistance to oxidation, as measured by tests similar to those of the present paper, is no indication of its suitability for impregnation use. Many interested in the problem believe that just as the lubricating properties of an oil are to be evaluated best by actual test in contact with the bearing metal, so the suitability of an impregnating oil is to be determined best by examination under voltage and in a paper-impregnated assembly. I therefore caution against attempts to extend the conclusions of the authors, especially conclusion number 7, to the extent that such studies are to be interpreted as providing a basis for the determination of the *suitability* of the oil for impregnation use.

Among the oxidation products of mineral oil are acids of low volatility and water. In addition, at the higher test temperatures, oil distillation will occur. I ask whether the authors prevented the removal of such materials by distillation during the oxidation run. One of the major objections to oxidation runs of the present type is the volatilization and loss of those materials of greatest importance in the oxidation studies.

I also request data concerning the iodine value of the oil tested.

The dielectric strength data appear to lose significance because of the dehydration treatment and the removal of oxidation-formed moisture and possibly the more volatile oxidation products before the dielectric test was made.

**J. B. Whitehead and F. E. Mauritz:** The linear relationships which Mr. Clark has found are interesting; there should be some significance to the slope of the power factor versus acid number characteristic. It may be possible to determine the relative proportions of organic acids to other compounds which are capable of dissociating.

We doubt that the withdrawal of the volatile products of oxidation has an important influence on the inherent power factor. Evacuation also removes absorbed oxygen and thus stops the oxidation process. Recently we have found evidence that the oxidation process itself is attended by ionization or dissociation, and that the lowering of power factor on evacuation is due to the cessation of the oxidation process rather than to the removal of oxidation products.

No iodine determinations were made on the oils studied.

In reply to Mr. W. M. Goodhue, obviously it remains to be shown how other oils behave as related to time, and also as to the correlations here studied, and whether there are other correlations with chemical structure. We do emphasize however the striking linear relations we have shown.

In reply to Mr. Herman Halperin, other workers who have thus far reported linear relationships are Clark in this discussion and Sommerman at the National Research Council meeting this past November. Sommerman's paper appears in ELECTRICAL ENGINEERING for May 1937.

It would be interesting to determine the effect of metallic soaps. However, under experimental conditions, it would be difficult to determine the relative contributions of the metal acting as a catalyst or inhibitor for further deterioration and that caused by the metallic salt or soap formed.

The ratios in figure 11 were not determined from data taken from figure 10, as Halperin may believe, but from the individual readings of acid number and saponification number on the oil at a given state of deterioration. This method is, of course, much more accurate.

In reply to E. J. Rutan, the reproducibility of acidity results taken on different oil samples depends almost entirely on the cleanliness of sampling and, more particularly, on the preparation of the titration cell. With due care different samples of the same oil would have a maximum deviation from the average of 0.009 in acid number. This value should be considered as a residual due to impurities introduced and not as directly proportional to the acidity of the oil being measured. It is also imperative to use clear, nonturbid titer and to check its acidity before each oil determination. Great care and labor are necessary in preparing the titration cell, especially for low values of acidity. The agar-agar bridge should be changed after every determination, and for simplicity and speed in routine laboratory measurements we would ask Mr. Rutan to consider also the titration cell developed at Massachusetts Institute of Technology, which involves a glass electrode and which seems much easier to clean.

The oil samples used in the breakdown tests were degassed and dehydrated. Each point on the curves is the average of 15 breakdowns, 5 each on 3 identical samples. While the spread of values was of the same order as the observed average, we feel the latter to be a reliable figure. Slight increases of dielectric strength with increasing acidity in the low range have been reported by others.

# Vibration-Measuring Instruments

C. D. Greentree

# Dynamic Balancing of Small Gyroscope Rotors

O. E. Esval and C. A. Frische

**Discussion of papers published in the June 1937 issue, pages 706–10 and 729–34, and presented for oral discussion at the vibration and balance session of the summer convention, Milwaukee, Wis., June 25, 1937.**

**P. L. Alger** (General Electric Company, Schenectady, N. Y.): These papers give evidence of the rapid progress being made in measuring and describing the various sorts of vibration which give rise to noise and other undesirable effects of machine operation. The need for absolutely smooth operation of motors driving grinding machines and other machine tools, as well as the need for quieter operation of all types of machines, make it important that adequate measuring devices be more generally used, and that methods of describing these measurements be agreed upon by industry as a whole. Difficulties frequently arise now because of customers specifying that motors be furnished with a definitely limited amount of vibration, without saying whether the vibration of the shaft or the bearings is to be measured, and whether the motor is to be mounted on a rigid base, on rubber pads, or in some other way. A revision of the test code for polyphase induction machines has recently been approved, I believe, which includes a provision for measuring the unbalance of small motors in terms of the amplitude of motion of the bearings, when the motor is freely supported on elastic pads. I believe this is a very sensible provision, that will do much toward clarifying understanding on the refinements of design and manufacture necessary to meet industry's requirements.

The next step is to bring into use more adequate instruments for measuring the motion, so that the results obtained by different observers at different times will be in agreement. This evidently requires better instruments than have heretofore been used, and so I believe Mr. Greentree's paper, outlining the requirements for suitable instruments, is an important contribution. As he points out, it may be desirable to measure the velocity of the motion or its acceleration rather than to either measure amplitude directly or to attempt to obtain the amplitude from calculations based on the measured velocity or acceleration of the vibration. If, as is usually the case, the vibration is not sinusoidal in character, there will be no simple relationship between the acceleration, the velocity, and the amplitude of the motion as measured;

and, if, as Mr. Greentree suggests, the measurement of the velocity of the vibration is the most convenient and accurate means of testing, then we ought to be thinking about specifications and industry standards in terms of vibration velocity, rather than amplitude.

The AIEE subcommittee on sound has completed a draft of a test code for apparatus noise measurement, which when published will make available general recommendations on means of measuring noise or any piece of apparatus, based upon the American Standards recently published by the ASA. With the 2 fields of vibration and noise measurement both clarified by these proposed test methods, there appears to be left one further task in this vibration measurement field to be undertaken. That is the question of evaluating the performance of various types of elastic mountings intended to isolate the vibration of a machine from its foundation.

There are a great many varieties of elastic supports now in use and proposed for motors and other machines. Many different types of such supports are, of course, desirable for different applications, so that no general agreement on what type is best can or should be reached. However, it does seem desirable to develop acceptable means of comparing the performance of different types of support by some method, for example, of measuring the vibration transmitted to a foundation with and without the use of an elastic base. Probably it is too early to take the question up in any formal way, but I shall appreciate hearing from any one interested as to the desirability of such measurements of elastic base performance being included in any of the Institute test codes.

## Vibration Isolation of Machinery

**Discussion of a paper by L. H. Hansel published in the June 1937 issue, pages 735–8, and presented for oral discussion at the vibration and balance session of the summer convention, Milwaukee, Wis., June 25, 1937.**

**Frederick C. Lindvall** (California Institute of Technology, Pasadena): Relating to the paper, "Vibration Isolation of Machinery," by Mr. Hansel, one or 2 points have suggested themselves to me as being worthy of inclusion in this general discussion of vibrations.

In the first place, electrical engineers should find the general problem of vibration isolation to be one which is of considerable interest inasmuch as through the electromechanical analogy the problem becomes a simple one of electrical-circuit elements and sinusoidal a-c quantities which lend themselves at once to the symbolic or complex method of solution.

A second point which should be emphasized is the convenient form in which the natural frequency of an elastic system as discussed may be expressed:

$$f = \frac{1}{2\pi}\sqrt{\frac{g}{\delta_{st}}} \text{ *cycles per second}$$

$g$ = gravity acceleration
$\delta_{st}$ = static deflection in units of $g$

Thus it is apparent that if the static deflection of the system is known the natural frequency is also known; from the static deflection, in turn, the spring constant of the elastic support may be deduced when the desirable static deflection has been determined.

A general calculation chart or nomogram which I have found very convenient in vibration studies is one expressing transmissibility of an isolation system directly in terms of the parameters static deflection and frequency of vibration. The mathematical expression on which the chart is based is given by a form similar to equation 1 of Mr. Hansel's paper.

The chart is constructed on log-log paper by laying out the transmissibility curve in terms of the ratio of applied frequency to natural frequency of the system; then through the middle of the chart a horizontal line is drawn which serves as a reference line *A-A*, for entering this transmissibility curve. The horizontal lines *B-B* and *C-C* are suitably scaled in terms of frequency and static deflection, respectively, their positions relative to each other being indicated by the obvious tie that a straight line connecting any particular static deflection on *C-C* with the corresponding resonant frequency on *B-B* should pass through the point *O* on the reference line *A-A*. Then for any desired transmissibility the corresponding abscissa is noted on *A-A* at some point, say *P*. Through *P* and the frequency to be isolated to the extent of the selected transmissibility, a straight edge is laid giving at once the necessary static deflection of the elastic support. This static deflection and the weight at the supports give at once the spring constant. It is, of course, obvious that straight lines through the point *O* relate at once the static deflection with the corresponding resonant frequency. This chart may have a family of resonance curves corresponding to different degrees of damping in the elastic system, the most convenient parameter to be used being the ratio of selected damping to critical damping of the system.

And now a word of caution, or perhaps it should be called "sales resistance," which Mr. Hansel has suggested but which I believe should receive further emphasis. There is no magic in vibration pads or isolation materials. This belief in magic seems, in the minds of many engineers, to be intimately associated with certain materials—one in particular being rubber. In the first place, the term "rubber" is indefinite since we all know the tremendous range of rubber compounds in both elasticity and internal damping, and any rubber or similar material which is to be used as an elastic support should be regarded simply for what it is; namely, a spring which may have either a high or low degree of internal damping. This spring, in turn, is useful as an isolation device to the extent indicated by the transmissibility of the system.

One further point: The engineer employing vibration isolation material should have the 2 basic problems, transmission of vibration and transmission of noise, in mind, because an elastic support of metallic nature which may give an adequately low factor of transmissibility will be capable of transmitting noise to an extent that may be objectionable; whereas some other material, such as felt, or rubber, with the same static deflection will achieve the same desirable transmissibility and minimize noise transmission through elimination of direct metallic connection.

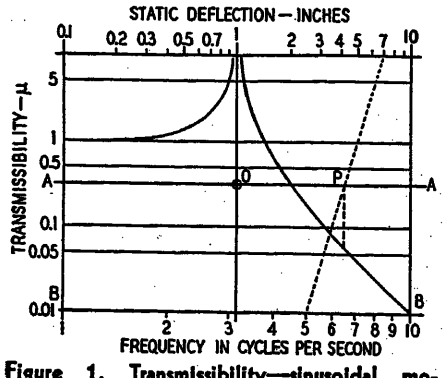



**Figure 1. Transmissibility—sinusoidal motion, no damping, one degree of freedom**

* Note: $f = \frac{3.12}{\sqrt{\delta_{st}}}$ cycles/per second

$\delta_{st}$ = static deflection in inches

**P. L. Alger:** See discussion, page 1305.

## A-C Motor Protection

**Discussion and author's closure of a paper by C. W. Kuhn published in the May 1937 issue, pages 589–93, and presented for oral discussion at the general power applications session of the summer convention, Milwaukee, Wis., June 22, 1937.**

**E. Herzog** (U.S. Army Air Corps, Wright Field, Dayton, Ohio): The author claims adequate protection by means of thermal overload relays even in case of longer starting periods. As pointed out in the previous discussion present long-time thermal-overload relays do not offer enough protection in starting high-inertia load. In the starting of blowers where air loading increases rapidly as the blower comes up to speed, the condition becomes most serious. The writer has been able to obtain satisfactory protection only in one way, i.e., by separate protection during the starting and the running periods even with across-line-starting motors. This naturally increases the cost greatly.

**C. W. Kuhn:** It has not been possible to obtain motor protection with general-purpose thermal-overload relays when starting high-inertia load. Such overload relays must be designed to protect many different classes and designs of a-c motors. Their tripping time must, therefore, be sufficiently short to protect those motors having limited capacity for starting conditions.

The use of special "slow tripping" thermal overloads permits starting high-inertia

loads without unnecessary tripping of the overload. Consequently, smaller overload heaters can be used than would be possible with the faster-tripping standard-type thermal overload. These slow-tripping overloads of lower current rating can be made such as to completely protect motors with high-inertia starting load.

## Coincidental Electric Drives

**Discussion and author's closure of a paper by L. E. Miller published in the May 1937 issue, pages 578–82, and presented for oral discussion at the general power applications session of the summer convention, Milwaukee, Wis., June 22, 1937.**

**L. M. Nowacki** (General Electric Company, Schenectady, N. Y.): Mr. Miller described a very interesting application of a coincidental electric drive, namely, the winding of strip material on a reel. A requisite of the drive is the maintenance of approximately constant tension. The d-c motor is most adaptable for the application. Nevertheless, the question arises, can the same result be obtained with an a-c motor?

Exact coincidence can be obtained with 2 wound-rotor motors used as power Selsyn units or Synchrolocks. The reel drive requires a continually decreasing speed of rotation and an increasing torque. The change in the Selsyn motor speed may then be accomplished by a differential Selsyn unit placed in the rotor circuit between the transmitter and receiver Selsyn, or it may be accomplished by the use of a variable speed transmission interposed between the main drive and the Selsyn generator. As in the case Mr. Miller described, a regulator would be required with the function to control the speed of the differential Selsyn unit or the pulley ratio of the mechanical transmission. If the regulator is to operate on a constant-current principle, it will be necessary to vary the input voltage to the Selsyn units in order to maintain constant rotor current with increasing torque.

The application of an a-c motor to the coincidental reel drive does not appear impossible. A suitable regulator, if developed may provide an a-c drive as flexible as the d-c drive described by Mr. Miller.

**E. Herzog** (U.S. Army Air Corps, Wright Field, Dayton, Ohio): The double-winding motor controlling the field rheostat appears to be the heart of the entire control scheme proposed. A torque motor with spring restraint and a single winding should be able to accomplish the same purpose. The author states that the double winding was used to give the characteristics of an infinitely long spring. A more detailed explanation of this point would be welcome to the writer.

**L. E. Miller:** Mr. Nowacki has suggested a very intriguing problem in the use of a-c with Selsyns or Synchrolocks driving a reel on which material is being wound. There is considerable question as to whether the amount of apparatus required could be reduced materially in using a-c as suggested. Like many problems of this sort considerable thought, experimentation, and actual trial will be necessary before any definite conclusions can be drawn on the subject.

Mr. Herzog has brought up the point that a spring might be used instead of the spring or reference winding on the control motor. This is absolutely correct only in case a spring of infinite length is used and deals with finite torque.

Otherwise a greater torque is required of the torque winding as the reeled material approaches full diameter and slowest speed. This greater torque requires a larger current in the torque winding and therefore in the armature of the motor driving the reel and this in turn gives a greater pull or tension on the material as the diameter of the reeled material increases. In other words a spring could be used only where the conditions were such that a varying tension could be permitted on the material.

In closing, attention should be called to 3 errors which occurred on page 581 of the paper. First, in figure 4 the rheostat in series with the spring winding should be marked 1 instead of 2; second, in figure 4 the legend $D$ should be "regulator field contactor"; third, the first sentence of the second paragraph starting on page 581 should start, "the torque winding $T$ of the regulator. . . " instead of "the torque winding $R$ of the regulator. . . ."

## New Oil-Filled Cable Lines in Chicago

**Discussion and authors' closure of a paper by Herman Halperin and G. B. Shanklin published in the June 1937 issue, pages 739–48, and presented for oral discussion at the power transmission session of the summer convention, Milwaukee, Wis., June 22, 1937.**

**Wm. A. Del Mar** (Habirshaw Cable & Wire Corporation, Yonkers, N. Y.): In summarizing the paper by Halperin and Shanklin, the former said that there is nothing mysterious about the installation and operation of oil-filled cable; that it can be handled without difficulty by crews trained in work on cables of the solid type. This inspires me to add that there is nothing mysterious about its manufacture. On the contrary, the manufacturing processes are based on better-understood principles than in the case of solid-type cables. The mobility of the oil makes it possible to ascertain the condition of the oil and the perfection of impregnation along the entire length by simple tests made at the ends, not only when new, but at all times in its life. This is not the case with solid-type cable, the condition of which must at all times be taken more or less on faith.

The perfect electrical record of oil-filled cables has enabled manufacturers' engineers to devote their attention to improving economy, whereas in the case of solid-type cable the main effort is directed toward improving reliability. This drive toward economy has resulted in simplified accessories, thinner insulation, and cheaper lead, as described in the paper.

**Herman Halperin:** It is gratifying to have a public statement from a manufacturer of the efforts of manufacturers to improve the economy of oil-filled cable.

Although considerable effort has been and still is being directed toward improving the reliability of the solid type of cable, considerable effort has been and still is being given toward improving the economy of such cables.

The essential consideration from the standpoint of a utility engineer is over-all economy, that is, total annual charges per kilovolt-ampere of carrying capacity. In some cases special considerations, such as limitations of diameters of existing ducts or limitations of the personnel of a utility, swing a decision to one or the other type of cable, although the initial installed cost of the cable and accessories is somewhat higher than would have been the case if a type of cable were used other than the type actually selected.

## Impulse Operation of Magnetic Contactors

**Discussion and author's closure of a paper by Carroll Stansbury published in the May 1937 issue, pages 583–8, and presented for oral discussion at the general power applications session of the summer convention, Milwaukee, Wis., June 22, 1937.**

**E. Herzog** (U.S. Army Air Corps, Wright Field, Dayton, Ohio): The author describes a very ingenious solution for the short time operation of magnetic contactors. The process is clearly designed to be used in the resistance welding of nonferrous metals where now vacuum-tube control is used. The writer having used these in the past would like to have the author furnish more detailed information on several points. What is the accuracy of timing of the new process? How is a change in timing accomplished? Are there any chance variations of large amounts as the operation is repeated? How would the life of the contactor compare with the life of the tubes in the 2 types of equipment? A rough comparison of first cost and maintenance of the 2 types would be of interest.

**Carroll Stansbury:** The questions asked by Mr. Herzog are the essential ones which must be satisfactorily answered before control of the type described can be seriously considered for short-time welding of nonferrous metals.

### Accuracy

It will be clear from the paper that the major causes of inaccuracy in contactor control are eliminated by the method. Reference to figure 3 will show that anything which affects the speed of motion of the magnet armature at the instant the contacts touch will affect the closed period slightly by causing the motion to be in accordance with a different one of the family of curves. About the only thing which may cause this type of variation in practice to any serious extent is a considerable variation in line

voltage. On the other hand, a reasonably constant line voltage is an essential requirement for this type of welding to obtain constant energy input into the weld for a given welding period.

There remains the question of variation in the number of cycles passed by the contactor due to possible variation in the arc on the contacts. We have found it possible on a number of practical installations to control this factor so that such arcing as is obtained is quite uniform and that there is no perceptible variation in the welding results throughout a large number of operations. One particular installation, which is operating at $^1/_2$ cycle on current on the order of 250 amperes at 440 volts, has continued to give welds with this timing over a period of several months without perceptible variation. Only occasional phase adjustment is necessary.

### Time Adjustment

This question is covered under the above heading in the paper. The amount of capacity in circuit is varied by cutting in or out individual electrolytic capacitors in parallel.

### Chance Variations of Large Amount

Neither our laboratory nor field experience with this control indicates occurrences of this sort.

### Contactor Life

As brought out in the paper, when operating on the true impulse basis in which the magnet does not seal, the conditions normally producing magnet wear are absent and a contactor should last for several years even on frequent operation. The magnet life on contactors of the best grade used in resistance welding work where the contactors seal in operation is on the order of 20 million operations. This life should be multiplied many fold when the magnet does not seal. So far no contactor operated by the impulse method has shown appreciable wear except on the contacts. It will be evident that with the arcing held to a minimum by this method of control the contact life should also be increased many fold and our experience indicates that this is the case.

### First Cost and Maintenance

It is difficult to give any data regarding first cost of control of this type relative to control of all-electronic type which would be applicable throughout the full range of ratings which might be required. Actually, most of this controller is electronic and it is probably correct to say that the essential difference is that the 2 power tubes are replaced by contactors. Taking the material involved apart from the power tubes or the contactors as roughly about the same, the question really reduces to a comparison of first cost and maintenance of the contactor versus the power tubes. It has been pointed out above that the contactor should last indefinitely with only occasional replacement of contacts, whereas it is the writer's understanding that the power tubes either have to be replaced periodically or are of the continuously-pumped variety which doubtless involve maintenance of the pumps and associated parts.

Actually, the necessary apparatus associated with the contactor in this type of control appears to be somewhat simpler than that associated with the power tubes in those types of all-electronic control with which the writer is familiar. The present form represents a considerable simplification in comparison with the earlier forms of this control, and it is probable that further developments will bring out the possibility of still further simplification.

## System Recovery Voltage Determination by Analytical and A-C Calculating Board Methods

**Discussion and authors' closure of a paper by R. D. Evans and A. C. Monteith published in the June 1937 issue, pages 695–705, and presented for oral discussion at the power transmission session of the summer convention, Milwaukee, Wis., June 22, 1937.**

W. F. Skeats (General Electric Company, Philadelphia, Pa.): The authors have developed 2 major ideas which will undoubtedly be of value in certain fields in the determination of recovery rates. The introduction of symmetrical components is helpful particularly in the calculation of the recovery characteristic of line-to-ground faults and the use of the calculating board promises a reduction of labor especially in the determination of the slower voltage-recovery curves.

In the introductory discussion, the suggestion is made that recovery characteristics be specified by stating both co-ordinates of one point on the curve instead of merely the slope of the steepest tangent passing through the origin. This information is somewhat more specific; however, the authors themselves point out that one point on the curve may be the important one for one interrupting device and a different point for some other device, so that there may often be some question as to which point to specify. To give all the information, the complete curve should of course be shown. Comparison of curves of different shape is likely to involve uncertainties, however, and to overcome this, the suggestion was made 2 or 3 years ago that the basis of comparison be the rate of rise based only on points on the recovery curve whose magnitude is at least 80 per cent of the normal voltage peak, with special consideration given to lower points on the curve which correspond to a higher rate where it is a question of breaker application rather than evaluation of test results.

There are one or 2 points with reference to the use of symmetrical components which will bear comment.

1. The paper states that the method of connecting the phase-sequence networks for recovery rate determination is the same as for the steady-state condition, with the apparent implication, supported by the example given in the case of the double-line-to-ground fault, that the proper connection is the same as that used to determine the current flowing in the case under consideration. Except for line-to-line or line-to-ground faults, this is incorrect for, while the calculation of steady-state current correctly ignores the interval during which less than the full number of phases are faulted, this interval must be considered in determining voltage recovery phenomena. The arrangement to be used for the first phase to clear of a double-line-to-ground fault is therefore that of the impedance encountered by current passing from one terminal of the 3-phase circuit to ground with a second terminal grounded.

2. Barring asymmetrical circuit conditions apart from the fault, the difference between positive- and negative-phase-sequence impedances exists only in rotating machinery and arises from the fact that while one is associated with a flux path that is stationary with respect to the field structure and therefore does not change throughout the cycles, the other is associated with a flux path which rotates with respect to the field structure and may therefore be subject to cyclic variation. In the course of 500 microseconds the motion of the rotor has negligible effect, so that the use of the same value for positive- and negative-phase-sequence impedances is justified. It is suggested, however, that inasmuch as with the current zero occurring at the crest of the voltage wave, the flux path in the rotor is that of the quadrature axis, the quadrature-axis subtransient reactance be used in place of the negative-phase-sequence reactance. This is of importance particularly in laminated-rotor machines without amortisseur windings.

3. For very careful calculations it is occasionally desirable to take into account the fact that the capacitance is not the same for the 3 phases in the interval between clearings on the various poles of the breaker. This greatly increases the difficulty of the solution by symmetrical components and is often easily taken care of in the "single phase" solution, so that in such cases the single-phase solution becomes the simpler even neglecting the labor of changing the constants over from one system to the other.

With reference to the use of the calculating board, I should like to make the following comments.

1. From the standpoint of circuit breaker performance, the cases in which recovery rate should be investigated are in general those in which the capacitance on the one hand is small and can usually be lumped so as to make the calculation relatively simple, but on the other hand consists of a number of minor elements so that considerable labor and possibility of error are involved in determining it. Thus the use of a calculating board eliminates only a minor part of the total labor.

2. Moreover, unless the calculating board is specially designed and very carefully used, it seems likely that it would introduce stray capacitances sufficient to cause appreciable errors in such cases.

Except in cases where a recorded recovery transient is to be compared with a calculated curve for the purpose of analyzing effects introduced by the breaker, great precision is not required for circuit-breaker work, errors up to 25 per cent being tolerable. This being the case, the determination is not so much a precise calculation of complex circuits, as a matter of good judgment in making simplifying assumptions. It would seem, therefore, that per-

haps the greatest use of the calculating board, from the standpoint of circuit-breaker application, may be in the investigation of such assumptions and the formulation of rules for making them sound.

In applications of expulsion protective gaps, on the other hand, the calculating board offers an appreciable saving in effort.

**H. P. St. Clair** (American Gas & Electric Company, New York, N. Y.): In this paper Messrs. Evans and Monteith have presented an interesting and helpful contribution to the literature on voltage-recovery transients, and the proposed method of direct measurements of transients by means of the a-c calculating board may prove to be very useful. For instance, if it is necessary to determine the recovery-voltage characteristics in connection with the operation of flashover tubes at various points on the transmission network, this method would simplify the problem since determination by analytical methods would become extremely complicated.

However, it should be pointed out that regardless of the difficulty of calculating recovery transients at various points on transmission lines, the actual severity of such transients is inherently much less than the severity of recovery transients obtainable on station busses with no transmission lines connected and with only the capacitance-to-ground of the busses, transformers, or generators themselves. Therefore, in determining the severity of recovery voltage transients which must be handled by circuit breakers, we are concerned chiefly with the station type of circuit, where it is possible to encounter the higher voltage-recovery rates.

For this general type of problem, therefore, it is questioned whether the authors' proposed method will actually provide much help.

In the first place, these circuits giving the most severe recovery transients are usually of a fairly simple nature and can be calculated fairly readily after the constants are known. In such cases where we are interested primarily in the worst condition which the given circuit can offer, the most difficult part of the problem is an accurate determination of the small values of capacitance involved in the station bus and in the transformer or generator windings. The authors have referred briefly to this problem in the paper, and it is obvious that the a-c calculating board cannot be of any assistance in connection with this part of the problem. It is doubtful, therefore, whether its use in such cases would be justified.

In the second place, it is doubtful whether the equipment described by the authors would be adequate to record very severe voltage-recovery transients since such transients frequently involve a time duration of only a fractional part of those which the authors discuss. All of the typical records reproduced by the authors both from analytical determinations as well as from direct measurements are of comparatively slow transients which would not be of particular interest in the circuit-breaker problem. For example, in figure 22 the recovery transient for a line-to-ground fault on a 132 kv line is shown with approximately 130 volts per microsecond. All of the other transients shown are more or less of this order. Actually, circuit breakers have been called upon to handle recovery rates at least as high as 4,000 or 5,000 volts per microsecond, and for such transients, it is believed that the rotating type of recording device as used by the authors could not possibly be operated at sufficient speed to give the necessary time scale.

As stated above, the most difficult part of the problem in connection with extremely high rates of recovery voltage is the determination of small values of capacitances involved in more or less simple setups. For this problem it is likely that a greater contribution would be some device either for directly measuring transients in the circuit itself or of measuring the capacitance of the circuit directly. For example, the high-frequency generator or oscillator may be used for determining the natural frequency of the circuit and thereby arriving at the capacitance since the inductances involved are generally known.

The authors are to be congratulated, however, for having worked out a very interesting application of the a-c calculating board and one that may prove of great value in its field.

**J. R. North** (Commonwealth & Southern Corporation, Jackson, Mich.): Experiences which we have had with arc-interrupting devices have time and again brought to our attention the need for more information and data concerning recovery voltage. The methods of analysis described in this paper by Messrs. Evans and Monteith will be of considerable assistance to power system engineers in applying interrupting equipment.

The question of recovery voltage is important not only in the application of circuit breakers, but in all arc-interrupting devices such as fuses, lightning arresters, and protector tubes which may be located at stations or out on lines. Also, the problem is not confined to fault conditions. For example, circuit breakers used for normal switching of synchronous condensers, and line charging reactors, have at times shown considerable distress due to a high rate of rise of recovery voltage. Certain lightning arrester troubles have also been encountered which could be traced to rapid recovery voltage of the system.

Fuses usually clear faults in a relatively short time. The curves shown in figure 26 show that the voltage rise during the first 200 microseconds is much steeper for a fault having a duration of one-half cycle than for a fault of one cycle duration. This would seem to indicate that fuse and protector tube applications require particular attention from the standpoint of recovery voltage.

The reduction of a power system of any size to a simple equivalent network system such as is shown in figure 11 involves considerable work. It would be desirable to have a more detailed explanation as to just how this is accomplished, and with particular regard to obtaining the proper values of equivalent system constants to give the correct values for both normal system frequency and for the natural frequency of the system. It would also be interesting to know how this is taken care of on the a-c calculating board, which is designed for 440 cycle operation.

In the caption for figure 27, it is believed that reference should be made to figure 18 rather than figure 19.

The check between the values obtained by the authors using the analytical method and the a-c calculating board with the field tests is indeed interesting. With more test data available, it would appear that the burdensome analytical studies could be confined to special problems involving only a few elements of a system. It is, therefore, urged that measurements be made of recovery voltage whenever the opportunity presents itself in connection with other system tests. These data will facilitate the application of the methods outlined in the paper to general system studies.

**S. B. Crary** (General Electric Company Schenectady, N. Y.): The authors are to be congratulated for the presentation of a paper which should prove to be of real benefit in studying the effect of various factors on the recovery voltage characteristics.

In using a minature system or model, it is well to view rather critically the assumptions required in order that the model may be used to predict or explain actual system performance. Unfortunately, the most important cases of arc suppression which result in extreme or high recovery voltage are the ones which do not permit of easy representation by a miniature setup. As shown by the authors, high peak values of recovery voltage may be obtained when the current is interrupted off of normal current zero. The amount and manner in which the circuit is interrupted off normal current zero is a function both of the actual arc characteristic of the interrupting device itself and the circuit to which it is connected. For those cases when the arc characteristic is not influenced appreciably by the connected electrical circuit and the characteristics of the interruptor are known, then a device can be made which will duplicate the performance of the actual device. However, for those cases when the interruption phenomena are dependent upon the electrical circuit as well as the interruptor, it becomes exceedingly difficult to build a model which will duplicate actual performance, this case may well be most easily obtained by test of the actual circuit and interruptor.

Another source of high recovery voltage, as shown in the paper "Circuit Breaker Recovery Voltages" by R. H. Park and W. F. Skeats (AIEE TRANSACTIONS, March 1931, pages 204–239), is that due to the saliency of rotating machines, which cannot be easily reproduced in a static setup.

**E. M. Hunter** (General Electric Company, Schenectady, N. Y.): Messrs. Evans and Monteith have given a very interesting discussion on using the a-c calculating board for estimating system recovery voltages. The procedure which they describe should be very useful to those interested in making a large number of independent recovery voltage calculations on a system.

Interest in recovery voltages centers mainly around the application of oil circuit breakers and expulsion protective gaps to different electrical systems. In modern oil-circuit-breaker applications only the very fast recovery rates of the order of several

thousand volts per microsecond need to be considered. These very fast recovery rates usually result from circuits which contain only small amounts of capacitance, such as is found, for example, in transformers and bus work. It is often difficult to reproduce a miniature of this type of circuit and the authors' comments on the suitability of their a-c board for studying these fast transients would be of considerable interest.

The recovery voltages associated with the application of expulsion protective gaps usually are not in excess of several hundred volts per microsecond and accordingly, are of a much lower rate than those encountered in oil-circuit-breaker applications. Usually the mathematics governing the circuits to be analyzed are not too involved, and the recovery voltages can be calculated provided the system constants are known. The biggest obstacle in making any analysis of recovery rates today is the determination of the system constants. A big step toward the solution of the recovery rate problem came with the development of a practical 3-element cathode-ray oscillograph, such as is described in Messrs. Rudge and Wade's paper on "Expulsion Protective Gaps" presented at this convention. With this measuring instrument it is now possible to make field tests and actually determine the recovery rates. With system constants unpredictable, there is a need for more field tests. Once system constants are known, the a-c calculating board will be a useful tool for extending the study of system recovery voltages.

**L. R. Ludwig** (Westinghouse Electric & Manufacturing Company, East Pittsburgh, Pa.): The problem of a-c circuit interruption has long been a very important one, both as far as circuit breakers of high interrupting capacity and smaller apparatus are concerned. However, even until 1928, the notions of the phenomena involved in a-c interruption were vague and incomplete. Comparatively recent papers on the subject glibly discuss the "quenching" effect of oil on an arc, and bemoan the necessity of interrupting a circuit by means of a "burning" arc at all.

In 1923, Doctor Slepian began to visualize the true physics of a-c circuit opening, as a result of research with grids and a vacuum arc. By 1925 his "deion" ideas were formulated, and in 1928 in Denver, he presented a paper entitled "Extinction of an A-C Arc" which for the first time called attention to the facts that the arc space between the separated electrodes of a breaker had to deionize before any appreciable voltage could be applied without restriking, that the time available for this deionization was a function of the circuit, and that interruption depended on the relative progress of deionization and voltage recovery.

This paper, mildly discussed at the time, has become the source-book from which our present accepted knowledge has been derived. As appreciation of Doctor Slepian's work grew, there was a rush to the laboratory to test circuit interruptions under actual system voltage recovery conditions. But what were these actual conditions? How to set the laboratory was the problem. The theory was clear enough, but determination of time to crest and recovery voltage under operating conditions was not simple.

The circuits were analyzed mathematically, but several approximations were needed. For several years there has been no completely practical and simple method for determining voltage recoveries.

Now Mr. Evans and Mr. Monteith have devised a tool for the determination of recovery voltage which is accurate, practical, and complete. Their idea of using the calculating board for this purpose is simple, but considerable ingenuity was required in carrying it out. For example, their use of repeated faults in order to get oscillographic records is a clever means of surmounting a mean obstacle.

The methods they have described are simple, check beautifully with field tests as well as calculation, and permit the study in the laboratory of field conditions which cannot be satisfactorily resolved by mathematics alone. We have been given a new yardstick for gauging circuit-interrupter requirements, and the added certainty of testing will prove beneficial to the development and application of breakers and deion protector tubes particularly.

An excellent example of the utility of the Evans-Monteith method is illustrated in their figure 3. It has often been customary in dealing with recovery voltages to speak only of the rate of rise of voltage, and its crest value. Such a description of the facts lacks generality; it is applicable only when testing a device having a recovery curve similar to $D$ in the figure. Mr. Evans and Mr. Monteith have been able to study system recovery curves so much more accurately with the calculating board method that earlier discrepancies become very apparent. We can now begin to deal with the entire recovery curve, rather than with one or 2 points on the curve which are presumed to be critical values but may not be. We cannot easily enjoy the certainty of dealing with the complete facts.

**H. G. Brinton** (General Electric Company, Pittsfield, Mass.): The Evans-Monteith paper considers the recovery voltage as the sum of 2 components, (*a*) the steady-state component and (*b*) the natural-frequency component.

The first component is sometimes called the restored voltage and is the generated voltage that is suddenly impressed when the 60-cycle inductive drop in generators, transformers, etc., is suddenly removed by the 60-cycle current stopping at zero.

The second component usually rises so rapidly that the first component can be considered as a constant or continuous voltage during the brief period in question. It is the transient voltage appearing on the capacitance in shunt with the circuit opening device when the restored voltage is suddenly impressed on the circuit. In the worst case this circuit is oscillatory and the recovery voltage rises rapidly at the natural frequency of the circuit.

In a 3-phase circuit the first component is sometimes impressed on a rather complicated network. In calculating the recovery voltage conservative assumptions are made so that the actual recovery voltage will not exceed the estimated value which is used in making the application of expulsion gaps or similar devices.

Oscillographic tests may be made on actual service setups and also on miniature laboratory setups. The 2 methods are complementary to each other rather than competitive. The field tests deal not only with recovery voltages under various conditions but also with the life and characteristics of the circuit-opening device and its effect on the system. These field tests are a necessary part of the development and improvement of the circuit-opening device.

Field tests cannot be carried on continuously and miniature laboratory setups afford a valuable means of obtaining a greater amount of data and of broadening out the test program.

A number of field tests on the operation of expulsion gaps and the resultant recovery voltages have been made recently. In general, it has been found that the calculations have been conservative and satisfactory in placing an upper limit on the expected value of recovery voltage. These tests are very valuable in supplying data on the effect of circuit conditions and of variations in the device tested.

In general the factors which tend to increase the recovery voltage are (*a*) limitation of the short-circuit current by inductance principally rather than by resistance so that the generated restored voltage is near a maximum when the current goes out at zero; (*b*) an oscillatory circuit on which the restored voltage is impressed so that the recovery voltage may rise to about twice the restored voltage; (*c*) a small value of the product of inductance and capacitance in the oscillatory circuit so that the natural frequency is high and the recovery voltage rise is steep.

**H. M. Trueblood** (Bell Telephone Laboratories, Inc., New York, N. Y.): This paper takes a valuable further step in the advance of our means of understanding phenomena which are not only important from an engineering standpoint, but also of great interest in themselves. In some of the studies* that have been carried on by the joint subcommittee on development and research of the Edison Electric Institute and the Bell Telephone System, an important feature has been the matter of overvoltages on power systems at times of ground faults, and the relation of these overvoltages to the use of devices for limiting fault currents. Such investigations make contact at several points with the subject of this paper, and the methods described by the authors should be helpful in them, particularly in the study of specific situations.

The main object of the paper is evidently to present practical working methods, applicable over an enlarged range of practical conditions, and with no more appeal to theoretical considerations than is needed to justify the expectation that the methods described will be accurate enough for engineering purposes. I do not wish to depart from this point of view in discussing the paper, particularly since the involved nature of the subject makes it impossible for theory to go far without clinging to the hand of experiment. The checks that the authors

* Engineering Reports of the Joint Subcommittee on Development and Research, volume IV, pages 105–137 (1937); Gilkeson and Jeanne, "Overvoltages on Transmission Lines," ELECTRICAL ENGINEERING (AIEE TRANSACTIONS), volume 53, September 1934, pages 1301–09.

give of results from both methods against measurements on actual systems are gratifyingly good, although they seem rather limited in extent. Additional data from further field work should serve to indicate what modifications may be necessary to insure results within engineering precision, as well as to define the limitations of the new methods as the latter now stand. In view of the rather high frequencies that seem to be important in these phenomena, one matter that may offer difficulty is the determination of the degree of refinement necessary in the equivalent networks. This would be involved in both the analytical method and the use of the calculating board. In the former, in fact, one might run up against another obstacle, arising from the fact that actual power systems are not altogether symmetrical, so that the decomposition into the usual sequence networks is not strictly justified. Unbalances among the 3 networks, unimportant from some points of view at low frequencies, acquire increased significance at higher frequencies. If this sort of difficulty should prove important, it could presumably be taken care of, up to a certain point, in the calculating board setup, at the cost of some complication. The question, of course, is purely one of how much practical difference it would make.

As I understand, the calculating board used is ordinarily operated at 440 cycles and with impedance elements differing by a conversion factor from the elements of the actual network. I think some further detail about how the board is set up and used in this new application would be of interest, since the results sought go rather beyond the usual range.

**R. D. Evans and A. C. Monteith:** The discussions indicate that the methods presented in the paper have application to a variety of problems of interest and importance to the industry. The authors are appreciative of these discussions and are encouraged to continue their general study of system recovery voltage and to develop further the methods and their applications.

When a paper describing new analytical methods is presented the discussion is usually concerned with the proper field of application. In the present case the discussion follows these lines. The paper presents 2 general methods of solution and much of the discussion is concerned with the choice. It is the authors' opinion that the simpler circuit problems should be studied by the analytical methods while the more complicated circuit problems and general investigations should be studied by the a-c calculating-board method. The 2 methods can be used to advantage in complementing each other. For the particular problem of opening the last circuit breakers on a bus, we believe that the analytical methods are adequate and not too cumbersome. For such calculation we believe the symmetrical component method of solution described in the paper provides a simplification over previous methods and at the same time gives a better visualization of the various factors entering into the problem.

Several of the discussers have raised a question as to the applicability of a-c calculating-board method for problems involving the higher rates of recovery voltage, basing their view on the limitations of recording apparatus and relative importance of stray capacitance. In this connection it may be observed that the equipment described in the paper for the a-c calculating-board method is suitable for recording much higher natural frequencies than those shown in the few examples. This range can be extended by the use of equivalent circuits of lower natural frequencies, when used with appropriate corrections for the change in the fundamental frequency. By this method difficulties in recording and the effect of stray capacitance are minimized. The limitations of the polar form of recording can of course be overcome by the use of a cathode-ray oscillograph which incidentally was originally developed for surge testing. Thus, for the study of high-speed transients, the a-c calculating-board method is more flexible than would be indicated by some of the discussions. Several discussions have dwelt on the limitation of the a-c calculating-board method in arriving at the recovery voltage for the opening of the last circuit breakers on a bus section. It should be appreciated that there is a large number of other problems in connection with circuit breakers, as well as with other pieces of apparatus on the system for which the a-c calculating-board method is applicable.

Two of the discussers have raised the question as to the frequency used with the a-c calculating-board method. While the board was designed for 440-cycles supply, practically all of the transient studies have been made with a separate 60-cycle supply although some studies have been made with other lower frequencies such as 25 cycles.

Doctor Trueblood's discussion is valuable in bringing out the multiplicity of factors entering into the recovery voltage problem and the technical difficulties involved in the circuit problem. He has ably summarized the authors' approach to the problem which has been to provide a practical method giving engineering accuracy. We are in hearty agreement with Doctor Trueblood, Mr. North, Mr. Brinton, and others, on the desirability of obtaining further system tests to establish benchmarks which are themselves valuable and which will provide a sound basis for broader analyses by the methods presented.

Mr. North's discussion is valuable in that it emphasizes the fact that there are a number of pieces of apparatus whose performance is vitally affected by recovery voltage characteristics. He has also raised the question of the method for reducing an extensive power network to a relatively simple equivalent. It is difficult to formulate a general procedure since to a considerable extent each network must be considered as a special case. In general, the complicated system may be set up on the a-c calculating board in a manner similar to that used for load studies when line capacitances are taken into account, with the additional complication of setting up the network on a 3-phase basis and making the zero-sequence circuit of proper value in a manner similar to that shown in figure 15. In the case of very large networks it may be necessary to set up at one time only a part of the system and to obtain an equivalent network for this part.

We agree with Mr. North that the reference in figure 27 should be to figure 18 instead of figure 19.

Mr. Skeats has suggested that recovery-voltage characteristics for circuits and apparatus be defined in terms of the rate of rise to certain points on the recovery voltage wave. The authors are of the opinion that a better and more complete picture of the voltage recovery problem both from the standpoint of the system and of the apparatus will be obtained by the method used in the paper which defines the recovery voltage in terms of a curve plotting magnitude and time. Having such a curve in mind it is convenient to express particular points of interest in terms of magnitude and time to crest. The phenomenon of arc interruption reviewed by Mr. Ludwig is a subject which must be thoroughly understood in order to broadly consider the recovery-voltage problem.

Mr. Skeats' point concerning the connection of the sequence networks is not clear. It is assumed that he refers to the fact that a switching operation is required for changing the connection of sequence networks when representing the opening of one pole of a breaker on a double-line-to-ground fault. This is a complication with the sequence network method of representation but it is of course not encountered with the 3-phase method which has been more generally used by the authors. The sequence network, however, does assist in separating the components of the total recovery voltage and thus gives a better visualization of the phenomena taking place.

Mr. Skeats suggests that the machine reactance used in recovery studies should be based on the quadrature subtransient reactance on the basis that the current is interrupted at the crest of the voltage wave at which time the flux path in the rotor is in the quadrature axis. However, the recovery phenomenon generally of interest is that corresponding to the clearing of some unbalanced fault on the transmission system and for such conditions the flux path in the rotor will not be wholly in the quadrature axis. Hence some combination of the reactances corresponding to both direct and quadrature axes should be used. The negative-sequence reactance is an average of these reactances and was suggested in the paper as the value to be used in recovery voltage investigations. A more important correction than the cyclic variation in reactance may be due to the harmonic distortion which occurs with unbalanced faults on salient-pole machines without dampers. This point, mentioned by Mr. Crary, has been recognized by the authors. The effects of harmonic distortion are admittedly difficult to include in setup but can be compensated for by separate correction. The use of such a procedure for this very special case is believed to constitute only a minor limitation to the general value of the method.

Mr. Crary has also raised a question of the fault representation for the interruption of an arc at other than its normal current zero. If the arc characteristics are known, a fault representation device may be devised and its effect introduced into a calculating-board study. One such arc representation device is described by the authors in connection with figure 18. The a-c calculating-board method permits interruption at any desired point. As pointed out by the authors, interruption of an arc on a system will ordinarily take place at or close to the normal current zero because of the fact that

the recovery voltages for interruption on either side of this point are higher than at the normal current zero.

In connection with Mr. Hunter's discussion, we do not understand the difficulties which he anticipates in the determination of circuit constants for systems on which flashover protector gaps are to be applied. It is our opinion that if the physical layout of the system is known the electrical constants may readily be calculated with engineering accuracy.

## Characteristic Constants of Single-Phase Induction Motors

**Discussion and author's closure of a paper by Wayne J. Morrill published in the March 1937 issue, pages 33–38, and presented for oral discussion at the power generation and electrical machinery session of the summer convention, Milwaukee, Wis., June 24, 1937.**

P. L. Alger: See discussion, page 1312.

P. H. Trickey (Diehl Manufacturing Company, Elizabethport, N. J.): I was very much interested in Mr. Morrill's paper partly because of its usefulness and partly because he has used a similar method of attack to that used in my paper on shaded-pole motors.

In checking the 2 papers against each other, I find several points of interest. In the first place in my own paper the first sentence of the paragraph on harmonic reactance should read "The above reactance $X_m$ is here defined as the magnetizing or mutual reactance." In the second place, after taking the differences of the total and magnetizing reactances, the terms were rearranged, and the term $\sin^2 \beta/2$ was inadvertantly omitted from the denominator of the constant $C_h$ which should read

$$C_h = \frac{1.232\ \alpha - \mathrm{Sin}^2\ \beta/2}{\mathrm{Sin}^2\ \beta/2}$$

Having made this correction and putting the constant 3.19 in Mr. Morrill's equation for permeance, it can be shown that the 2 equations became identical for the special case of one coil per pole with a pitch equal to the pole area of the salient-pole motor.

In developing these formulas, I feel that Mr. Morrill has very definitely contributed to the more accurate calculation of motor constants. The formulas which my associates were using when I first began to calculate motors, were the original formulas of C. A. Adams, published in 1904. However, to partly compensate for a wide divergence between calculation and test, they were using Adams' "belt leakage" even on squirrel-cage motors. After Mr. Veinott developed the formulas for skew leakage, and after I had worked up some curves for the reactance of closed-slot rotors, we attempted to drop the fallacious use of the belt leakage. We found that we were always low if we omitted it and high if we used it. So for a number of years now we have been arbitrarily using $^1/_3$ of the calculated belt leakage, and have had very satisfactory results. We have justified it, as partly compensating for some differential leakage not covered by the zigzag.

I have lately checked 4 repulsion-start induction motors, comparing the present method of zigzag plus $^1/_3$ belt to Mr. Morrill's stator and rotor harmonic leakage.

In all the cases; the present method, Mr. Morrill's method and test values were very close together, but in every case Mr. Morrill's method was closer to test than the present method.

Mr. Morrill has given us some very useful formulas which can be applied directly to repulsion-start induction motors. Would it be out of place to ask him if similar formulas are available for the rotor reactance of the squirrel-cage rotor?

REFERENCES

1. AN ANALYSIS OF THE SHADED POLE MOTOR, P. H. Trickey. ELECTRICAL ENGINEERING (AIEE TRANSACTIONS), 1936, page 1007.

2. THE LEAKAGE REACTANCE OF INDUCTION MOTORS, C. A. Adams. International Electric Congress, St. Louis 1904 *Transactions*, pages 706–24.

**Wayne J. Morrill:** I am pleased to receive the discussion from Mr. P. H. Trickey, announcing close agreement between calculation and test which had been obtained by him using the method of my paper.

Mr. Trickey asked whether similar formulas are available for the rotor reactance of squirrel-cage rotors. It was my intention to point out in the paper that the developed formula for rotor-air-gap reactance applies equally well to squirrel-cage rotors and wound rotors.

## End-Winding Inductance of a Synchronous Machine

**Discussion and author's closure of a paper by B. H. Caldwell, Jr., published in the April 1937 issue, pages 455–61 and 474–5, and presented for oral discussion at the power generation and electrical machinery session of the summer convention, Milwaukee, Wis., June 24, 1937.**

G. W. Hampe: See discussion, page 1318.

P. L. Alger (General Electric Company, Schenectady, N. Y.): The appearance of the 4 papers by Beckwith, Caldwell, Douglas, and Morrill, carrying further the analytical study of leakage reactance, and the recent appearance of an article on "Induction Motor Leakage" by Mr. L. H. Carr (Metropolitan Vickers Gazette, volume 16, May 1937, pages 426–31) indicate that there is still much to be done in making the knowledge of this important subject adequate for design purposes. Professor Douglas' suggestion of procedure for end-connection reactance calculation, and Mr. Caldwell's actual carrying out of such a process for the end leakage reactance of synchronous machines, are particularly important contributions. I believe that Mr. Caldwell's results are more exact and give a more satisfactory understanding of the variations of end leakage reactance with design proportions than any methods heretofore published. Further work in this field is still desirable, however, first to verify the practical application of his results over a wide range of machines, second to add methods of allowance for the additional reactance due to the presence of magnetic retaining rings, such as are used with high-speed machines, and third to determine the end reactance when the secondary currents flow in a distributed armature winding or a squirrel cage, instead of in a salient-pole field winding.

I also believe that Mr. Morrill's contribution in presenting a method of more accurately calculating the air-gap reactance of single-phase motors is important. The results in some ways conflict with those obtained by Mr. Carr in the paper mentioned above, Mr. Carr preferring the method of calculating the average overlap of the teeth to obtain the permeance of the combined zigzag leakage flux paths, instead of using the difference between the total air gap flux and the fundamental component for rotor and stator separately, as used by Mr. Chapman and Mr. Morrill. Also, Mr. Carr suggests that the variations in the air gap fringing coefficients for the fundamental and the tooth harmonic fluxes introduce an error when Mr. Morrill's method is used. While further work should be done to reconcile these different views, my own belief is that Mr. Morrill's method is substantially correct.

Another problem to be solved in this reactance calculation field is that of determining the leakage reactance for various types of irregular or multiple windings, such as are used in part-winding starting of motors and double-winding operation of alternators. These windings have relatively large air-gap leakage reactance components due to the large harmonics in the field form, and they also have additional slot reactance, depending upon the arrangements used, as discussed in the paper presented before the Institute in 1929, entitled "Double Windings for Turbine Alternators (P. L. Alger, E. H. Freiburghouse, and D. D. Chase, AIEE TRANSACTIONS, volume 49, January 1930, pages 226–44). I believe that the orderly system of notation and the use of connection tensors, suggested by Mr. Kron, are helpful in analyzing these problems of irregular windings, and I hope that a paper can be presented before the Institute dealing with this aspect of the subject in the near future.

J. F. H. Douglas (Marquette University, Milwaukee, Wis.): Caldwell's fourth assumption, namely that there is 100 per cent eddy-current shielding in the end laminations, is equivalent to the use of a Rayleigh insulating surface, and is a conservative assumption. Thus his values of inductance are smaller than the true values, but if they are, as indicated by the discussion, higher than previous published values they are nearer the truth.

With regard to the factor (2) which disappears between Caldwell's equations 12 and 15 I believe that this is the point he chooses to introduce the effect of both end windings, and that his equation 15 is substantially correct.

It should be pointed out next that the writer has carefully checked the various formulae as far as equation 25 and suggests

a slight modification only in equations 13 and 23. Thus the work appears to be substantially accurate and in accordance with the postulates. The method is, moreover, of considerable power, and leads to convergent series and a workable formula for inductance.

The capabilities of the method, transcend the postulates, Caldwell's third postulate is equivalent to placing a Rayleigh conducting plane tangent to the ends of the winding and increases the inductance perhaps 5–10 per cent. By moving the plane away from the poles and using a double harmonic series as is used in the theory of the square drum head this error may be reduced ["Fourier Series, Surface, Zonal, and Spherical Harmonics" (a book), Byerly].

Caldwell's fourth postulate, namely that of 100 per cent eddy-current shielding may be replaced by its opposite 0 per cent shielding and the method would still be applicable. In figure 1 is shown a wave of mag-

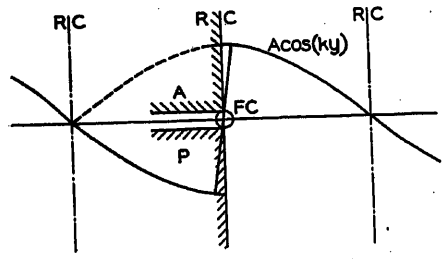



**Figure 1. Magnetomotive-force wave with no shielding**

netomotive force varying in the $y$ direction, the right-hand wave and the left-hand dotted wave are in accord with Caldwell's fourth postulate, the solid curve indicates the needed change to make the polar and armature iron an equipotential surface. $P$ represents the poles, $A$ the armature, $FC$ the fictitious conductor closing the gap, and $RC$ represent Rayleigh conducting planes. The series of harmonics is now a double series, contains terms of double frequency only in $y$ and converges more slowly than before. Thus Caldwell's method should be capable of considerable further development.

Comment should be made on the ingenious experimental technique shown in figure 10. This is believed to be a very useful contribution. In this figure it appears as if the long side of the triangular test coils returns on the outside of the end connections. It is believed that this misses considerable flux, and that the correct location of the return conductor should be on the air-gap side of the end connections and adjacent to the tips of the teeth.

One important consequence of Caldwell's analysis, and equally true even when different postulates are used, is that the field is essentially a cosine function of $x$. This means that the field in the end zone is substantially a revolving field for either positive-or negative-sequence components, and a pulsating field for zero-sequence currents.

I wish here to record my reasons for believing that Caldwell's fourth postulate of 100 per cent eddy-current shielding is needlessly conservative. This is an important point, since a particular case showed decidedly greater inductance with 0 per cent shielding. The largest difference is made by flux leaving ends of stator teeth and reaching the pole shoe. Here there is no shielding in the rotor as it moves synchronously with the flux (positive sequence assumed) and little shielding is offered by the teeth as they are too constricted for eddy currents. In the second place the flux leaving the side of stator laminations is undoubtedly cut down somewhat by eddy currents, but it is suggested that flux penetrating only 2 or 3 laminations would find an easy return path, and the shielding should not be large. There is enough evidence available from the loss caused by lapped-over butt transformer joints, and in the reactance of core-type transformers to estimate the probable shielding of eddy currents. Caldwell's assumption is nearer correct for cross-magnetizing flux than direct, nearer for negative and zero phase sequences than for positive. It is suggested that further experiments are very much needed.

In commenting on Caldwell's figure 11 the solution of a particular case indicated the plane $aa'$ to be nearer the end connection than the pole core, I conclude that Caldwell's fringing is an important factor, and as pointed out it could be calculated as part of the end-zone flux.

In place of the author's equation 13 for pitch other than 100 per cent I get the magnetomotive force as a double summation of surface harmonics of the type

$$M = \sum_{n=1}^{n=\infty} \sum_{m=1}^{m=\infty} A_{mn} \times \cos\,(mxP/D) \sin\,(nky) \quad (1)$$

where the value of $A_{mn}$ is given by

$$A_{mn} = \frac{32\,(ni)\,(p)\cos\,(1.57\,mp)}{(3.14)\,(m)\,(n^2 - m^2p^2)} \sin\,(1.57n) \quad (2)$$

This reduces to the form of Caldwell when there is 100 per cent pitch. We request Caldwell to give more details in his discussion.

In attempting to check Caldwell's equation 23 I get a slightly different result. Calling $k$ the ratio of slot width to tooth pitch,

$$K_m = K_{pm}K_{hm}'\left(\frac{3}{3.14m}\right)^2 \times \left(\frac{\sin\,(km30°/s)}{k\sin\,(m\,30°/s)}\right) \quad (3)$$

It is believed that the neglect of the last term in equation 3 introduces an error less than 10 per cent with the postulates adopted by Caldwell, but with 0 per cent shielding, and a less rapidly converging series the term may be of consequence.

**Ernst Weber** (Polytechnic Institute of Brooklyn, Brooklyn, N. Y.): The general outline for the computation of the reactance of end connections as given by J. F. H. Douglas, is extremely interesting and certainly opens a wide field for experimental as well as mathematical research. The specific application of mathematics to this particular problem exposed in the paper by B. H. Caldwell illustrates the power of the judicious combination of theory and experiment. There are, however, a number of points to be considered in a more thorough study of this leakage problem. The Fourier series employed by Caldwell presupposes an infinite grid system of square loops. In reality, taking into account the magnetic image of the end coils one would have a single infinite line of diamond-shaped coils and the Fourier-integral method should be employed to obtain the proper field distribution perpendicular to the magnetic mirror. The apparent agreement between measured and computed values might be essentially due to the simple geometric form used. This agreement fails immediately when measurements are made on completed machines as evidenced in table II of the paper, where the error in the mutual inductance is 29 per cent and the error in the self-inductance 13 per cent.

On account of the simplifications introduced by Caldwell, one cannot possibly expect his formulas to hold in actual machines. I should like to call attention to a very thorough study of this problem extending over a period of almost 15 years, which leads to formulas taking into account all the details of actual machinery. The mutual linkage, for example, between field coil and stator winding is taken into account there and not ignored. I am referring to the set of volumes "Elektrische Maschinen" by R. Richter, successor to E. Arnold, at the Technical University "Fridericiana" in Karlsruhe, Germany. Four volumes have appeared, published by J. Springer, Berlin, Germany. The first volume, dealing with the general elements of electrical machines, published in 1924 (price approximately $11.00), gives on page 281 an exposition of the general problem of end-connection leakage. Some of the salient points of Richter's presentation are: distinction of the useful flux (linked with stator winding and field coil or rotor winding in general) and true leakage bux; computation of the leakage inductances by means of Biot-Savart's law in its form modified by J. C. Maxwell; distinction between self- and mutual inductances of the stator coils taking into account the relative position for the various types of windings used in electrical machinery, and finally a general form for the specific end-connection leakage whereby factors are introduced obtained by experimental research on a large variety of coil models, executed in the laboratories of the Technical University of Karlsruhe under the supervision of R. Richter.

Volume 2, dealing with the synchronous machines and synchronous converters, published in 1930 (price approximately $12.60), gives on page 91 a general formula for the specific end-connection leakage, introducing correction factors taking into account the shape of the rotor, the combination of the coils into coil groups and the pitch of the individual coils. Curves are given for those correction factors which were determined experimentally.

Volume 4, dealing with synchronous machines, published in 1936 (price approximately $12.60), gives on page 161 the application of the general formula for the end-connection leakage to the types of windings used in asynchronous machines, and takes into special consideration squirrel-cage rotors and slip-ring rotors of various numbers of phases. Again, distinction is drawn between useful flux and individual leakage flux of the opposing windings and correc-

tion factors are given in table and graph form.

Since the formulas published in the set of volumes mentioned above have been checked carefully in the course of many years, and since the resources of the Technical University of Karlsruhe are of world-wide repute, it might be very valuable to compare the results there obtained with the procedure suggested in the papers before us.

**Leroy Coffin** (Allis-Chalmers Manufacturing Company, Milwaukee, Wis.): The subject of end-winding leakage reactance is of particular importance to designers of rotating electrical machinery because it forms an elusive part of the more important reactances. It may be a considerable part of the transient and subtransient reactances, particularly in machines with short cores, and for that reason the determination of these reactances may depend largely upon how closely the end-winding leakage reactance may be estimated.

Mr. Caldwell has made a very ingenious mathematical analysis of the end leakage field and it appears that with some modification to cover particular cases that we are now nearer a solution of this problem.

A flux map of this end-winding region shows a portion of useful flux extending well out into the space occupied by the coil ends and entering the stator teeth and core. The existence of this flux may be verified by means of iron shavings placed in a glass test tube. While this component of useful flux may be small in comparison with the flux in the air gap it is not necessarily small in relation to the total flux existing in the end zone. Each end conductor is also linked with flux which does no useful work. This we term leakage flux. We attempt to calculate the amount of this leakage flux but there is no way of readily measuring it. Exploring coils may fail to link all the leakage flux and are usually cut by useful flux. We thus measure the total flux, cutting the exploring coil but have failed to divide it into its respective components.

Most machines have masses of iron in this end zone, such as core end heads or finger plates, coil shields or end bells, and pole end plates or rotor-coil support rings. These, of course, change the reactance and their presence will require correction factors which will necessarily be empirical.

Caldwell's equation 16 gives values higher than those calculated by the usual methods. Calculations were made on a number of 3-phase machines, varying from 4 to 88 poles and in no case did the mutual leakage exceed 3 per cent to 4 per cent. A great many salient-pole machines have rotor pole end plates extending well out into this end zone. It would not seem that any appreciable amount of mutual leakage flux could exist between the 2 windings with this magnetic material between them.

In order to compare the various methods of calculating this end-winding leakage a hypothetical case was considered. It was assumed that we had a core which could be wound for 4 to 20 poles. The air-gap flux density, effective ampere conductors, and the output factor were arbitrarily kept constant in order to make the results comparable. Low-voltage insulation was assumed. Figure 2 shows the calculated per unit values of end-winding leakage reactance for a full pitch winding. The calculations were made by Caldwell's method and previously published methods.[1-3] No allowance was made for mutual leakage. No multiplying factor has been applied to the values obtained by Still's method. He recommends a figure of 1.7 to 3.5, depending upon the type of machine. Figure 3 shows calculated values for the same machines wound with $^2/_3$ pitch. This shows the influence of short pitch on the various methods. This example does not mean that the variation by different methods will always be as shown here. The results depend upon the amount of insulation on the coil, the ratio of slot to tooth width, the angle of the V part of the coil, and various other factors. However, with the various methods now available, used in conjunction with tests on actual machines, the designer should be able to estimate this end-winding leakage reactance with reasonable accuracy.

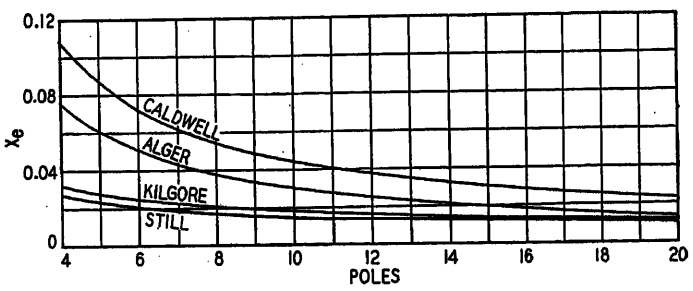



**Figure 3. Comparison of end-winding leakage reactance calculated by different methods**

2/3 coil pitch

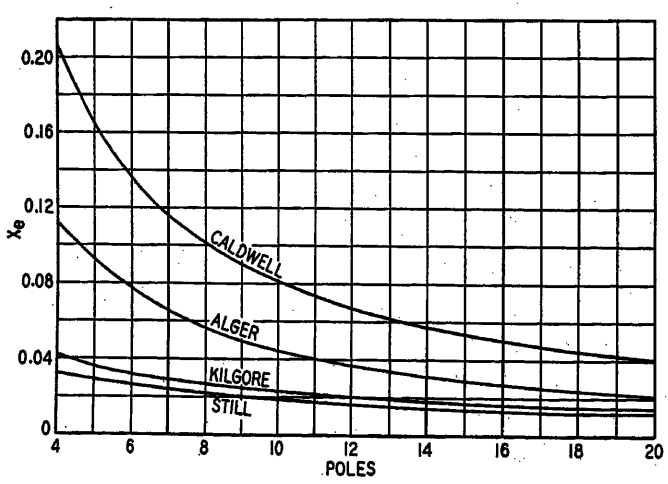



**Figure 2. Comparison of end-winding leakage reactance calculated by different methods**

Full-pitch winding


REFERENCES

1. THE CALCULATION OF THE ARMATURE REACTANCE OF SYNCHRONOUS MACHINES, P. L. Alger. AIEE TRANSACTIONS, volume 47, page 493.

2. END CONNECTION REACTANCE OF SYNCHRONOUS MACHINES, Alfred Still. AIEE JOURNAL, July 1930.

3. CALCULATION OF SYNCHRONOUS MACHINE CONSTANTS, L. A. Kilgore. AIEE TRANSACTIONS, volume 50, page 1201.


**B. H. Caldwell, Jr.**: The appearance of the factor 2 in equation 15, which has been questioned by Mr. Coffin, has been carefully checked both by Mr. Douglas and the writer, and the conclusion is that with the stated assumptions (15) is correct as it appears in the paper. In proceeding from (12) to (15) a multiplier of 2 does appear to take account of both ends of the end winding.

There may be some confusion regarding the definition of $n$. Perhaps a clearer definition would be to define $n$ as the number of V-shaped end-winding conductors per phase per pole. Throughout the paper the V-shaped conductor has been used as the unit. This corresponds to the number of series connected turns of the armature winding as a whole.

There happens to be an easy way of comparing the result given by (15) with Mr. Alger's result (reference 1 of the paper). His equation 13 for the peripheral component of end-winding leakage flux, when expressed in the nomenclature of this paper, is

$$\frac{X_{EP}}{2\pi fP} = \frac{12\,\pi\,D\tan\alpha}{P}\,K_{pl} \qquad (1)$$

Equation 15 differs from (33) only in that the tan $\alpha$ is replaced by sec $\alpha$. For $\alpha = 60$ degrees the ratio of (15) to (33) is 1.155. Now Mr. Alger adds the axial component of end-winding leakage to $X_{EP}$ to obtain the final expression for the total leakage, while the mutual linkage is subtracted from (15) to obtain the final expression for the leakage inductance, hence it appears logical to expect the 2 methods to agree with fair accuracy.

Mr. Douglas calls attention in his (1) and (2) to an approximation not specifically mentioned in the paper. The approximation involved is equivalent to assuming curve 1 of figure 4 instead of curve 2 as the magnitude of the space fundamental of flux density along the $y$-axis. Curve 2 which is theoretically correct has its maximum at

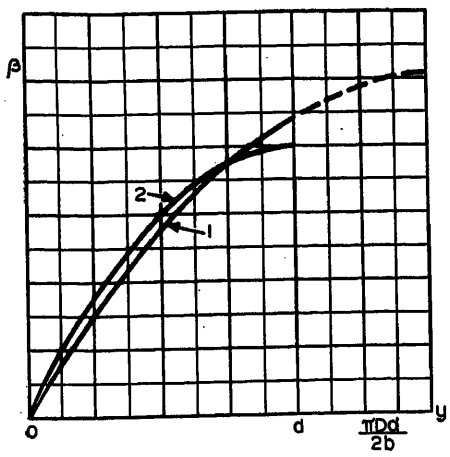



Figure 4

$y = d$, while the assumed curve 1 has its maximum beyond $y = d$. Only the region between $0<y<d$ is involved, and the simplification of the expression for the pitch factor warrants the approximation. For $^3/_4$ pitch this introduces an error of about 3.5 per cent.

The approximation pointed out by Mr. Douglas in his equation 3 is specifically noted in the paper. Space limitation prevented discussing it in detail. As he points out, it may lead to considerable error in some cases, particularly where the ratio of slot to tooth pitch is large. However, Mr. Douglas apparently overlooks the fact that, because of the angle of the end connections, the ratio of the peripheral dimension of the conductor in the end zone to the tooth pitch is much closer to unity than it is in the core length, which makes the approximation quite good for the fundamental. In cases where the series of equation 22 converges slowly equation 21 instead of 23 should be used to compute $K_m$.

Both Mr. Coffin and Mr. Douglas have pointed out the importance of fringing flux across the air gap. Measurements with exploring coils as well as flux plots indicate that they are correct. I would like to refer them to the discussion of this under "conclusions" in my paper. What I have attempted to calculate and measure is end winding *leakage* inductance. It seems obvious that practically all of the flux lines which enter either the pole directly or the rotor pole end plates will thread the pole coil, appear as fringing flux at an adjacent pole, and complete their paths by returning through the stator iron. There is, of course, some flux which passes from a tooth side to the adjacent tooth side. This is truly leakage flux and F. W. Carter in a discussion of a paper, "The Reluctance of Some Irregular Magnetic Fields," J. F. H. Douglas, AIEE TRANSACTIONS, volume 34, 1915, pages 1067–1134, has calculated this as a correction for the slot leakage flux. This seems to be a logical way to handle the other components of fringing flux. Thus this flux would contribute components to the flux of armature reaction and differential leakage as well as the slot leakage. Except for machines with a very short stacking these fringing components would probably be a very small correction. On this basis I have chosen to ignore the fringing flux in calculating the end-winding leakage inductance, and it enters the problem only in that it distorts the end-winding leakage field.

In the exploring-coil method of measuring the end-winding leakage inductance this question of fringing flux again appears. As Mr. Douglas points out, the exploring coils are not linked by all of this fringing flux. However, they were in the same positions for both the measurement of the self and the mutual flux, hence the omitted part would add to each of these values in the same way and cancel in the final result.

It is not my purpose to minimize the importance of calculating the fringing flux. Although it does not, according to the postulates of my paper, constitute a part of the end-winding leakage flux and except in rare cases the corrections of slot leakage, differential leakage, and inductance of armature reaction to account for it are probably small, it is very important in calculating losses. Most of this flux enters unlaminated sections of iron, hence it is probably responsible for a large part of the magnetic losses of machines.

For this reason, further work along the lines suggested by Mr. Douglas is very desirable. Also, as Mr. Alger points out, the method outlined should be useful in calculating the inductance of a larger class of machines. The discussion of this group of papers has revealed many useful suggestions and it is to be hoped that these suggestions will be the subject of further theoretical and experimental study by the various authors.

# Reactance of End Connections

**Discussion and author's closure of a paper by J. F. H. Douglas published in the February 1937 issue, pages 257–9, and presented for oral discussion at the power generation and electrical machinery session of the summer convention, Milwaukee, Wis., June 24, 1937.**

P. L. Alger: See discussion, page 1312.

G. W. Hampe: See discussion, page 1318.

Ernst Weber: See discussion, page 1313.

L. T. Rosenberg (Allis-Chalmers Manufacturing Company, Milwaukee, Wis.): The designer is always eager to adopt refinements in methods of calculation of performance that will consistently yield more accurate values. Heretofore, end-connection reactance has been computed on the basis of certain assumptions which gave reasonably good results in most cases. When test values of reactance showed poor agreement with calculation, it was not always easy to determine the exact source of the error, although it was only natural to suspect those places where approximations had been used.

In synchronous machines having magnetic rotor pole end plates with axially overhanging pole piece to support the rotor coil ends, and in turbogenerators not equipped with nonmagnetic rotor-coil retaining rings, the proximity of the magnetic material evidently had its effect upon the end-winding reactance. Since these effects are most pronounced in the immediate vicinity of the core and pole ends, and since in machines of moderate to large ratings the stator coils usually project straight out of the slots for a distance of from 2 to 6 inches and then bend radially outward at an angle, it would seem reasonable that end-connection reactance might well be divided into 2 distinct parts; that part corresponding to the straight stickout with the proximity of iron accounted for in accordance with Doctor Douglas' paper, and the remainder corresponding to the V-shaped ends considered to be far enough away from the iron to be unaffected as treated by B. H. Caldwell in a companion paper. A rigid solution on this basis may prove to be less difficult and thus permit taking account of the conical shape of the end winding plane.

The application of the Schwarz-Christoffel transformation to the solution of magnetic fields as described in the paper will generally lend itself to the expression of permeances as a function of the physical dimensions in the form of curves, thus facilitating practical use of the results. End-connection reactance might then be computed in very much the same manner in which we now use the Carter coefficient to calculate the effective air gap of a slotted armature surface.

J. F. Calvert and E. K. Rohr (Iowa State College, Ames): We have several items which we wish to discuss in connection with Professor Douglas' paper and will introduce these approximately in the order in which he has presented them.

1. In his discussion of figure 2 of the paper, he describes how ampere turns applied across the air gap may be replaced by current-carrying conductors of proper strength. However, for his figure 1 and the lower view shown in figure 5, where imaging is proposed, we would like to ask why the air gap magnetomotive force has not been replaced by a current sheet (or Rayleigh insulating surface for magnetic flux)?

2. Referring now to the right-hand drawing in figure 2 of Professor Douglas' paper, we do not believe that this presents a strictly correct treatment of the problem. Either it must be assumed that other conductors exist such that there will be the same magnitude of magnetomotive force for the air gap over each coil, or else, if only one coil is to be assumed in the air gap, as is shown in his figure 2, the return current at the air gap for the single coil end must divide and travel along the air gap in 2 paths. This is illustrated further in figures 1 and 2 of this discussion. If only one coil is to be assumed in the machine and it spans one-fourth of the air gap periphery, figure 1*a* of the discussion shows the air gap magnetomotive force to be replaced, and figure 1*b* shows how this should be accomplished. If 4 coils, each of one-fourth pitch, are to be assumed and are so disposed that the magnetomotive force on the air gap is symmetrical, figures 2*a* and 2*b* of this discussion show how the air gap magnetomotive force should be replaced by current-carrying conductors. We assume that for the right-hand drawing of figure 2 in the paper, Professor Douglas is assuming that

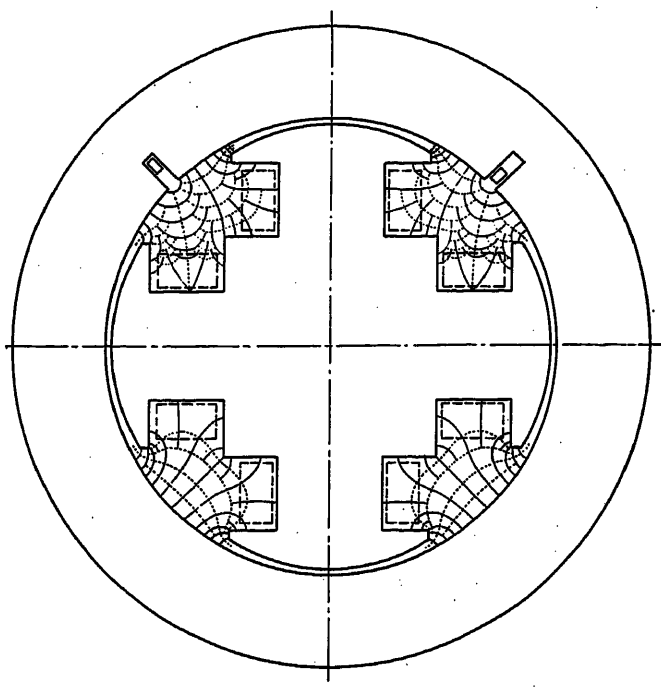


FIGURE 1a

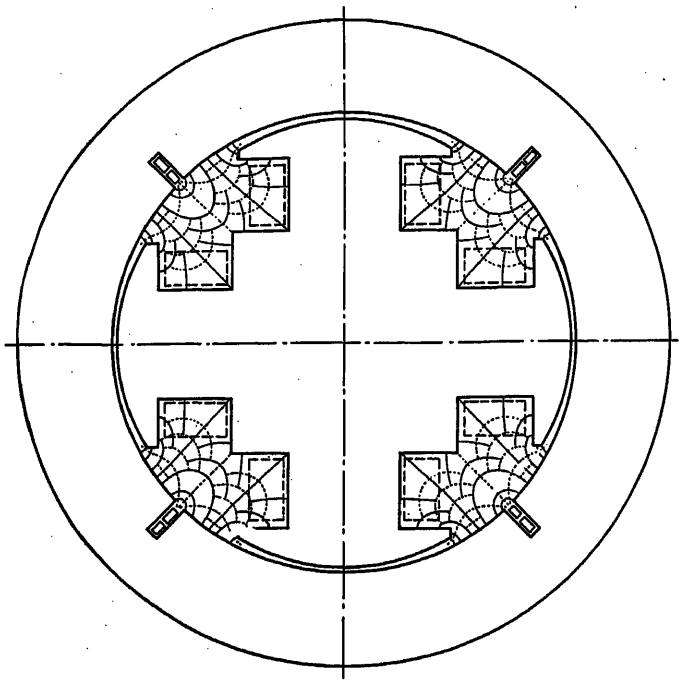


FIGURE 2a

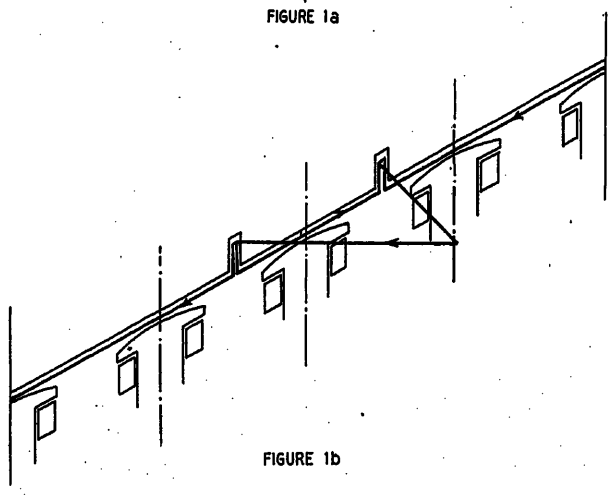


FIGURE 1b

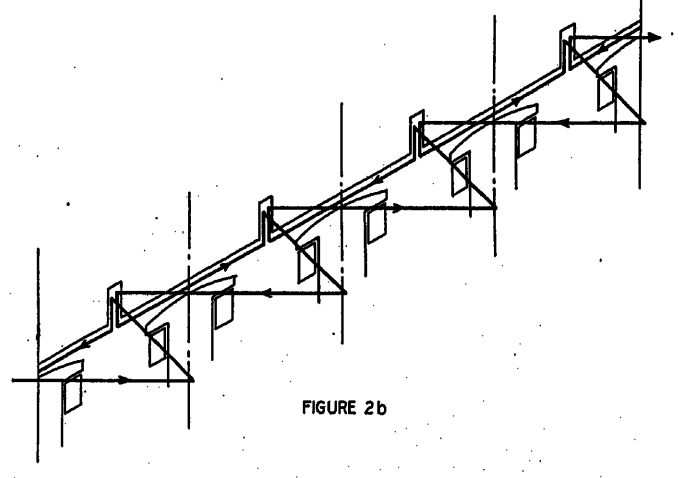


FIGURE 2b

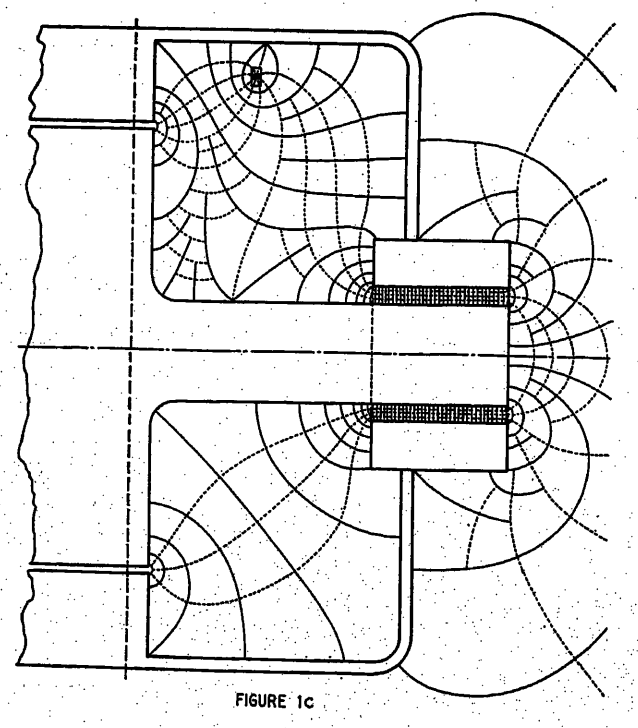


FIGURE 1c

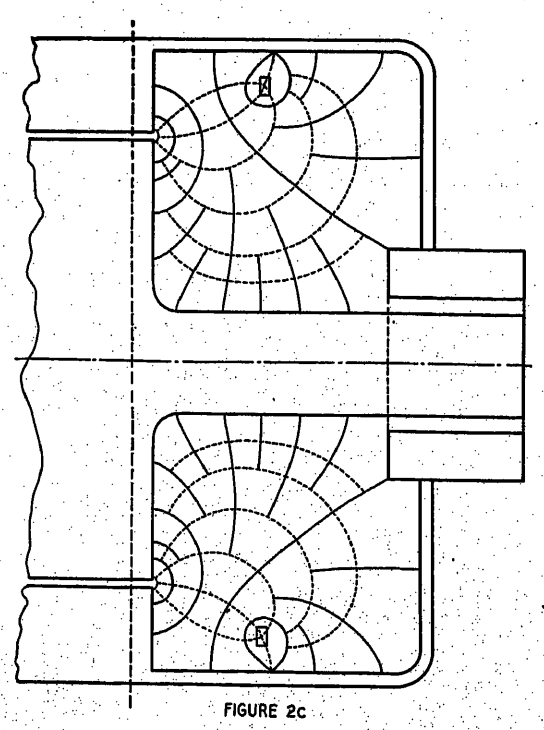


FIGURE 2c

**Figure 1a. Only one full pitch coil excited**

Solid lines show the flux. Dotted lines show the ampere turns, and also the directions and relative densities for the current when the air space in this plane is replaced by a current sheet or Rayleigh insulating surface for magnetic flux

**Figure 1c. Approximate flux and magnetomotive-force distribution on the radial plane through the pole center line with only one full pitch coil excited in a 4-pole machine**

Note the map is only 2-dimensional. Also note that the stator finger-plate and end-plate and also the overhang on the pole end-plate are neglected to give a plane surface and thereby permit imaging. This has been done to be most nearly in conformity with the paper

**Figure 2a. Same as figure 1a except with one full-pitch coil per pole excited as shown**

**Figure 2c. Same as figure 1c except for one full-pitch coil per pole**

an even number of coils are disposed around the machine in a manner similar to that indicated by figures 2*a* and 2*b* of this discussion. Figures 1*c* and 2*c* of this discussion show the end zone flux mapped on the assumption of a 2-dimensional field. It must be recognized that a 2-dimensional analysis here is only approximate, but it does give the general direction of the magnetic flux, and the orthogonal surfaces.

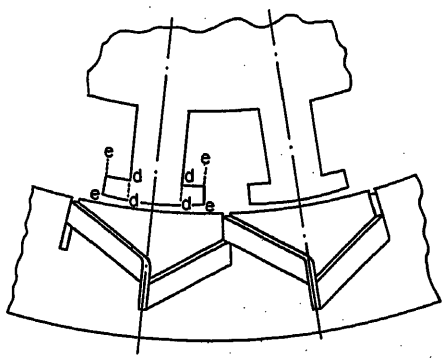



**Figure 3**

3. In his discussion of figures 5 and 6 of the paper Professor Douglas assumes a Rayleigh insulating surface to be located in a plane parallel to the edge of the field poles. It would appear that Professor Douglas intends to neglect the pole overhang or pole-shoe. However, we would like to ask first whether this Rayleigh insulating plane is to be assumed at *e-e* or at *d-d* as designated in figure 3 of this discussion, or at some intermediate location, and second on what basis a Rayleigh insulating surface in this zone between *e-e* and *d-d* can be assumed to be a plane? We feel that this assumption is an ingenious development, and if it can be adequately justified may prove to be a useful artifice, but we also feel that further justification for the assumption of a plane for this surface should be presented.

4. The pole and armature present Rayleigh conducting surfaces for magnetic flux in the end zone. However, the interpolar space may be considered merely as a widening out of the air gap in the radial direction. Therefore, in the polar zone as defined in the

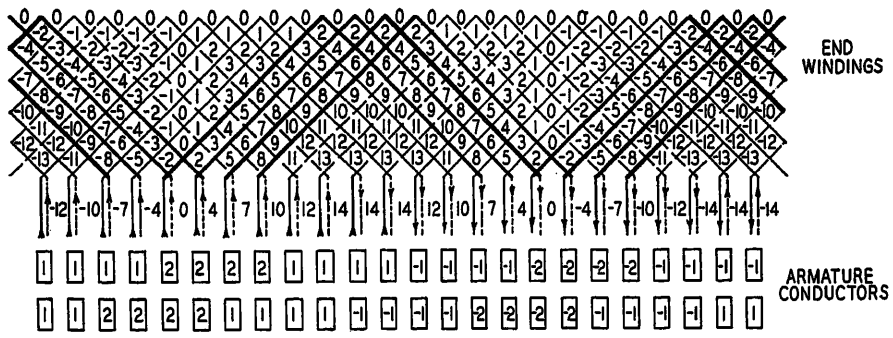



**Figure 4. End-winding and air-gap magnetomotive forces**

Three phase, 4 pole, 48 slots, coil span = 10 slot pitches

paper, the pole and armature do not form a continuous Rayleigh conducting surface, but must have a Rayleigh insulating surface between them to represent the air gap as illustrated in figure 3 of this discussion. That this must be done, is not made clear in that part of the paper in which figure 5 of the paper is discussed.

5. The use of the Rayleigh conducting surface $RC_2$ in the lower right-hand corner of figure 5 of the paper would seem to be a reasonable assumption for those machines in which the frame and end bracket overhang the coils, and do present such a conducting surface for magnetic flux over both the polar and interpolar zones. However, the assumed plane should be so located as to most nearly represent these magnetic parts. It may need to be closed in on machines with bracket-type bearings making reasonable allowance for the space between bracket arms. (See figures 1*c* and 2*c* of this discussion which are for a machine where the actual bracket arms came outward on diagonal lines from near the frame to the bearing.)

6. To be in conformity with the paper, we have confined our discussion to the case of one full-pitch armature coil per pole. We wish now to discuss the actual cases of distributed windings. Exploring coils will show that the flux lines pass through the armature end winding in directions reasonably nearly perpendicular to the conical surface between the 2 layers of the end winding. Reasons for this can be offered.

If no iron were present at all and the coil span was not a great percentage (one-fourth or less) of the armature bore, then the reluctance inside and outside the coil would not be greatly different and the flux field near the conical surface of the end winding would be almost symmetrical with respect to this conical surface. This would mean that the flux would pass nearly perpendicularly through this surface between 2 layers of coils in the end winding. The introduction of iron into the problem produces tremendous effects where it is near the coils. However, it is not near the conical surface of the end winding and will not produce great effects here just as the imaged conductors with the iron removed would not produce great effects on densities near the coil which is imaged—provided the spacings between coil surface and iron are relatively great as is the case for most of the armature end winding.

It might be desirable to make use of the magnetomotive forces through this surface at various points as mentioned before. The end zone like the air gap and interpolar zone is merely part of the air space between the rotor and stator. On the basis of these 2 remarks, it might seem desirable to extend the usual magnetomotive-force diagram for the air gap to the end zone as is illustrated in figure 4 of this discussion. This viewpoint has been discussed in more detail in the paper "Additional Losses in Synchronous Machines," AIEE TRANSACTIONS, volume 46, 1927, pages 84–97, by C. M. Laffoon and J. F. Calvert. We offer this merely as a possible treatment. We wish to point out that our figure 4 of this discussion merely gives the approximate magnetomotive force distribution and not the reluctance for paths through the winding. The effects here might be considered analytically by assuming the magnetomotive-force distribution mentioned above and considering the iron boundary conditions as they exist in the end zone. Another possible attack would be to excite the armature coils with direct current, and explore the directions of flux with a compass. The discussers are of the opinion that the experimenter would then deduce that exploring coils placed within the conical end winding would show practically the total linkage in this zone under a-c conditions. The flux distribution under these d-c conditions will be practically the same as under normal a-c conditions because sufficient eddy currents cannot flow in the armature end plates and frame to alter greatly the flux distribution under normal load. That this must be true can be reasoned as follows: The armature winding carries the full armature magnetomotive force in the end winding. If the flux is to be kept out of the end plates, frame, etc., damping currents of practically equal magnetomotive force would have to flow in these parts. When one considers the depth of current penetration in the iron which is normal at the commercial frequencies, the loss densities are many times higher than can actually exist without greatly overheating the machine. Another method of attack here is to neglect saturation and calculate by means of 2-dimensional flux maps what the flux entering the iron parts will be. Then calculate the saturation produced making due allowance for proper flux penetration in solid parts. Then by use of Rosenberg's formula consider the ampere turns present in eddy currents. These eddy currents will be found small enough to have little effect on the general shape of the end zone flux.

We hope that Professor Douglas will give a detailed discussion of how he intends to consider the various phase groups in the end

zone either with or without the use of the Rayleigh insulating plane to divide the space into polar and interpolar spaces when he proceeds to the cases of actual armature windings.

7. In addition to the use of Rayleigh insulating and conducting planes as Professor Douglas describes them, we wish to suggest that any surface in a magnetized space may be replaced by combinations of current and magnetic sheets for use in electrical machine calculations. This has been illustrated in the paper "Forces in Turbine Generator Stator Windings," by J. F. Calvert, AIEE TRANSACTIONS, March 1931, pages 178–94, and the scheme might have some value in this work of Professor Douglas' as well as in that for which it was used where the forces exerted on armature end windings were to be calculated.

**J. F. H. Douglas:** I quite agree with Mr. Alger's remark that considerable work is yet to be done. My paper is really more of a program for research, than anything else. It is gratifying to know that it seems to be a sound procedure.

Mr. Rosenberg's suggestion is interesting and of value. It is equivalent to assumption of a Rayleigh insulating plane perpendicular to the shaft at some point approximately 2–6 inches from the pole. Caldwell's method would be rigorously applicable outside this surface, my method could could be applied inside this surface. However no advantage is gained as yet. If immediate results are wanted Caldwell's formula is apparently the best to date. If greater accuracy is wished for the future why asume this plane at all? The assumption of a Rayleigh plane always decreases the answer, we would not know at present where to place it for best results, and we would still lack a usable formula for immediate use. The chief merit of this suggestion seems to me as a means of adapting theory to fit test results at some later date if it prove that Caldwell's formula is lower than test, and that my method gives reactances larger than test values.

Referring now to the careful analysis of Messrs. Calvert and Rohr, in the sequence of their numbered points.

1. Their suggestion of a current sheet appears decidedly superior to my rather crude semicircular fictitious conductor. It meets boundary conditions theoretically, and leads to an added item of permeance of 0.7 line per ampere turn for each inch of pole width (0.27 per centimeter). Their figures are particularly elegant and instructive.

2. Their point that the current sheet should divide in the ratio of 75 per cent and 25 per cent in a 4-pole machine is perhaps theoretically right for an isolated coil. However the simplest unit from which to build up inductance, is, perhaps, one coil for each pole, and for this case the distinction is unimportant.

3. I believe that the radial Rayleigh insulating planes should be intermediate between the pole-shoe tip and the edge of the pole core: (1) not much error is caused by assuming the outer end of the pole tip as insulating, (2) not much error is caused by assuming the narrow strip between this plane and the pole edge as conducting, (3) these errors compensate.

Their second point is whether a plane Rayleigh surface can be assumed with propriety at all. A Rayleigh surface always causes some error, but this error is small when in regions of highest density the lines are nearly parallel to the surface. In this case near the air gap the actual lines are parallel to this plane. Near the trace of the conductor they meet it at 40 degrees, It is believed therefore that some error is made but less than that of other methods proposed. By moving the Rayleigh plane toward the interpolar axis we eventually arrive at a point where it is obvious that the permeance is too large.

I conclude that by assuming the Rayleigh plane intermediate between the pole tip and the pole edge, but nearer the pole tip, we will get a balance between calculations and experiment.

4. In figure 5 the air gap should have been shown perhaps. However, if we assume armature ampere turns and balancing field ampere turns, we do not need any current sheet in the air gap, and have a basis for computing that part of the flux in the end zone, for 2 important cases, namely Potier reactance, and the inductance of commutation.

5. I believe these comments to be well founded, and helpful where housing iron needs to be considered.

6. The suggestions should be considered by future investigators. I believe them as more helpful in guiding tests than as an aid to calculations.

Hopes are expressed for a detailed discussion of how I propose to consider various phase groups in the end zone. A closing discussion is hardly the place for much detail and, to be frank, the writer is not going to take up the detailed solution at this time. Enough has been done since the paper was published, however, to show that Laplace's equation is easily integrable for coils that are 45-degree isosceles triangles both for self-induction, and for mutual induction between coils in the same and adjoining phase belts. The coil is the first unit, the phase belt is naturally the second, and the mutual inductance between phases and adjoining pole pitches naturally follow.

## Approximating Potier Reactance

**Discussion and author's closure of a paper by Sterling Beckwith presented at the power generation and electrical machinery session of the summer convention, Milwaukee, Wis., June 24, 1937, and published in the July 1937 issue, pages 813–18.**

**P. L. Alger:** See discussion, page 1312.

**S. B. Crary** (General Electric Company, Schenectady, N. Y.): Mr. Beckwith's paper presents interesting data in regard to Potier reactance and methods of approximating it, which check with good accuracy a large number of test results. This information is valuable in that it increases our knowledge of machine reactances.

It is well to keep in mind that Potier reactance has only a limited field of usefulness, namely the approximate determination of field excitation for normal conditions of voltage and power factor. For any unusual conditions such as high terminal voltage or leading power factor or for the determination of the load angle and stability characteristics, the use of Potier reactance determined at normal voltage may give results which are too approximate. There appears to be no real reason for using Potier reactance for design computations as in such work all the machine quantities are available and the field excitation can be calculated by more accurate methods. For those cases other than for design computations Potier reactance can usually be determined by test.

The method which Beckwith has used for determining the pole saturation, by adding the transient reactance drop to terminal voltage to obtain the pole flux, can only be used for the condition of zero power factor, which is the condition for determining Potier reactance. For other power factors, if the approach is made from the armature, it would be necessary to add to the direct-axis component of terminal voltage the direct-axis component of transient reactance voltage drop. In order to determine these direct-axis components, it is necessary to know that component of saturation-magnetomotive force which is a function of the quadrature-axis flux, as saturation in the quadrature axis affects the machine angular displacement. These complications are to a considerable extent the reason for the use of Potier reactance for excitation calculations, as it provides a method which has been found to give approximately the correct excitation by a comparatively simple calculation. However, the use of Potier reactance does not give the proper load angle of the machine and in some cases does not give the correct excitation. The greatest disadvantage for its use is that it tends to conceal the true physical picture.

**G. W. Hampe** (Commonwealth Edison Company, Chicago, Ill.): The writer is pleased to see that the constants of synchronous machines are being subjected to careful analysis, both in regard to furnishing sound concepts and in development of methods of computation and test. As one who makes computations for systems containing synchronous machines, the writer can say that such studies are needed, and that the results should be made available to all who can make effective use of them.

If it is granted, for the present, that the primary concepts have been defined and methods of computation and test have been made available, what is the resulting advantage to the operating engineer? Manufacturing companies have always willingly furnished data on their machines, both old and new. Likewise, power companies have freely given information to their interconnected associates. Unfortunately, however, these communications have been haphazard and occasionally repetitive.

The writer suggests that a standard form or set of forms be developed so that all data pertinent to the electrical properties of a given machine can be recorded on one sheet. Part of the data for such a form, such as the reactances, would usually be supplied by the manufacturer, and the balance, referring to external reactors, field rheostats, etc., would

be filled in by the operating company. The writer would like to call this matter to the attention of the AIEE committee on synchronous machinery.

Such a form should *not* be made up with a view of obliging each manufacturer to compile all the data for every machine, large and small. When data are furnished, however, they should follow the standard definitions accepted, at that time, and the use of a standard form would systematize communications.

The papers, particularly the one by Mr. Beckwith, added to the rather scanty stock of published test data. More data are needed in regard to machine constants in general, particularly for large machines. As an example of this need, Mr. Beckwith offered an approximate formula relating Potier reactance to unsaturated transient reactance, which brings up the question of saturation. In the AIEE summer convention in 1931, Mr. S. H. Wright stated that the saturated transient reactance $x_d'$ was related to the unsaturated value by the formula:

$$x_d' \text{ (sat.)} = 0.88\, x_d' \text{ (unsat.)}$$

This formula was questioned, but to date the writer has not seen a satisfactory alternative. In some types of power system computations both the saturated and unsaturated values are needed, and usually one must be derived from the other by a formula of some sort.

The test methods known at present are not applied for several reasons. The manufacturer seldom has facilities for testing a large machine before shipment. The operating company could make the test, but it means trouble and expense, not only for the testing setup itself but because the machine may be badly needed on the system. A large part of the cost is hidden and indirect. Furthermore the operating company probably has only one machine of that class, and a refinement in data means little because of its limited applicability. The same expenditure for a test of system stability or relay performance yields data of greater value.

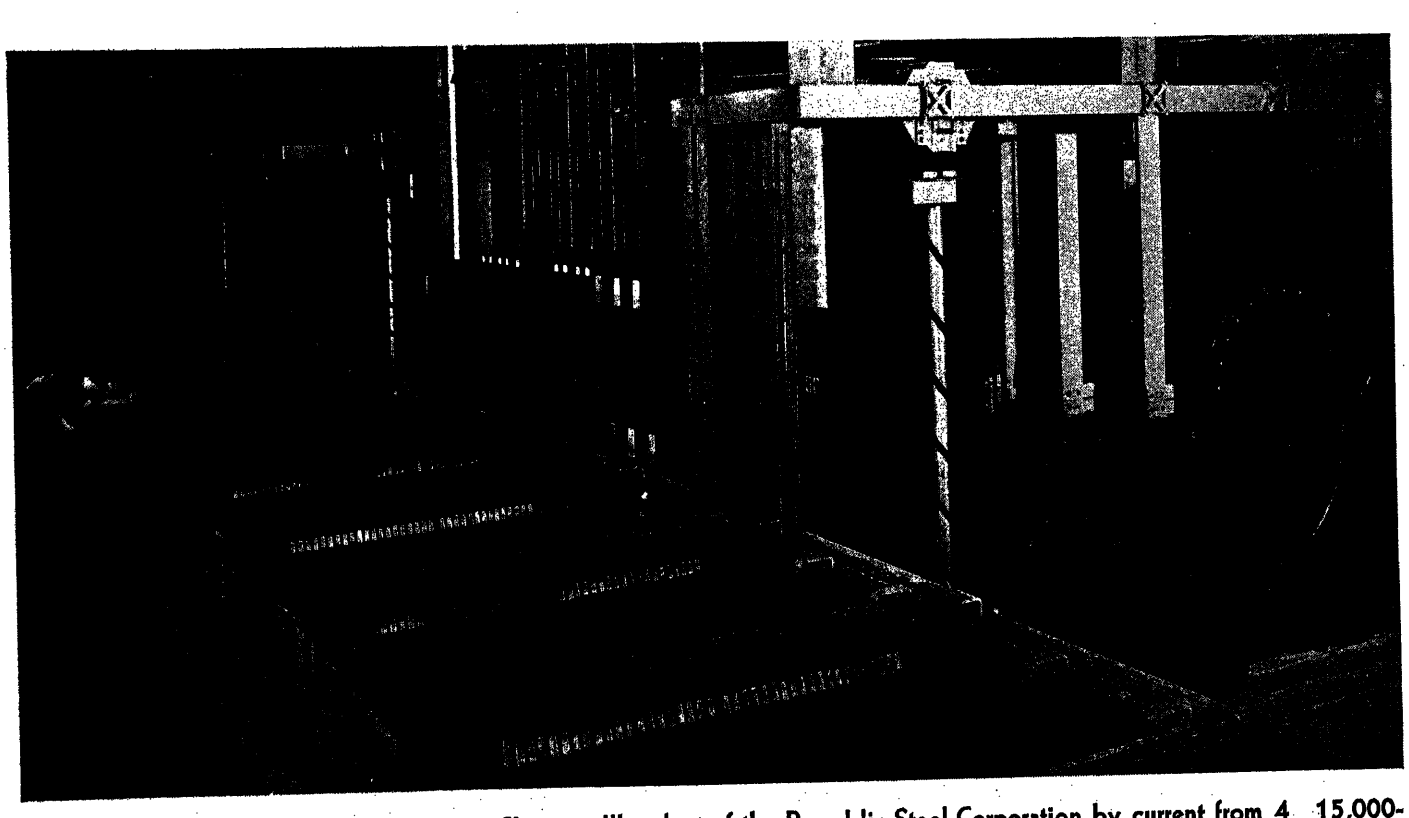
The manufacturer can profit by tests on individual machines, because he is concerned with a number of machines of the same class, and, furthermore, there should be occasional checks on general methods of computation and design. It would seem then that the manufacturer should co-operate more frequently with the operating company in securing test data, and it would seem that the manufacturer should share the costs.

**Sterling Beckwith:** Mr. Crary's comment that the use of Potier reactance tends to obscure the exact picture is quite correct, and should be borne in mind when using the reactance. However, a clearer picture of the magnitude and range of the reactance and its relation to other reactances should have the opposite effect. Mr. Crary limits the use of Potier reactance to the calculation of field currents, but a further use is for determining the effects of saturation on stability.

Although Potier reactance varies with current and voltage, it should be pointed out that most synchronous-machine reactances are subject to the same variation. Furthermore Potier reactance is subject to easier and more accurate test than are most reactances.

Mr. Hampe raises the question of saturation of transient reactance. The curve mentioned showing an average value of saturated reactance equal to 88 per cent of the unsaturated value does not take terminal voltage into account. Thus when the internal voltage is above normal the saturation factor may be much lower than 88 per cent. Tests with which the writer is familiar indicate that an average value is 83 per cent to 88 per cent for a dead short circuit at rated voltage, but that it may vary very greatly in different machines.

Perhaps Mr. Hampe's suggestion of a standard form for machine characteristics might be filled to some extent by references to the "Proposed Test Code for Synchronous Machines." One advantage of references to such a test code is that definitions are usually definite and unambiguous, whereas any abbreviated form might lack this advantage. A summary sheet added to the test code might make it more suitable for the purpose.



**Steel wire is electrogalvanized in the new Chicago, Ill., plant of the Republic Steel Corporation by current from 4 15,000-ampere d-c generators. The current is distributed to 27 sets of porcelain-insulated fingers which make contact with 40 strands of wire that pass continuously through the 140-foot electrolytic bath at speeds from 35 to 70 feet per minute. Thickness of the zinc coating is controlled by speed of wire travel and current density. Electrogalvanizing produces a coating that is considered superior to hot galvanizing because of its better adherence, greater uniformity, and purity, but difficulties of cleaning and deposition, solved only recently, retarded development**

# News
## Of Institute and Related Activities

## Pacific Coast Holds Successful Convention at Spokane

TWO hundred and sixty-six members and guests enjoyed the 25th Pacific Coast convention, which was held at Spokane, Wash., with headquarters in the Hotel Davenport, from Tuesday morning through Friday, August 31–September 3, 1937. On the part of those in attendance full advantage was taken of the technical sessions, student sessions, entertainment, sports, and inspection trips, which had been well arranged by the convention committee, and many were afforded the opportunity of meeting old acquaintances.

The opening session on Tuesday morning was called to order by Dean H. V. Carpenter, convention chairman, who introduced Arthur W. Burch, mayor of Spokane. The mayor welcomed to the city those attending the convention and he advised that Frank G. Sutherlin, commissioner of public utilities, would be delighted to have members inspect the electric plant up the river.

President Harrison expressed appreciation on behalf of the Institute of the welcome extended by Mayor Burch, who had been ill but came down to greet the assemblage on his second day out. He complimented the District and Section officers upon the favorable manner in which the conventions, student activities, and student prizes have been conducted on the Pacific Coast. At the conclusion of the opening of the convention R. W. Sorensen proceeded with the conduct of the selected subjects session.

### Technical Sessions

A keen interest on the part of those who attended the 6 technical sessions and 2 student sessions was maintained throughout the duration of each session. One of the 6 technical sessions, which dealt informally with the subject of electric house heating, was held on Wednesday evening with Professor F. O. McMillan presiding. Doctor C. E. Magnusson, director of the Engineering Experiment Station, University of Washington, presented a summary and recommendations of the investigation on the electric heating of homes in the Mont Lake district of Seattle. The work was originally done for the State Planning Council. The complete report of this work, with results and conclusions, is available in Bulletin No. 93, "Electric Power Markets in Washington —Part I, Electric Heating of Residences," recently published by the Engineering Experiment Station, University of Washington. Dean H. V. Carpenter of the State College of Washington, presented a paper on the same subject, which reported the results of experiments on different methods of heat storage for electrically heating the specially constructed and insulated houses at Mason City. These papers were discussed by several well-known executives and engineers of operating companies in the Pacific northwest, who found the studies to be most valuable but not in agreement with the practical problems of power distribution, as experienced in operating company work. Another session, on the subject of communication, which was held jointly with the members attending the Institute of Radio Engineers' meeting, was well attended and considerable interest was manifested in the 6 papers which were presented.

Most of the convention papers were personally presented by their respective authors, and, in cases where the authors were unable to attend, comprehensive and effective presentations were made by F. C. Lindvall, California Institute of Technology, P. B. Garrett, Westinghouse Electric & Manufacturing Company, H. H. Skilling, Stanford University, W. C. Smith, General Electric Company, and S. B. Wright, Bell Telephone Laboratories, Inc.

### Student Technical Sessions

In accordance with the practice followed for a considerable number of years, 2 student technical sessions were held as parts of the convention technical program. Eleven papers, as listed below, were presented:

**Wednesday Afternoon**

J. S. Mascovich, chairman, University of Santa Clara Branch, presiding.

Balanced Feed-Back Amplifiers, Edward L. Gintzton, University of California

A Method of Measuring Losses in Small Transformers, Bruce Morgan, California Institute of Technology

Laboratory Equipment for Construction of Experimental Electron Tubes, H. P. Blanchard, Stanford University (presented by Leonard M. Jeffers, Jr., chairman, Stanford University Branch)

Magnetic Focusing of the Electron Gun, L. Dale Harris, University of Utah (presented by William R. Wilson, chairman, University of Utah Branch)

Influence of Utensils on Heat Transfer from Electric Range Elements, William G. Short, Oregon State College

**Thursday Afternoon**

Gordon B. Allan, chairman, Montana State College Branch, presiding.

A High Impedance Detector Circuit With a Diode, John W. Stoker, Jr., Montana State College

Torque in Induction Disk Instruments, G. I. Goumeniouk, University of British Columbia

Variable Gain Amplifier and Its Application, J. F. Kalbach, University of Washington (presented by Rush Chase, University of Washington '37)

Electrostatic Air Purification, W. D. Arms, University of Idaho (presented by W. T. Connely, University of Idaho, February '37)

Measurement of the Field Strength of Radio Station KWSC, William Lean, State College of Washington

Characteristics of A-C Welding, O. C. Bixler, University of Southern California (presented by A. E. Harrald, chairman, University of Southern California Branch)

The quality of the presentations was high despite the facts that several authors were absent and their papers were presented by students and recent graduates not directly connected with the work discussed. The subject matter of all maintained a high degree of interest throughout the 2 sessions and some of the papers were discussed by students and others.

### Conference on Student Activities

A joint conference on student activities for representatives of the student Branches in Districts 8 and 9, and the University of British Columbia Branch, as well as District officers and others interested, was held at a dinner meeting on Wednesday evening, with an attendance of 38, as reported in more detail below:

**Branch Chairmen**

John Draper, University of Arizona, Tucson
Bruce Morgan, California Institute of Technology, Pasadena
Peter Duyan, University of California, Berkeley
Gordon B. Allan, Montana State College, Bozeman
Guy K. Patterson, University of Nevada, Reno
Victor S. Carson, Oregon State College, Corvallis
J. S. Mascovich, University of Santa Clara, Santa Clara, Calif.
Leonard M. Jeffers, Jr., Stanford University, Calif.
William R. Wilson, University of Utah, Salt Lake City

**Counselors**

W. B. Coulthard, University of British Columbia, Vancouver
F. C. Lindvall, California Institute of Technology, Pasadena
Abe Tilles, University of California, Berkeley
J. H. Johnson, University of Idaho, Moscow
A. L. Albert, Oregon State College, Corvallis
W. G. Angermann, University of Southern California, Los Angeles
E. F. Peterson, University of Santa Clara, Santa Clara, Calif., and chairman, committee on Student activities, District 8
H. H. Skilling, Stanford University, Stanford University, Calif.
A. LeRoy Taylor, University of Utah, Salt Lake City
O. B. Osburn, State College of Washington, Pullman
R. E. Lindblom, University of Washington, Seattle

**Others Present**

J. P. Jollyman, vice-president, District 8
A. M. Bohnert, secretary, District 8
C. E. Rogers, vice-president, District 9
S. E. Caldwell, secretary, District 9
F. Ellis Johnson, director, and chairman, committee on student Branches
E. A. Loew, member, committee on student Branches
R. W. Sorensen, director, and member, committee on student Branches
H. V. Carpenter, chairman, Pacific Coast convention committee
R. H. Hull, chairman, student activities subcommittee, Pacific Coast convention committee
H. H. Henline, national secretary, and several professors, students, and others as guests—total 38

## Analysis of Attendance at 1937 Pacific Coast Convention

| Classification | Spokane | Dist. 9* | Dist. 8 | Dist. 10 | Misc. | Totals |
|---|---|---|---|---|---|---|
| Members | 28 | 35 | 25 | 5 | 15 | 108 |
| Men Guests | 22 | 43 | 23 | 2 | 7 | 97 |
| Women Guests | 20 | 20 | 16 | 1 | 4 | 61 |
| Totals | 70 | 98 | 64 | 8 | 26 | 266 |

* Outside of Spokane Section territory.

Professor E. F. Peterson of the University of Santa Clara, chairman of the committee on student activities in District 8, presided, and presented as the first item for consideration a list of suggestions for the guidance of counselors in Districts 8 and 9 which had been prepared by a committee including all counselors in Districts 8 and 9, with Professor Peterson as chairman. After an extensive discussion of the individual suggestions, the committee was given a vote of thanks and requested to continue the work and report again at the next conference.

It was voted to recommend that the board of directors consider the possibility of re-establishing the cash prize of $100 for the best Branch paper prize.

Many of those present expressed strong hope that such a joint conference, with traveling expense allowance to official representatives, may be provided for regularly so it will not be necessary to request special action each year. There was some discussion of the best time for such conference from the standpoint of attendance by students.

Vice-presidents Jollyman and Rogers, Directors Johnson and Sorensen, chairman and member, respectively, of committee on student Branches, Professor E. A. Loew, member of that committee, and National Secretary Henline were called upon for brief remarks, and all responded, giving information and opinions regarding various phases of student activities in the Institute.

After the adjournment of the conference, the counselors of the 2 Districts met in separate groups and elected as chairmen of the District committees on student activities:

Pacific District (Number 8)—Professor H. H. Skilling, Stanford University
North West District (Number 9)—Professor A. LeRoy Taylor, University of Utah

### Entertainment

On Tuesday evening a number of members and guests enjoyed an informal reception and dancing held in the Marie Antoinette Room of the Davenport Hotel. The entertainment concluded with the banquet and presentation of sports prizes, which took place on Thursday evening and which was well attended. Splendid entertainment in the form of aesthetic dancing, singing, and music rendered by the Mann Brothers orchestra was furnished. Toastmaster J. E. E. Royer, vice-president and general manager of the Washington Water Power Company, conducted the banquet in true social fashion by admonishing those in attendance "to forget their kilowatt words" and enjoy themselves. President W. H. Harrison of the AIEE and President H. H. Beverage of the IRE greeted the guests.

### Presentation of Sports Prizes

The sports prizes were presented in person by the well-known pioneer in hydroelectric developments in the northwest, John B. Fisken. The competition for the Fisken cup resulted in a tie between C. E. Boozier, Portland, C. H. Cutter, Seattle, and R. H. Dearborn, Corvallis, which was decided by the rolling of dice. Dean Dearborn won the trophy with C. C. Boozier runner-up. W. E. Wallace, Seattle, won the guests' competition with J. F. Gogins, Spokane, runner-up. Prizes were presented for the remaining events open to both members and guests: low gross, J. C. Henkle, Portland; longest drive at hole number 3, M. P. Buswell, Seattle; approach nearest pin at holes numbers 9 and 17, J. C. Henkel and H. A. Boring, Seattle; kickers handicap, L. R. Elder, Portland; and high gross, C. B. Carpenter, Portland. Birdies were scored by J. E. E. Royer, J. W. Butler, Schenectady, J. C. Henkle, M. P. Buswell, and J. W. Ferguson, Seattle. The women's putting contest was won by Mrs. W. H. Ude, Spokane, with Mrs. Chet Reis, runner-up. First prize for approach was won by Mrs. M. M. Phegley, Glendale, Calif., and second prize was won by Mrs. H. B. Hodgins, Spokane. The winners of consecutive flights were respectively as follows: Mrs. J. H. Siegfried, Kennewick, Mrs. C. E. Rogers, Seattle, Mrs. M. M. Phegley, Mrs. S. B. Wright, South Orange, N. J., Mrs. J. C. Bird, Seattle, Mrs. A. C. Schwager, San Francisco, Calif. Mrs. R. W. Sorensen, Pasadena, and Mrs. A. H. Beckwith, Spokane. Excellent prizes consisting of leather luggage, golf clubs, a silver platter, golf balls, and favors were made possible through the courtesy and financial support of several manufacturing and operating companies in the Pacific Coast region.

### Women's Entertainment

Under the guidance of Mrs. L. R. Gamble, Seattle, chairman, women's entertainment committee, a pleasant series of events was arranged. Tuesday morning the women got together for the purpose of becoming acquainted with one another, after which the group divided; one group took a drive about the city and gardens, while the other attended the "movies" at the Fox Theater. Luncheon was held in the Elizabeth Rooms of the Hotel Davenport. On Wednesday morning shopping tours were conducted and a bridge-luncheon was held at Glen Tana. Winners of prizes were Mrs. J. F. Spease, Portland, Mrs. C. C. Boozier, Portland, Mrs. Charles North, Kamloops, B. C., Canada, and Mrs. J. H. Neher, Philadelphia, Pa. Mrs. J. C. Bird of Seattle won the auction. One of the prizes consisted of a jar of herbs obtained from the beautiful gardens at Glen Tana. Thursday the principal event consisted of a scenic drive through the residential districts and civic gardens of Spokane, which was followed by a putting tournament and tea at the Spokane Country Club and a musical hour with selections rendered on the harp and cello.

### Trips

The principal trip was held on Friday, when over 250 members and guests of the AIEE and the IRE left the Hotel Davenport by bus and private car at 8:00 a.m. to see the Grand Coulee Dam, now in process of construction. Addresses on the features of the project were given by A. F. Darland, C. D. Riddle, and Mr. Banks, and a model of the dam was seen in the West Vista House. Luncheon was served in the contractor's mess hall on the east side of the river. The return to Spokane was made via Grand Coulee, and Dry Falls where the Columbia River once outrivalled the Niagara.

During the convention, trips were taken in private cars to various points of interest in Spokane and vicinity. Among the places visited were the Up-River Hydroelectric


## Membership—

Mr. Institute Member:

AIEE meetings and other activities get under way about this time of the year in many Sections.

I hope you will plan to get the most out of your Institute connections this season by attending what conventions, Section meetings, and other affairs you can, and by taking an active part in them in some way.

You may also be able to assist a nonmember friend by taking him with you and by introducing him to other members. If he becomes interested and is eligible for membership your membership committee will help him in making his application. Just write to your Section membership chairman or to headquarters.

L. L. Webb

Assistant Chairman
National Membership Committee

Station of the water department, the Ray and Hartson Pumping Plant, the radio tower of KHQ-KGA, and the Inland Paper Company mill, as well as the beautiful residential section and gardens in the city.

The personnel of the committee and the subcommittee chairmen which made all of the foregoing events possible is as follows: H. V. Carpenter, chairman; R. D. Sloan, vice chairman; M. F. Hatch, secretary; Reinier Beeuwkes, S. E. Caldwell, J. B. Fisken, L. R. Gamble, J. C. Gaylord, C. R. Higson, N. B. Hinson, R. H. Hull, H. S. Lane, F. O. McMillan, H. L. Melvin, H. S. Osborne, George Quinan, C. E. Rogers, R. W. Sorensen, and A. Vilstrup: L. R. Gamble, meetings and papers; J. S. McNair, finance; L. A. Traub, transportation; H. W. Webbe, housing; J. R. Murphy, entertainment; J. B. Fisken, sports; H. B. Hodgins, publicity; R. H. Hull, student activities; D. H. Olney, registration; Earl Baughn, inspection trips; and Mrs. L. R. Gamble, women's entertainment.

# AIEE Board of Directors Meets at Institute Headquarters

THE regular meeting of the AIEE board of directors was held at Institute headquarters, New York, August 3, 1937.

Present: *President*—W. H. Harrison, New York, N. Y. *Past-President*—A. M. MacCutcheon, Cleveland, Ohio. *Vice-Presidents*—O. B. Blackwell, New York, N. Y.; C. Francis Harding, Lafayette, Ind.; I. Melville Stein, Philadelphia, Pa.; A. C. Stevens, Schenectady, N. Y. *Directors*—C. R. Beardsley, Brooklyn, N. Y.; F. M. Farmer, New York, N. Y.; F. Ellis Johnson, Columbia, Mo.; C. R. Jones, New York, N. Y.; W. B. Kouwenhoven, Baltimore, Md.; K. B. McEachron, Pittsfield, Mass. *National Treasurer*—W. I. Slichter, New York, N. Y. *National Secretary*—H. H. Henline, New York, N. Y.

Minutes of the meeting of the board of directors held June 24, 1937, were approved.

Report was presented and approved of recommendations adopted by the board of examiners at its meeting held July 21, 1937. Upon the recommendation of the board of examiners, the following actions were taken: 3 applicants were transferred to the grade of Fellow; 29 applicants were elected and 35 were transferred to the grade of Member; 124 applicants were elected to the grade of Associate; 20 Students were enrolled.

Disbursements in July amounting to $27,618.84 were reported by the finance committee and approved.

Approval was given to a proposed meeting of the Southern District in Miami, Fla., in November 1938.

Announcement was made of the appointment by the president of Institute committees for the new administrative year, beginning August 1, 1937. (A list of committee members was published in ELECTRICAL ENGINEERING for September, pages 1217–21.)

The board confirmed the appointment by the president of H. P. Charlesworth as chairman of the Edison Medal committee for the year beginning August 1, 1937, and of C. R. Jones, Everett S. Lee, and H. S. Osborne as members of the committee for terms of 5 years each beginning August 1, 1937, and of L. W. W. Morrow to serve for the unexpired term, ending July 31, 1939, of L. C. Nichols, deceased. From its own membership, the board elected C. R. Beardsley, A. M. MacCutcheon, and K. B. McEachron to serve on the committee for terms of 2 years each, beginning August 1, 1937.

The board confirmed the appointment by the president of F. J. Chesterman, C. F. Hirshfeld, and A. H. Kehoe as members of the Lamme Medal committee for terms of 3 years each, beginning August 1, 1937.

It was decided to discontinue the Advisory Committee to the New York Museum of Science and Industry, as there appeared to be no further need for this committee, the museum having become well established on a definite basis.

Representatives of the Institute on various bodies were appointed for the year beginning August 1, 1937, and the appointment of certain representatives was deferred until further information could be obtained regarding the activities of the organizations, the necessity for continued representation thereon, or concerning suitable individuals for appointment.

W. I. Slichter was reappointed a representative of the Institute on the Library Board of the United Engineering Trustees, Inc., for the 4-year term beginning in October 1937; and L. W. Chubb was nominated for reappointment by The Engineering Foundation board to the research procedure committee of Foundation, for the term of one year beginning in October 1937. J. B. Whitehead, past-president of the Institute, was appointed to fill the unexpired term, ending in October 1939, of E. B. Meyer, deceased, on the John Fritz Medal Board of Award.

Local honorary secretaries were reappointed for the term of 2 years, beginning August 1, 1937, as follows: Frederick M. Servos, for Brazil; A. P. M. Fleming, for England; Renzo Norsa, for Italy; P. H. Powell, for New Zealand; A. F. Enstrom, for Sweden.

The following amendments to the by-laws were adopted:

Section 32, to include the District vice-chairmen of the membership committee, amended to read as follows:

**Sec. 32. To facilitate co-operation among the Sections there shall be an executive committee in each geographical district, including in its membership the vice-president representing the District on the board of directors, as chairman, a District secretary to be appointed by the vice-president, as secretary, the vice-chairman of the national membership committee, who may be a member of the District executive committee in another capacity also, and the chairmen and secretaries of the Sections within the District; also, in order to encourage co-operation between Sections and Branches, the chairman of the District committee on student activities.**

Section 41 was amended to read as follows, in order to define the boundaries of Sections, which were recently revised in accordance with recommendations of the special committee to revise Section territories:

**Sec. 41. Unless otherwise authorized by the board of directors and approved by the Sections and finance committees, the territory of a Section shall be defined as follows: A Section shall include those counties lying wholly or partly within a circle having its center at the headquarters of the Section and a radius of 50 miles. With the additional approval of the vice-president of the District involved, other unassigned counties, to be known as auxiliary Section territory, may be assigned to a Section. If, for the purpose of establishing a new Section, or for any other reason, it becomes desirable to reassign counties in auxiliary Section territory, this may be done without the approval of the Section to which such auxiliary territory is assigned, provided the change meets with the approval of the Sections committee and the vice-president of the District. All other questions with regard to overlapping of Section territories shall, if possible, be decided by agreement by the Sections concerned, otherwise by the Sections committee. Both ordinary and auxiliary Section territories shall be defined by county line boundaries.**

Section 65 was amended by the substitution of the name "committee on basic sciences" for "committee on electrophysics."

Section 76 was amended to read as follows:

**Sec. 76. The membership committee shall consist of one vice-chairman from each geographical district and a suitable number of other members, all to be appointed by the president; also the chairmen of the membership committees of the Sections of the Institute, *ex-officio*.**

**This committee shall bring the advantages of membership to the attention of desirable candidates for admission to the Institute, through such measures as it may consider advisable to interest prospective members who have the standing and qualifications specified for the various grades of membership. Under the general direction of the chairman, the vice-chairman may enlist the co-operation of the Sections and Branches within his District in such work. The committee shall have such other duties as may be delegated to it by the board of directors.**

The following appointments by the standards committee of Institute representatives on subcommittees of the Sectional Committee for Revision of National Electrical Safety Code were approved: W. R. Bullard—Grounding; C. A. Powel—Part I; T. H. Haines—Part II; E. B. Paxton—Part III; S. B. Graham—Part V.

Upon the recommendation of the standards committee, approval was given to (1) Revised Code for Protection Against Lightning, developed by the sectional committee *C-5* under ASA procedure, and (2) Revised Test Code for Polyphase Induction Machines.

An invitation to nominate an individual for the award of the 1938 Kelvin Medal was referred to a committee consisting of the president of the Institute and the chairmen of the Edison Medal and Lamme Medal committees to make a nomination.

The report of the special committee on Institute activities, on which action was deferred at the June meeting of the board of directors, was considered. The committee reported that, in accordance with instructions, it had prepared a general session at the 1938 summer convention of the Institute, which consisted of an address by Ralph E. Flanders on "The Engineer in a Changing World," followed by questions from the floor, and, after intermission, a discussion by members of the Institute on the topic "How Can the Institute Programs be Made of Greatest Value to the Membership?" This discussion was opened by 6 prepared discussions which had been reviewed by the special committee, and which presented various points of view (published in August issue of ELECTRICAL ENGINEERING, pages

1054–58). As a result of this session, the special committee recommended, in brief, that major emphasis should continue to be given to the technical programs substantially along the present lines; that the programs of national conventions and District meetings of the Institute frequently include sessions at which subjects of general interest to all the membership are discussed, including broad technical subjects presented in such a form as to be of general interest to electrical engineers, and also discussions of social and economic subjects closely related to engineering, which subjects should be presented by authorities in the fields discussed, and, in many cases therefore, would take the form of addresses by men who are not members of the Institute; and that the inclusion or omission of such a general session in the case of each convention or meeting be decided by the committee in charge of the program of that convention or meeting. The board approved the report of the special committee on Institute activities.

Other matters were discussed, reference to which may be found in this or future issues of ELECTRICAL ENGINEERING.

## Additional Awards for 1936 Institute Papers

In addition to the national and District prize awards for papers presented before the Institute during 1936 announced in ELECTRICAL ENGINEERING for June 1937, page 756, and September 1937, page 1208, additional awards for District 8 have now been announced. These awards are:

DISTRICT 8

Prize for Branch paper awarded to James W. McRae for his paper "The Magnetic Vector Potential," presented at the summer convention, Pasadena, Calif., June 22–26, 1936.

Prize for graduate student paper awarded to Edward L. Ginzton for his paper "Balanced Feed Back Amplifiers," presented at meeting of University of California Branch, April 1937.

## New System of Photometric Units

THE International Committee on Weights and Measures at its biennial meeting in Paris, June 23–29, 1937, adopted a new system of photometric units intended to replace both the "international" and the Hefner units. The following report on this action has been made available by E. C. Crittenden (A'19, M'22) assistant director, National Bureau of Standards, Washington, D. C., who has been closely associated with the development. This action of the international committee is expressed in a resolution translated as follows:

1. Beginning January 1, 1940, the unit of luminous intensity shall be such that the brightness of the black-body radiator at the temperature of solidification of platinum will be 60 candles per square centimeter.
This unit will be called the "new candle," ("bougie nouvelle") with appropriate translation into the various languages.

2*a*. The values for photometric magnitudes of sources of light differing in color from the primary standard shall be determined by a procedure consistent with the luminosity factors, formerly called "visibility factors," adopted by the International Committee on Weights and Measures.

2*b*. To assure uniformity among the national laboratories of the different countries in passing from the new primary standard to secondary standards of the incandescent-filament type operating at higher efficiency, the procedure adopted for the present is the use of blue filters which, interposed between the photometer and one of the standards to be compared, will make the colors in the 2 parts of the photometric field the same.

The international bodies concerned had previously agreed, first, that the use of the luminosity or "visibility" factors adopted by the Illuminating Engineering Society and the AIEE was the only method of hetochromatic photometry which could be generally accepted; and, second, that the primary standard of light should be the black body at the platinum point. In order to fix the values of all the units, it remained only to agree upon a numerical value for the brightness of the primary black-body standard.

The freezing point of platinum, 2,046 degrees Kelvin, is only about 50 degrees below the color temperature of the old carbon-filament standards; the black-body standard therefore might have been considered simply as a reproducible means of representing the international candle at that color. However, if this had been done, several very troublesome questions would have been left unsettled.

While nominally only 2 units of candlepower are in use today, actually there are several units differing enough to cause annoyance in the lamp industry. The ratings of tungsten-filament lamps, first of vacuum type and later gas-filled, have been established without any specific international agreement. Consequently there are slight, but systematic, differences between different countries which use "international" candles or lumens, and still greater discrepancies exist between the international and the Hefner units as established for the 3 general types of lamps. For carbon lamps the ratio between the 2 units accepted in 1909 was 1.11; for vacuum tungsten lamps at color temperatures near 2,360 degrees Kelvin it is 1.45; for gas-filled lamps in the neighborhood of 2,600 degrees Kelvin it is 1.17.

Furthermore, if the old basic units were retained both international and Hefner ratings of tungsten lamps would have to be changed to bring them into accordance with recent agreements regarding photometric methods to be used in comparing lights of

## Sodium Lights for Railroad Crossings




General Electric Photo

THE Ohio Public Utilities Commission has approved the use of sodium lights for railroad crossing illumination. In the accompanying illustration is shown a typical installation of 2 sodium luminaires at the point where route 40 crosses the tracks of the Cleveland, Cincinnati, Chicago, and St. Louis Railroad.

## Future AIEE Meetings

**Middle Eastern District Meeting**
Akron, Ohio, Oct. 13–15, 1937

**Winter Convention**
New York, N. Y., January 24–28, 1938

**North Eastern District Meeting**
Pittsfield, Mass., Spring 1938

**Summer Convention**
Washington, D. C., June 20–24, 1938

**Pacific Coast Convention**
Portland, Ore., date to be determined

different colors. Most of the present tungsten standards were derived from the carbon-filament standards representing the international candle of 1909 by measurements with the common Lummer-Brodhun photometer, which has a fairly large field of view. For nearly all groups of observers this gives somewhat larger values for the bluer lights than are obtained with a small photometric field such as was used in determining the standard "visibility factors."

In brief, in order to get the ratings of tungsten-filament lamps on a consistent and systematic basis, some readjustment is necessary in all countries. Such a basis is now urgently needed also for the precise rating of gaseous conductor lamps and other sources of colored light. Consequently, when a new standard was to be adopted as a means of defining the basic unit, the time seemed opportune to make an adjustment which might bring all countries into agreement.

Determinations of the brightness of the black body at the platinum point in terms of the international candle had been made in several countries, and the value on this basis was about 58.9 candles per square centimeter. The National Bureau of Standards proposed that the round number 60 be taken for the brightness, making the unit at this color 1.8 per cent smaller than the old unit.

In preliminary discussions in 1935 and 1936 it was indicated that, if the countries which used the international candle abandoned it for the proposed new unit, Germany was ready also to accept the new unit in place of the Hefner. The plan therefore was put formally before the International Committee on Weights and Measures as a joint proposal of the national laboratories of France, Great Britain, and the United States, which have had the responsibility of maintaining the international candle.

At the same time the plan was submitted to the International Commission on Illumination, which asked the views of all its national committees. In order to determine the opinion of American interests, Preston S. Millar, president of the United States national committee of the ICI, formed a special subcommittee including representatives of all the national organizations specially concerned.

At a meeting held February 5, 1937, this subcommittee unanimously favored the proposal, and consequently the United States national committee gave its approval. During June, meetings were held in Paris by the special committee on units and standards of the ICI and by the advisory committee on photometry established by the International Committee on Weights and Measures. These meetings settled questions of detail and cleared the way for definite action by the international committee.

While the action of the international committee establishes the principle of the new system, the determination of precise values for standards of the various types will require considerable time. Determinations in different laboratories will be necessary, and standard lamps of various types must be exchanged between countries for comparisons so as to make sure that all the national standardizing laboratories are in satisfactory agreement. Standards on the new basis must then be provided for lamp factories and testing laboratories in each country.

Some of this necessary laboratory work is already in progress, but it is hardly likely that all the measurements and all the formalities of final agreement can be completed in less than 2 years. The effective data of January 1, 1940, was set with this fact in mind. It also has the advantage of making the photometric changes coincide with a small adjustment of electrical units which is scheduled for the same date.

## NRC Insulation Committee to Meet in New York

The fall meetng of the committee on electrical insulation of the division of engineering and industrial research of the National Research Council will be held in New York, N. Y., November 4–5, 1937, with the Consolidated Edison Company of New York, Inc., as host. W. F. Davidson (A'14, F'26) director of research and tests, of the Edison company, is chairman of the committee on arrangements.

A program including 16 papers to be presented at 3 sessions has been arranged; fewer papers than usual have been scheduled this year in order to allow more time for discussion. Morning and afternoon sessions will be held November 4, and a morning session November 5; all 3 sessions will be held in the auditorium of the Edison company at 4 Irving Place. Inspection trips to nearby points of interest are being arranged for the afternoon of November 5. A dinner meeting is scheduled for the evening of November 4 at which Doctor A. von Hippel of the Massachusetts Institute of Technology, Cambridge, will speak on the subject "What Can Atom Physics Contribute to Insulation Research?"

**New ASTM Standards.** At its recent annual meeting the American Society for Testing Materials accepted 51 new tentative standards and revisions of 46 existing tentative specifications and methods of test. Among these were the following, covering methods of testing electrical insulating materials:

1. Test for Insulation Resistance of Electrical Insulating Materials (D 257–37 T) (revision of standard). Committee D–9 on electrical insulating materials.

2. Testing Flexible Varnished Tubing Used for Electrical Insulation (D 350–37 T). Committee D–9.

**Coffin Award for New York Company.** The Consolidated Edison Company of New York, Inc., won the annual award for 1936 of the Charles A. Coffin Foundation, established by the General Electric Company. Presentation of the award was made to J. C. Parker (A'04, F'12) vice-president of the company, during the recent annual convention of the Edison Electric Institute. The award comprises the Charles A. Coffin Gold Medal, a certificate, and a check for $1,000 to be deposited in the treasury of the Consolidated Edison Employees Mutual Aid Society, Inc. Determination of the winner of the award was made by a committee of judges consisting of C. W. Kellogg (A'19, M'23) president of EEI; K. T. Compton (F'31) president of Massachusetts Institute of Technology; and L. H. Egan (A'08, M'15) president of the Union Electric Light and Power Company of St. Louis, Mo. The committee was particularly impressed with the all-around progress made by the utility during recent years, culminating in its splendid accomplishments for the year 1936. Progress was reflected in practically all fields of activity, including improvement of relations with consumers, refunding of bonds, reorganization of units, and the development of greatly improved generating and distribution facilities.

## 1939 Fairs to Have Electrified Farms

Electrified farms, complete in all details according to recent announcements, are to be among the feature displays of the Golden Gate International Exposition and the New York World's Fair in 1939. With an estimated 1,118,000 farms in the United States all served with electric power, these exhibits are expected to have wide significance in their demonstration of the possibilities of efficient and effective utilization of electric energy in house, barn, dairy, shop, and field.

As announced, the demonstration farm at the New York Fair will comprise some 32,400 square feet. To assure that the farm will be in full and effective operation when the Fair opens, it is expected that the building will be completed; that dairy cattle, poultry, and bees will be in their places; that crops will be growing and fruit trees will have been established before the Fair opens.

The exhibit at the Golden Gate Exposition will be in the Palace of Electricity, where a model farm, completely electrified for operations from dishwashing to forced crop production, will include demonstrations of protection against insect and walnut and prune dehydrators.

## ICI Conference Held in Paris

On the occasion of the Paris Exposition and the attendant International Congress on Lighting Applications, a conference of delegates of International Commission on Illumination national committees was held June 22 and 23, 1937, to recommend plans for the forthcoming plenary session. Twenty-five delegates from 11 countries were in attendance, the United States being represented by C. H. Sharp (A'02, F'12, member for life), E. C. Crittenden, (A'19, M'22), and A. L. Powell (A'13, F'26).

The conference recommended that the program of the plenary session be expanded to include papers on latest lighting developments. To facilitate this and allow a longer interval after the Paris Congress, it was recommended that the sessions be postponed until 1939. The Netherlands committee, host of these sessions, announced

that they would probably be held at the attractive Scheveningen seashore resort in the outskirts of The Hague.

In the event of postponement it was suggested that interim meetings be held on aviation and automobile lighting. In this connection it was reported that the International Standards Association had laid out an extensive program of automobile standardization, including that of lighting equipment.

It was expected that the *Proceedings* of the 1935 sessions, which have been delayed in publication, will be available early this fall. A pamphlet, in French, has been made available which gives the recommendations officially adopted by the International Commission on Illumination in the 1935 sessions in Germany. A list of the technical committees with the work assigned to each also is included. Requests for copies should be addressed to G. H. Stickney, secretary-treasurer of the United States National Committee of ICI, General Electric Company, Nela Park, Cleveland, Ohio.

# Current Items From American Engineering Council

## Government Reorganization

Government reorganization, including all of the ideas advanced for a public works department, was left in the muchly tangled mass of unfinished business by the first session of the 75th Congress, according to a recent "news letter" from AEC. It had the President's blessing, but the advantages to be gained by the elimination of duplication of work and the improvements proposed for administrative procedure were handicapped by moves to effect radical changes in fiscal and personnel administration and discouraged by strong opposition from within the government agencies themselves.

Council's staff advised with the several committees on government reorganization and maintained close contact with those members of both houses of Congress who had to do with reorganization legislation. In spite of the very friendly relationship, however, the public works recommendation of the American Engineering Council and the President's Committee did not become an issue. No specific reason has been given for its omission from the general bills which were introduced, but it is believed to have been considered too provocative.

Assuming that engineers generally agree that most public works are well designed, honestly executed and administered without conscious or deliberate waste or extravagance, Council made the following statement to the Select Committee on Government Reorganization of the United States Senate urging the establishment of a department of public works for the sake of economy in the conduct of government construction business. A public works department was also recommended as an ideal medium for the co-ordination of our engineering and construction resources during periods of economic depression and as a more effective means of mobilization for national defense.

"Engineers believe that the President should have effective managerial authority over the executive branch of the Federal Government commensurate with his responsibility under the Constitution of the United States, but they are not as concerned with strengthening the executive as they are with the larger aim of strengthening the administrative management system of the United States as a whole. They feel that the need for reorganization of the many agencies rests not only on the idea of savings, as considerable as they may be, but upon a very real need for a more economical and effective organization which could be more easily understood and controlled by the people. It is realized the reorganization of the many units of the executive branch of the Federal Government is an enormous undertaking, but engineers urge reorganization under direction of the Chief Executive on the basis of standards set up by Congress to provide up-to-date management for whatever activities may be decided upon by the people.

"Engineers have for many years favored the use of the merit system in personnel administration, and they now endorse the idea of expanding civil service to cover all nonpolicy-determining positions. They recognize the civil service system as a valuable part of government management under a nonpartisan Civil Service Commission and urge salary adjustments throughout the service so that the Government may attract and hold in a career service men and women of the highest character and ability. Such a career is possible only when government service is concentrated and most of its positions are filled through civil service. In that way, opportunities for advancement open up to employees in the whole career system instead of the limited confines of a small service. Under such circumstances, engineers feel that direct appointments by the President should be reduced to a very small number of only the highest positions, and all other civilian positions should be filled by the heads of departments, without fixed term, through civil service with adequate tests to determine fitness.

"Engineers, who have made enormous contributions to the social advancement and economic welfare of their country and to civilization, feel that they are qualified by training and experience to advise their Government regarding engineering and public works activities. On that assumption, they recommend the creation of a public works department to which the President should be authorized to transfer such major engineering and construction work for government agencies as may be practicable. Engineers believe that a public works department should be authorized to co-ordinate the design, construction, operation and maintenance of all large-scale public works which are not incidental to the normal work of other departments, to act as an agent of other departments on engineering public works to administer federal grants to national, state, and local agencies for construction purposes, and to gather information with regard to public works needs and standards throughout the nation. They believe that a relatively small staff could and should direct such work in the hands of engineers in private business throughout the United States, without confusion and waste or the loss of valuable time.

"Such reorganization should promote efficient government in all of its branches, because it is now extremely difficult even for persons charged with executive duties and legislative responsibilities to properly comprehend many of the problems that arise among scores of scattered agencies. As related functions falling in the same field or having the same general purpose could be brought into organic connection and their operations made capable of consideration, as a whole, it should be easier for the Chief Executive to formulate programs for submission to Congress; and the Congress should be able to give more intelligent consideration to legislation and reach less hurried decisions regarding appropriations. The service agencies could perform their work with more certainty, and the public could more readily comprehend the work of the government, more directly exercise that general control which should obtain under a popular government, and more easily transact business with the government's agencies."

Excerpts were included from resolutions by the American Society of Civil Engineers and the American Engineering Council's assembly to the effect that both organizations would support "the enactment of suitable legislation designed to create a federal department of public works, as proposed by the President of the United States, with definite provision for excluding the Army engineers and their river and harbor work from this department." It was also stated that existing working organizations need not be disturbed by the reorganization process, and that all questions involving the redistribution of duties should be subject to decisions by proper authorities in the light of subsequent experience and investigation.

## Scientific Research Legislation

Engineers may find much to interest them in the provisions of bill H. R. 7939 instigated by Congressman Randolph of West Virginia, which is "to provide for the promotion of general welfare in relation to the economic efforts flowing from scientific and technological developments" in the United States. It is based on the premise that we must continue to create new "capital outlets," that the chief source of such outlets is the development of new industries, and that scientific research is the foundation of the greater portion of our modern industries.

The bill properly differentiates between social science and natural science and advances a practical philosophy designed to unite the sciences in the application of scientific discoveries and inventions to human needs. One of the principal objectives is the stimulation of pure science as a foundation for applied science which is recognized as the greatest factor in the development of the resources of the nation.

Engineers who have studied the effects of the impacts of technological developments upon civilization may not find much that is new to them in this legislation except that the usefulness of science, pure and applied, to our social and economic well being, as a nation, is appreciated by members of Congress. Even though they may not agree with Congressman Randolph's ideas, engineers have an opportunity to applaud his efforts to effect a national recognition of the true value of technology and to contribute criticisms as well as constructive suggestions to the advancement of that cause.

# Letters to the Editor

CONTRIBUTIONS to these columns are invited from Institute members and subscribers. They should be concise and may deal with technical papers, articles published in previous issues, or other subjects of some general interest and professional importance. ELECTRICAL ENGINEERING will endeavor to publish as many letters as possible, but of necessity reserves the right to publish them in whole or in part, or reject them entirely.

ALL letters submitted for consideration should be the original typewritten copy, double spaced. Any illustrations submitted should be in duplicate, one copy, to be an inked drawing but without lettering, and other to be lettered. Captions should be furnished for all illustrations.

STATEMENTS in these letters are expressly understood to be made by the writers; publication here in no wise constitutes endorsement or recognition by the American Institute of Electrical Engineers.

## Suggestions for AIEE Programs

*To the Editor:*

At the recent meeting of the Section delegates where Institute publication policies were discussed, the sentiment was almost unanimously expressed that ELECTRICAL ENGINEERING should include a considerable percentage of articles dealing with economic and social aspects of engineering problems, and with readable articles of a general nature. The publication committee will presumably make plans for publishing such general articles, and I infer that the membership at large would similarly like the technical program committee to arrange sessions dealing with general problems.

In thus broadening the Institute field, it is important not to duplicate the programs of other organizations, nor to depart from the factual basis of all good engineering work. It also seems to me desirable to make this departure from our accustomed ways gradually, and especially not to allow controversial subjects of purely political or social nature to displace engineering discussions.

With this in mind, I should like to suggest 3 specific types of articles or discussions for the Institute to add to its programs, or to use more frequently.

First, I think it very desirable to include articles dealing with economics or social problems, so long as these are written from an engineering viewpoint, or on the basis of facts, in such a way that the ideas presented will fit into the framework of engineering knowledge. To me, it appears that the laws of economics are quite analogous to the laws of physics. We have, for example, Hamilton's "principle of least action" which says that in nature motions always occur in such a way as to make the total action of the system a minimum. In economics it appears that society always endeavors to carry out its processes in such a way as to expend the least total effort. We seek to measure effort of every sort, past, present, and future in terms of a common unit, the dollar.

Thus, it should be possible to explain the laws of prices, the development of new industrial processes, and the displacement of old ones, on the basis of a principle of economy of effort as inexorable as the law of gravitation. Looked at in this way, we may think of the laws of economics as engineering principles we are already quite familiar with. And, the task of the engineer may be outlined as that of obtaining a more correct measure of the effort involved in each element of a process, in terms of immediate dollars, and the expression of the laws of variation of effort with changes in the process. As long as only a few individuals or materials are concerned, the problem is simple. However, bringing in the large numbers of individuals, the diverse sources of material, and the long periods of time that must all be considered under modern conditions, makes the problem much more difficult. What the engineer must do is to visualize the laws of economy of effort in simple terms and then widen his vision to include the increasingly large units of society that are involved in modern industry.

I believe there is need for many articles and discussions of economic and social problems prepared along the lines of such an engineering philosophy, and these should form a very desirable addition to the Institute's program. On the other hand, I strongly oppose having the Institute become a forum for the discussion of economic and social subjects in the language and with the methods already used by experts in these fields. We should not attempt to tell the economists or the experts in any other field how to do their job nor criticize them for the way in which they are doing it. We should simply tell men who are trained in engineering how they can apply their engineering knowledge to deal with the economic and social problems they meet in their engineering work.

Second, I think it desirable for the Institute to have articles and discussions of a general expository or descriptive nature, dealing with large-scale engineering projects or application engineering. Engineers need to know what is going on in other fields, to understand its purpose and its importance, and to know where they can find details if they need them. In every field of application engineering, methods and points of view change so rapidly, that nearly every purely technical article is out of date within 5 years. There is, therefore, a large field for periodic articles reviewing the fundamental principles of each branch of engineering and giving references to up-to-date sources of detailed information. Such articles and discussions might well take up as much as one-third of our Institute programs, in my opinion.

Finally, I should like to suggest that the Institute also accept articles and hold discussions on methods by which engineers can play a more important rôle in the world at large. I believe that the Institute can help engineers both by education and by inspiration to gain greater recognition, but such recognition must be the result of their individual actions rather than any prestige conferred upon them by the Institute. Programs should be designed to encourage individual actions by engineers in their own communities, and on no account planned to make the Institute take part as a whole in controversial questions of politics or government. The basis of all engineering progress is fact. Facts must be understood and presented by individuals. They cannot be properly voted upon nor advocated by mass action.

Specifically, I think that in this social field the best way to proceed is for papers to be presented telling just how particular engineers have acted to marshal facts and bring them to the attention of the proper authorities, and have so educated the public as to promote right decisions on affairs of public importance. For example, the method by which the engineers of Cincinnati have organized to interest the public in addresses on engineering subjects should be described before the Institute, thus inspiring engineers elsewhere similarly to bring their facts out in the open. Also, the procedure should be discussed by which any individual engineer may by his interest in the problems of the community in which he lives and the judicial point of view given by his engineering training, bring together community organizations of widely different views and weld them into a force for united public action. Articles in this field which described things of public importance actually done by engineers, or with an engineering—that is, a fact-finding—basis should be of great value and inspiration to the Institute membership.

Summarizing, I believe the Institute ought to enlarge its program to include, first, articles and discussions dealing with economics and social problems described in engineering terms; second, expository or descriptive articles of a general nature showing the state of the engineering art in different fields; and, third, articles describing actual achievements by engineers in the social and governmental field.

Very truly yours,

P. L. ALGER (A'17, F'30)

Engineering General Department, General Electric Company, Schenectady, N. Y.

## Branch Activities Are First-Page News

*To the Editor:*

The first page of the July 1937 issue ELECTRICAL ENGINEERING contains a parting message from retiring President MacCutcheon. It is entitled "Branch Activity." When he became president there was no Institute work of which he knew less, and when he retired, there was "no phase in which I am more interested or which I feel is better conducted." He gives 4 columns of observations, anecdotes, and concrete suggestions.

The report of the board of directors in the same issue records the number of branches as 119 with a total of attendance of 46,000.

The number of Enrolled Students is 4,500 and the number of applications of students for membership is 2,250.

ELECTRICAL ENGINEERING is publishing articles which give a fine presentation of the engineer in his nontechnical relations. In August, Dean Bush presents his "The Engineer and His Relation to Government." Doctor Flanders, eminent engineering economist, and past-president of the American Society of Mechanical Engineers, deals with "The Engineer in a Changing World." Past-President MacCutcheon visions the engineer of tomorrow. Mr. Blaker, an engineering student, speaks his mind on "The Engineer's Responsibility to Society." Mr. Wilkinson describes an experiment in the recognition of engineers in which the careers and qualities of notable recent graduates are recorded. And, in the September issue, President Doherty of Carnegie Institute of Technology, noted industrial engineer and educator, deals with "Engineering Education and Democracy," and indicates the qualities which the student should develop who aims to be a creative engineer.

All this affords to the engineering student a wealth of information, suggestion, and guidance.

This material might well afford the subject matter for presentation and discussion at student Branch meetings. It presents various phases of the larger engineering career which the future opens to the engineering student of today.

Very truly yours,

C. F. SCOTT (A'92, F'25, HM'29, past-president, member for life)

Professor of Electrical Engineering Emeritus, Yale University, New Haven, Conn.

## Graphical Solution of Similar Impedances in Multiple

*To the Editor:*

Figure 2 illustrates a simple method of determining the equivalent impedance of 2 similar impedances in multiple, such as the pair illustrated in figure 1. It must be remembered that the ratio of reactance to resistance in each branch is the same. The construction is as follows: Choose any desired reference or base line as $AB$. Erect perpendiculars to this base line at any desired distance apart and of lengths, to any convenient common scale, equal to the impedances, as $Z_1 = 8$ and $Z_2 = 5$. With diagonals join the opposite ends of the perpendiculars as shown by the dotted lines. Then, the equivalent impedance of the multiple combination is, to the common scale, the length of the perpendicular from the intersection of the diagonals to the base line, as shown by $Z_{12}$.

Figure 1 (left)

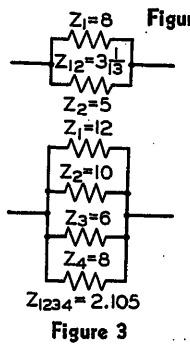



Figure 3

Figure 2

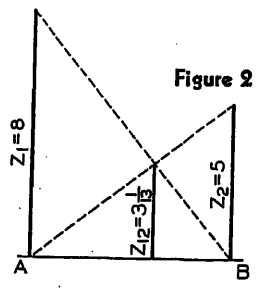
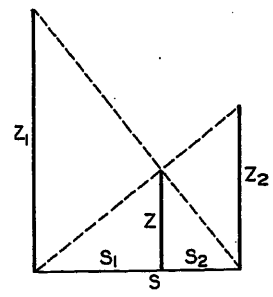



Figure 6




For more than 2 similar impedances in multiple, as in figure 3, they may be grouped in pairs and the resultant of the pairs combined as in figure 4; or take the resultant of the first 2, work it with the third, then the resultant of this combination is worked with the fourth; etc. This is illustrated in figure 5. A comparison of figures 4 and 5 will show that the resultant $Z_{1234}$ is the same in either case.

The equivalent resistance of a group of multiple resistances or the equivalent reactance of a group of multiple reactances may be determined graphically in this way, they being special cases of similar impedances in multiple.

*Proof:* From similar triangles in figure 6:

$S_1/Z = S/Z_2$, therefore $S_1 = ZS/Z_2$ and
$S_2Z = S/Z_1$, therefore $S_2 = ZS/Z_1$

Therefore $S_1 + S_2 = ZS(1/Z_1 + 1/Z_2)$; but $S_1 + S_2 = S$;

therefore $S = ZS(1/Z_1 + 1/Z_2)$, or

$1 = Z(1/Z_1 + 1/Z_2)$ or $1/Z = 1/Z_1 + 1/Z_2$ or

$$Z = \frac{Z_1 Z_2}{Z_1 + Z_2}$$

It will be noted that the expression is the well-known one for similar impedances in multiple. Also it is evident that the expressions are independent of the distance, $S$, between perpendiculars.

Very truly yours,

E. C. GOODALE (A'27)

Inspector, Puget Sound Power and Light Company, Olympia, Wash.

Figure 4

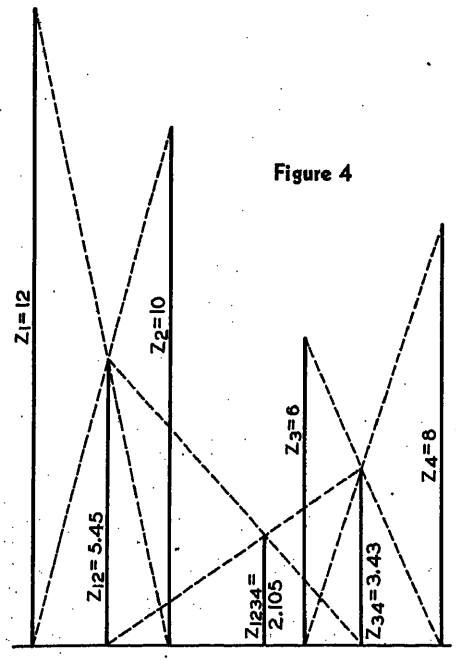
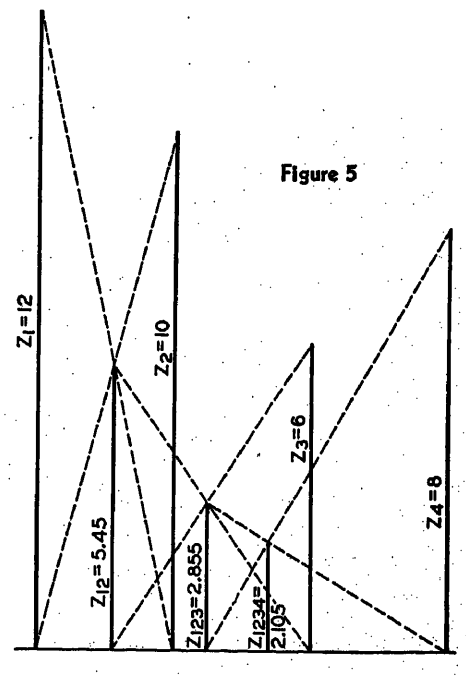



Figure 5




## On the Characteristics of Human Nature

*To the Editor:*

Should it be required to state a term which, more uniquely than any other, supposedly characterizes western civilization the adjective "scientific" will not long fail to appear. It is commonly held that this term is peculiarly applicable in that other, or preceding, social systems lack the same. Some inspection of the matter at a critical level discovers, however, a slight confusion.

Presumably the uninitiated might gather that society is employing scientific method in day-by-day effort toward improvement. Search among popular or discriminating opinion discloses little such deliberated action as admitted, as contemplated, or as reasonably possible.

The exceptional suitability of scientific method and engineering persons to cope with the present untidy state of human affairs is widely admitted. After considering the method of action of engineers, it becomes plain there is no class of mortals less likely to be permitted undisguised use of its characteristic technique.

This is all as it should be in a world where men speak of "better things" with wistful optimism and concurrently are capable mainly of invidious self-regard and of acting largely through evidenced demonstrations of force and chicane.

But, regardless of such being the reality of the matter, there still remains an urge on technically biased persons to act for an improved social order. Admit the engineers to be as willing as the need is great; as yet there is little detailed information in the literature to aid the rank and file in its action on a creaking human polity.

No small part of the engineer's approach and method has been his insistence on the dimensions and behaviors of the material he must handle. If, therefore, he must now act on men in a society rather than supervise them in industrial pursuits, he might reasonably seek a chart of performance of this substance with which he is to deal. A quantity so varied and immense as the human animal can never be precisely covered. Any attempt must necessarily be fragmentary, even tedious. Nevertheless, the importance of having some basis for action, superficial and "practical" though it be in contrast to rigorous and theoretical, warrants almost any attempt at record.

With these limitations in mind, and with some misgivings as to the form of the data, the following notes are presented.

## Some Characteristics of Human Nature

*We hug deformities if they bear our name*—Glanville

*A. Human nature possesses but little constructive imagination.*

REASONS

Its philosophy is one of belief in pragmatic effectiveness, in results, in the value of experience, in cynical practicality. E.g., its expression "Nothing succeeds like success."

CONSEQUENCES

1. Learns slowly, if at all, and largely through action on its pocketbook. Therefore repetitions and detaily; easily flustered by any unexpected response of man or machine.

2. Unable to "see" much of anything through eyes or experiences of others.

3. Able to concede experiences, knowledges or skills to others only if gained in its "presence."

4. Unable to see any personal repercussions of its instinctive social and economic indifferentism.

5. Lacks that capacity for intellectual indignation which was called to the attention of the ancient Greeks, and which is essential to the preservation of a democracy. (This in contrast to an urgent interest in sensationalism.)

6. Capable of academic consideration of but few topics. Therefore (*a*) must be able to "take sides" on matters to become interested—must become personally identified. And this possible interest is

I. In direct ratio to personal or financial concern with the matter.

II. Without much regard to the social or economic principles involved in an "isolated" event.

III. Exploitable through sales efforts appealing to the more paltry emotions.

7. Distrustful, both of itself and of others. But it is extremely vocal in its own defense.

8. Amenable to power rather than to intellectual discipline. Therefore (*a*) responsive to the compulsions of organization rather than to the demands for responsibility in co-operative independence; (*b*) impressed by bigness—physical or financial.

9. Subjective rather than objective. Therefore (*a*) pays little attention to what others say. (*b*) gives much consideration to the words put into other's mouths. (*c*) intrigued by labels, e.g., "smartness," "exclusive import," "Republican," "New Deal."

10. Seeks distinction, while demanding to be just like everyone else.

11. Cherishes a naive belief that mass emotional satisfaction is possible in a social order based on competitive gain.

*B. Human nature is a gregarious one.*

REASONS

1. Lacks self-reliance.

2. Necessary that it act on people—competitively—if it is to sense "accomplishment."

CONSEQUENCES

1. Worst form of insult to it or by it is a considered removal of physical presence.

2. Naturally urban (as regards population density).

3. Prone to bother people by invasions of space, time, or thoughts.

4. The "pleasing effrontery" of sales techniques is acceptable to it.

*C. Human nature is emotional rather than rational.*

REASONS

1. It has "gotten by" in the mass, fairly acceptably up to now.

2. Mental inertia, coupled to unfamiliarity with and distrust of reasoning processes.

CONSEQUENCES

1. It avoids thinking processes by every means at its disposal. Therefore, it is prone to rely on its instincts when under stress.

2. It is arrogant.

(*a*). Particularly in the sense that it must pursue personal vindication through any amount of conversational bramble patches.

(*b*). Seemingly it cannot consider itself as other than unique, thus can accept nothing less than—

I. Instant, unquestioning obedience.

II. Complete, enthusiastic agreement with its prejudices, under the name, that is, of "judgments."

3. It is unctuous. Therefore:

(*a*). Prone to rely on symbolic action.

(*b*). Smug.

(*c*). Apt to make virtues of necessities, that is, to rationalize its compelled behaviors.

4. It is basically disagreeable.

*Reasons.* 1. Mass emotional satisfaction based on competitive gain is a self-contradictory concept.

*Results.* (*a*) Impatient, irritable, spiteful, malicious; (*b*) instinctively uses the *argumentum ad hominem;* (*c*) attempts extreme emphasis by becoming personally abusive; (*d*) stubborn, contrary, selfish, acrimonious, rancorous; (*e*) excitable and "nervous" particularly in presence of recognized personalized challenges to its "rights."

5. Hypersensitive to any possibility of critical implication in words or actions of others. Therefore, (*a*) possessed of a bustling, impressive activity; (*b*) rushes spontaneously to its own verbal defense; that is, it is "touchy" so is prone to argue by begging the question; (*c*) easily becomes indignant over its assignments of professed rectitude to others; (*d*) bristles easily.

6. Unable to carry on true argumentation.

7. Though "sporty" lacks many elements of true sportsmanship; hence (*a*) is unsuited to interdependent social and economic existence.

8. Its standards are largely pecuniary as distinguished from economic, intellectual, scientific, etc.

9. Its philosophical bias can be put as: *Ejus cogito igitur id est,* as opposed to Descartes' statement *Cogito ergo sum.*

REFERENCES

NOTE. The list of works given below serves somewhat the purpose of a bibliography. No claim whatsoever can be made as to completeness in the assembly. The literature on this subject grows each day. What appears here will but offer the interested reader a slightly enlarged field of inquiry.

Should he wish practical reference for day-by-day use in small compass, let him possess himself of an old-fashioned rhetoric book., There he will come upon those methods making most appeal to the common run of mankind in argumentation—vicious circle and *post hoc* reasoning, begging the question, the *argumentum ad hominem,* etc. Superficial and fallacious though they be, their general applicability will be apparent. Then, let him add a copy of Rostand's "Cyrano de Bergerac" to recognize the relish for *quel geste* and its fruits.

The other works, as available, will assume their places in the perspective.

BOOKS


THE MIND AND SOCIETY, Pareto.

DYNAMIC SOCIOLOGY, Lester Ward.

ON THE BIOLOGICAL BASIS OF HUMAN NATURE, Herbert Spencer Jennings.

AN INTRODUCTION TO THE PHILOSOPHY OF EDUCATION, Demiaskevich.

HISTORY OF THE GREAT AMERICAN FORTUNES, Meyers.

HALSEY'S HANDBOOK (particularly the section on the metric system in editions of about 1915)

DEBT AND PRODUCTION; HORSES AND APPLES — Bassett Jones.

THE THEORY OF THE LEISURE CLASS; THE PLACE OF SCIENCE IN MODERN CIVILIZATION; THE ENGINEERS AND THE PRICE SYSTEM — Veblen.

THE EPIC OF AMERICA, Adams.

THE RISE OF THE NEW WEST; SIGNIFICANCE OF THE FRONTIER IN AMERICAN HISTORY — Frederick Jackson Turner.

THE CONDITION OF THE WORKING CLASS IN BRITAIN, Hiett. (See also Engles' treatise of the same title dated 1844.)

PSYCHOPATHIA SEXUALIS, Krafft-Ebbing.

LIBERTY, Everitt Dean Martin.

MORAL MAN AND IMMORAL SOCIETY, Niebuhr.

WHERE IS SCIENCE GOING? Max Planck.

THE MODERN CORPORATION AND PRIVATE PROPERTY, Berle and Means.

CHRISTIAN FACT AND MODERN DOUBT, Buttrick.

MONOGRAPHS OF THE PRESIDENT'S (Hoover) RESEARCH COMMITTEE ON SOCIAL TRENDS IN THE U. S.

MIDDLETOWN; MIDDLETOWN IN TRANSITION — R. S. and H. M. Lynd

THE SYMBOLS OF GOVERNMENT, Thurman Arnold.

GOVERNMENT OF THE PEOPLE, Brogan.

THE TRAGIC ERA, Bowers.

GRAFT IN BUSINESS, Flynn.

THE INSOLENCE OF OFFICE, W. B. and J. B. Northrup.

THE POLITICIAN, Wallis.

WM. RANDOLPH HEARST, AN AMERICAN PHENOMENON, Winkler.

DYNAMITE, Louis Adamic.

DEMOCRATIC DESPOTISM, Desvernine.

FIFTY-FIVE MEN, Rodell.

DESERTS ON THE MARCH, Sears.

TOOLS OF TOMORROW, Leonard.

STICKS AND STONES, Louis Mumford.

THE ENGINEER SELLS HIS SERVICES, Hirst.

HOW TO WIN FRIENDS AND INFLUENCE PEOPLE, Dale Carnegie.

(There are some very pertinent remarks on these types of "success" books in the "Readers Guide" of *New York Herald Tribune* "book review section" of April 18, 1937.)

FICTIONALIZED MATERIAL

TONO BUNGAY, Wells.

OIL FOR THE LAMPS OF CHINA, Hobart.

LIFE WITH FATHER, Day (and enthusiastic reviews of the same.)

I CAN GET IT FOR YOU WHOLESALE, Weldman.

THE FORTY DAYS OF MUSA DAGH, Werfel.

THE CHERRY ORCHARD; THE THREE SISTERS, plays by Anton Tcheckhov.

PERIODICAL LITERATURE

IS MAN AN ABSURDITY, Bradley. *Harpers*, October 1936.

TRUSTING IN BRAINS, Canby. *Saturday Review of Literature*, June 13, 1936.

SCIENCE AND THE LAYMAN, Sullivan. *Atlantic Monthly*, September 1934.

DESIGN FOR A BOOK, Lippmann. *Atlantic Monthly*, September 1936 (and subsequent essays by the same author in this magazine).

THE SUCCESS FETISH IN EDUCATION, Steiner. *Phi Delta Kappan*, December 1936.

THE STATUS QUO, Tindsley. *Modern Language Journal*, February 1937.

REPORT OF THE AMERICAN HISTORICAL SOCIETY ON SOCIAL STUDIES IN EDUCATION (and, some pertinent remarks on the subject by L. E. Akeley, *Journal of Engineering Education*, May 1935).

Speech of Harold Urey at dedication of Mellon Institute, May 6, 1937. ("this is age of dissipation of natural materials of earth's crust," etc.)

Eighth Steinmetz Lecture, Mees. ELECTRICAL ENGINEERING, March 1934.

Very truly yours,

ANDREW DOUGLAS (A'18, M'29)

Physics and General Science Teacher, Murphy High School, Mobile, Ala.

## AIEE Publications

*To the Editor:*

I have read with much interest Michel G. Malti's letter in the September issue of ELECTRICAL ENGINEERING, as it expresses not only a thought I have had for some years, but also a thought I have heard expressed by many other engineers. I would go further than Mr. Malti and estimate that the number of engineers in class *b* would far exceed those in both classes *a* and *c*.

I confess quite freely that the biggest proportion of the articles appearing in ELECTRICAL ENGINEERING are so technical in nature that I am unable to follow them and, in fact, would have no interest in following them except in a few cases where, for some reason or other, I have a personal interest in the subject under discussion. I realize that due to the amount of specialization in the engineering field it would not be possible to have many highly technical papers applicable to the various fields of specialization, but I nevertheless feel that in a magazine which is for the whole membership the articles should, if possible, be of interest to a majority of members.

It is realized that as editor of a magazine for so diverse a group of people you have a most difficult job but, nevertheless, it may be of interest and perhaps of some help to you to learn what a number of your readers think, and I know from personal contacts that I am speaking for a number rather than for myself alone when I endorse Mr. Malti's program.

Very truly yours,

M. M. BRANDON (A'34, M'36)

Associate Electrical Engineer, Underwriters' Laboratories, Inc., New York, N. Y.

## Heat Transfer Efficiency of Range Units

*To the Editor:*

The interesting article by W. James Walsh published in the August issue of ELECTRICAL ENGINEERING has just come to my attention. It is certainly an excellent article.

In the interest of bringing out the true values of the diverse designs of electrical range units, I would like to make the following comments and suggestions which may possibly help to guide future and more thorough studies of this subject with the idea of setting up modes of test and examination to bring out comparatively all the qualifications of every type of unit.

My first comment, of course, is that the tests on which this paper was based are tests only on the stated units in their brand new condition and are, of course, laboratory tests rather than cooking tests extending over a period of time such as will demonstrate what I term the quality of "stability of efficiency" and "cooking and heating efficacy over an extended time period."

We all know, of course, that the true value of a heating unit or an electrical range is not fully demonstrated by what might be termed an instantaneous test when the equipment is brand new. Such equipment does not stay brand new.

It is subject to all kinds of use and abuse in practical household work and the buyer is naturally interested in the performance of the devices throughout the period of normal life expectancies.

Would it not be an excellent thing to have these tests repeated after each of the units has been in normal practical and identical cooking use approximating as nearly as possible household use in a family of average size?

Of course, there is always some little difference in ohmic resistance of units when new and the cooking tests on the new units ought to be made at identical rated wattage regardless of the voltage required on the new units.

Better still would be to have selected new units of each make which would have identical ohmic resistance or, in other words, which would possess identical normal rated wattage when new and then let the units be operated as above stated and tested subsequently at periods of 3, 6, 9, and 12 months practical use at the voltage which originally gave the normal rated wattage when new. This test should include boiling speed tests and other practical cooking tests at the identical original voltage.

Then after having made such tests, the efficiency tests should be repeated at the same voltage.

Then a third set of tests should be made under which condition the voltage applied to each unit might be increased so as to reestablish the original rated wattages on each unit and the efficiency test repeated.

In this way it would take account of the "stability of efficiency" and of "operating efficacy" after various periods of elapsed time during which the units had all been in identical and practical cooking use.

This would really show up what the market wants to know, which is not merely what a brand new article will do on a laboratory test in the way of a technical expression of electrothermal efficiency, but it would demonstrate the stability of the various qualities of the various units and would also demonstrate efficacy of which the efficiency is only one component.

I realize that the making of such tests under conditions that would be fairly identical as between units and also fairly comparative to practical use would involve some painstaking care and experience, but it would certainly be more nearly the proof of the pudding short of actual market experience on the part of the public.

I hope that these suggestions may be of some value in assisting efforts along this line.

Very truly yours,

E. L. WIEGAND

President, Edwin L. Wiegand Company, Pittsburgh, Pa.

*To the Editor:*

Mr. Walsh's paper in the August issue of ELECTRICAL ENGINEERING should go a long way in awakening the range designers to the fact that the modern electric range is an outgrowth of the old-time wood and coal range rather than the result of good engineering design. His efficiencies of heat transfer are suprisingly high, probably higher than one would find in the average kitchen. He used square-cornered utensils, whereas most range users use all types of round-cornered and odd-diametered utensils. His efficiencies would have been considerably lower had he used a random assortment of utensils such as one finds in the average kitchen.

In the not-far-distant future a complete range will include the utensils which are to be used with it. These utensils will be of such diameter as to cover the unit completely, and will have black bottoms and square corners (similar to those shown by Mr. Walsh), although square-cornered utensils are difficult to clean. A minimum of surface units will be built into the range however; most of them will be the well-type of unit, such as is now included in modern ranges as an "economy" unit. It is also likely that surface utensils and their covers will be insulated against heat radiation from their sides and tops. There is the possibility that some day immersion units will be adapted to boiling and stewing operations, thus raising the efficiency of heat transfer to the highest possible value.

Mr. Walsh is to be highly commended for bringing to the attention of electrical engineers quantitative data on a problem which has too long been subject to much speculation without factual basis.

Very truly yours,

WALTER J. SEELEY (A'19, M'28)

Professor and Head of Department of Electrical Engineering, Duke University, Durham, N. C.

# Personal Items

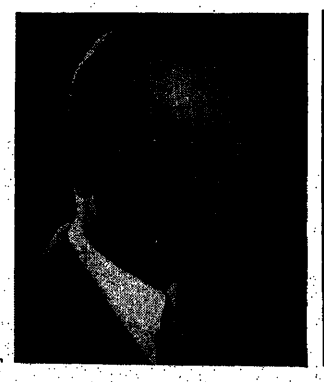
C. R. JONES (A'16, M'30, director) eastern transportation manager, Westinghouse Electric & Manufacturing Company, New York, N. Y., has been elected chairman of the Institute's committee on finance for the year 1937–38. He was born at Norristown, Pa., May 11, 1886. In 1907, he was graduated from the University of Pennsylvania with the degree of bachelor of science in electrical engineering. Since 1907 he has been continuously with the Westinghouse Electric & Manufacturing Company. For the first 2 years, until 1909, he was on the engineering apprentice course of the company at East Pittsburgh, specializing in railway work. For the next 2 years, until 1911, he was in the engineering and railway department of the company, also at East Pittsburgh, being transferred in the latter year to the New York office where he was assistant to the manager of the railway division until 1916. From 1916 to 1925 he was sales engineer in the New York office of the Westinghouse company, representing the company on large contracts involving both engineering and commercial phases. This included work in connection with the electrification of steam railroads and power supply and car equipment for the local rapid transit company. From 1925 to 1930, he was section manager of the transportation division of the New York office, continuing the same work, but in a supervisory capacity. In the latter year he became assistant northeastern transportation manager, and in 1931 transportation manager of what is now the eastern district. Mr. Jones is at present a director of the Institute and has served as a member of the national membership committee, 1928–31, and has engaged for a number of years in the activities of the New York City District (number 3). He has been active for several years in connection with the Institute's winter conventions. He is a member of the New York Electrical Society, New York Engineers' Club, and other organizations.

L. W. W. MORROW (A'13, F'25, past director) general manager of the fiber products division of the Corning (N. Y.) Glass Works, has been appointed chairman of the Institute's committee on constitution and by-laws for the year 1937–38. Mr. Morrow is a native (1888) of Hammond, W. Va., and was graduated from Marshall College in 1907 and Cornell University in 1911. During the scholastic year following his graduation in 1911 he served as an instructor at Cornell University, and in 1913 was appointed assistant professor of electrical engineering at the University of Oklahoma. During the year 1917–18 he served as professor of electrical engineering and director of the school of electrical engineering, before becoming assistant director of the U.S. Signal Corps school at Yale University. He served concurrently as an assistant professor of electrical engineering on the faculty of Yale University, and, following the World War, was retained in that position. In 1922 Mr. Morrow accepted a position as associate editor of *Electrical World;* in 1929 he became editor of that publication, but resigned in 1936 to become manager of the fiber products division of the Corning Glass Works. He has been active in the committee work and other affairs of the Institute, is at present a member of the technical program committee and the committees on co-ordination of Institute activities and publication. He is vice-president of the Thomas Alva Edison Foundation and the Institute's representative on the Engineers' Council for Professional Development. Mr. Morrow is a member of The American Society of Mechanical Engineers, American Electrochemical Society, and Sigma Xi.

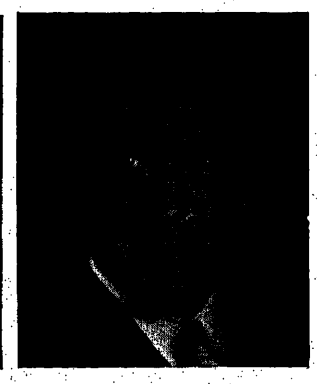
J. W. BARKER (M'26, F'30) dean of engineering, Columbia University, New York, N. Y., has been appointed chairman of the Institute's committee on education for the year 1937–38. Dean Barker was born June 17, 1891, at Lawrence, Mass., and was graduated from Massachusetts Institute of Technology with the degree of bachelor of science in electrical engineering in 1916, and master of science in electrical engineering in 1925. During the World War he served in the Coast Artillery Corps of the United States Army as artillery engineer and adjutant, and also as officer in charge of civil affairs of the American forces in Germany following the war. In 1925 he was appointed associate professor of electrical engineering at Lehigh University; 1929 he became professor and head of the department of electrical engineering, but in the following year was appointed professor and dean of the faculty of engineering at Columbia University, where he has remained since. Dean Barker has been a member of the Institute's committee on education since 1930, has served on the committee on production and application of light since 1929, and was chairman of that committee from 1933 to 1935. He was a member of the technical program committee from 1932 until 1937, and is at present a member of the publication committee and an Institute representative on the Iwadare Foundation. He is a member of the American Association for the Advancement of Science, American Society of Civil Engineers, The American Society of Mechanical Engineers, American Institute of Mining and Metallurgical Engineers, Society for the Promotion of Engineering Education, and has been active in the affairs of the division of engineering and research of the National Research Council.

W. D. A. PEASLEE (A'10, F'27) consulting engineer, Indianapolis, Ind., has joined the staff of W. S. Dickey Clay Manufacturing Company, Kansas City, Mo., as chief engineer. Mr. Peaslee was born at Grass Valley, Calif. He received the degree of bachelor of arts in electrical engineering from Leland Stanford, Jr., University in 1910, and that of electrical engineer in 1916 from Oregon Agricultural College, where he was an instructor. Following service as a captain in the U.S. Army during 1917–19, he became electrical engineer and later general manager of the Jeffery Dewitt Insulator Company, Huntington, W. Va. From 1922 to 1924 he was chief engineer of Belden Manufacturing Company, Chicago, and during 1924–25 was president and general manager of Terlee Electric and Manufacturing Company, Chicago. In 1925 he became assistant to president and general manager of Daven Radio Corporation, Newark, N. J., and 2 years later accepted the position of assistant to president, Underwriters Laboratories, Chicago, Ill., which he held for 8 years. He is the author of articles on a variety of subjects, and a member of The American Society of Mechanical Engineers, American Association for the Advancement of Science, Société Française des Electriciens, and others.

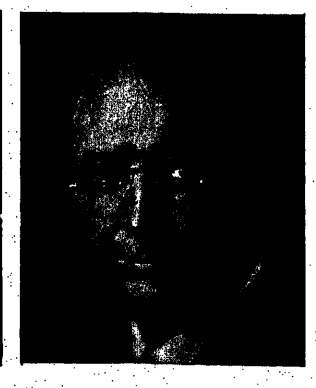
O. J. ROTTY (A'25, M'31) superintendent of substations, Union Electric Company of Missouri, St. Louis, has been appointed chairman of the Institute's committee on automatic stations for the year 1937–38. Mr. Rotty was born October 14, 1898, at St. Louis and received the degree of bachelor of science in engineering at the University of Missouri in 1921. Immediately following his graduation he entered the employ of the Union Electric Light and Power Company, which later became the Union Electric Company of Missouri. His first position with that company was concerned with the physical inventory of the utility properties, but in 1923 he was appointed general substation engineer, in which capacity he worked on the



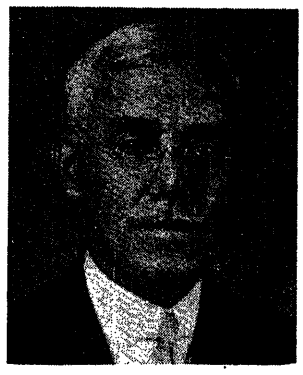
L. W. W. MORROW



J. W. BARKER



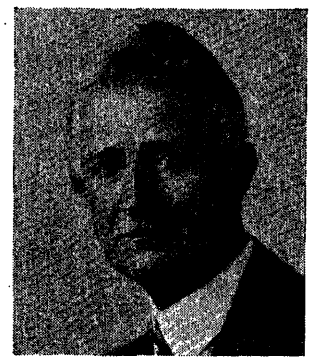
C. R. JONES



F. V. MAGALHAES



VANNEVAR BUSH



O. A. KNOPP

construction, testing, and operation of automatic substations. From 1926 until 1930 Mr. Rotty was substation engineer in charge of design, construction, testing, and inspection of automatic stations, and since 1930 he has been superintendent of substations. He has been a member of the committee on automatic stations since 1930, and has been an interested participant in the affairs of the Institute's St. Louis Section, having been Section secretary during 1929–30 and member or chairman of Section committees.

R. D. EVANS (A'21, M'26) central station engineer, Westinghouse Electric & Manufacturing Company, East Pittsburgh, Pa., has been appointed chairman of the Institute's committee on power transmission and distribution for the year 1937–38. Mr. Evans was born October 14, 1892, at Spring Water, Wis., and received the degree of bachelor of science in electrical engineering at the University of Oklahoma in 1914, following which he entered the employ of the Westinghouse Electric & Manufacturing Company as a general engineer. He has been affiliated with that company continuously, and has done much original work in studies of power generation and transmission, a-c railway engineering, electric furnaces, and inductive co-ordination. Mr. Evans has served the Institute as a member of the power transmission and distribution committee since 1924, and was a member of the committee on communication from 1924 until 1934; he was active also in the committee work of the former National Electric Light Association. He has presented several papers, principally on transmission-line calculations, power system stability, and network theory, before the Institute, and is co-author of a textbook on the theory of symmetrical components. In 1929 he was awarded the Triennial Montefiore Prize jointly with C. F. Wagner (A'20, M'27) for contributions to the theory of power system stability.

W. L. EVERITT (A'25, F'36) professor of electrical engineering at The Ohio State University, Columbus, has been appointed chairman of the Institute's committee on communication for the year 1937–38. Doctor Everitt was born April 14, 1900, at Baltimore, Md., and received the degrees of electrical engineer (1922), master of science (1926), and doctor of philosophy (1933), at Cornell University, the University of Michigan, and The Ohio State University, respectively. Following his graduation in 1922 he became affiliated with the North Electric Manufacturing Company, Galion, Ohio, as engineer in charge of the design and installation of relay-operated private automatic telephone exchanges. In 1924 he was appointed to the electrical-engineering faculty of the University of Michigan, was placed in charge of the courses in communication, and remained at that institution until 1926 when he was appointed assistant professor of electrical engineering at The Ohio State University; in 1929 he became associate professor; and in 1934, professor. Besides his regular teaching duties, Doctor Everitt has served as consulting engineer for several companies. He has been active in the local affairs of the Columbus Section of the Institute, having been Section chairman during 1931–32, and has served as a member of the committee on communication since 1932. He is author of a widely used textbook on communication engineering.

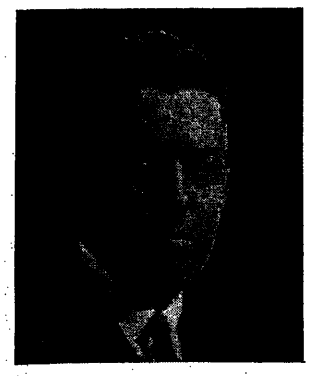
O. A. KNOPP (A'09, M'34) chief of the bureau of tests and inspection, Pacific Gas and Electric Company, San Francisco, Calif., has received the AIEE Pacific District prize for initial paper for his paper "Some Applications of Instrument Transformers." Mr. Knopp was born August 24, 1877, in Berlin, Germany, and received his technical education in that country. His first position in the electrical industry was as a testing engineer in the Bergmann Electrical Works, Berlin, in 1900. After several brief affiliations with companies in both Germany and the United States, he became superintendent of the standardizing laboratory and meter department of the Pacific Gas and Electric Company in 1908. In 1915 Mr. Knopp was made superintendent of the laboratory department; and in 1920, chief of the bureau of tests and inspection. He is a member of the American Society for Testing Materials, and was a long-standing member of the former National Electric Light Association. He served as a member of the Institute's committee on instruments and measurements from 1930 to 1934, and holds many patents on improvements in instruments and transformers.

R. R. WHIPPLE (A'30, M'36) assistant professor of electrical engineering at the University of Iowa, Iowa City, has accepted the position of designing illuminating engineer with The Trippe Manufacturing Company, Chicago, Ill. Mr. Whipple is a graduate of the University of Michigan, and had been a member of the faculty of the electrical engineering department at the University of Iowa since 1928. He has written several papers on illumination subjects, and is a member of the Illuminating Engineering Society.

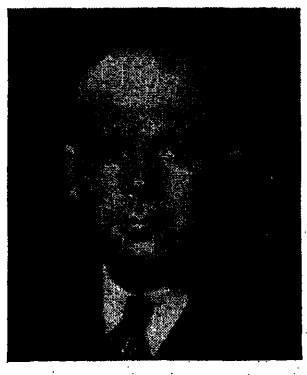
F. V. MAGALHAES (A'07, F'19) executive assistant to the president, Consolidated Edison Company of New York, Inc., New York, N. Y., has been appointed chairman of the Institute's board of examiners for the year 1937–38. A biographical outline of Mr. Magalhaes's technical career and his activities in the Institute appeared in ELECTRICAL ENGINEERING for August 1937, page 1064.

VANNEVAR BUSH (A'15, F'24, director, Lamme Medalist '35) vice-president of Massachusetts Institute of Technology, Cambridge, has been appointed chairman of the Institute's committee on co-ordination of Institute activities for the year 1937–38. A biographical sketch of Doctor Bush appeared in the March 1937 issue of ELECTRICAL ENGINEERING, pages 394–5.

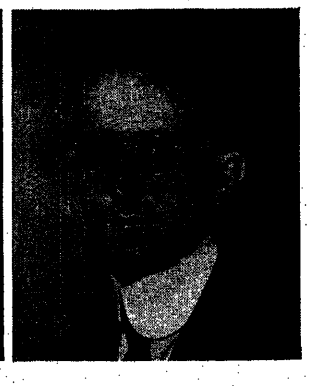
J. W. MCRAE (A'37) member of technical staff, Bell Telephone Laboratories, Deal, N. J., has received the AIEE Pacific District prize for Branch paper for his paper "The Magnetic Vector Potential," which was published in ELECTRICAL ENGINEERING for May 1936, pages 534–42, and presented



O. J. ROTTY



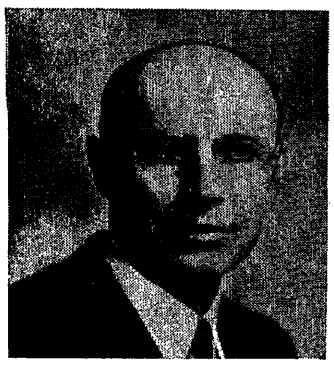
W. L. EVERITT



R. D. EVANS

at the 1936 AIEE summer convention, Pasadena, Calif., June 23, 1936. Doctor McRae was born October 25, 1910, at Vancouver, B. C., Canada, and received the degree of bachelor of applied science at the University of British Columbia in 1933, following which he entered California Institute of Technology as a graduate student and received the degrees of master of science (1934) and doctor of philosophy (1936). He has been a member of the technical staff of the Bell Telephone Laboratories since January 1937. He is a member of Sigma Xi.

J. A. KOONTZ, (A'11, M'20) hydroelectric and transmission engineer, Pacific Gas and Electric Company, San Francisco, Calif., co-author of the paper "Cable Vibration—Methods of Measurement" with J. S. Carroll (A'24, M'37) has received the AIEE Pacific District prize for best paper. Mr. Koontz was born August 27, 1883, at Aztec, N. M., attended Throop Polytechnic Academy, received the degree of bachelor of arts at Stanford University in 1908 and the degree of electrical engineer at the same



J. A. KOONTZ

institution in 1912. Upon graduation in 1909 he was employed by the General Electric Company for one year before he returned to Stanford as a graduate student and instructor, and after he received his engineering degree in 1912 he became associated with the Great Western Power Company, San Francisco, where he eventually became electrical engineer and remained until 1930. In that year he assumed his present position with the Pacific Gas and Electric Company. He has served as a member of 2 of the Institute's committees: power transmission and distribution, 1920–23; and membership, 1931–33.

H. J. McCREARY (A'24, M'36) has resigned as chief engineer of the Leich Electric Company, Genoa, Ill., to establish an office as a consulting engineer at Chicago. A graduate of the University of Nebraska, from which he received the degree of bachelor of science in electrical engineering in 1923, Mr. McCreary was employed by the Western Electric Company, Chicago, as inspection methods and development engineer from 1923 to 1925, and by the Automatic Electric Company, Chicago, as research engineer from 1925 to 1928. For one year he was laboratory engineer with the Grigsby-Grunow Company, Chicago, and for 3 years was development engineer for the Railroad Supply Company. From 1933 to 1935 he was chief engineer of the Chicago Television and Research Laboratories, and in 1936 became chief engineer of the Leich Electric Company. He has patented several inventions,-and is a member of the Western Society of Engineers.



J. S. CARROLL

J. S. CARROLL (A'24, M'37) associate professor of electrical engineering, Stanford University, Calif., co-author of the paper "Cable Vibration—Methods of Measurement" with J. A. Koontz (A'11, M'20) has received the AIEE Pacific District prize for best paper. A biographical sketch of Doctor Carroll appeared in the August 1937 issue of ELECTRICAL ENGINEERING, page 1064, in announcement of his receipt of honorable mention in the AIEE national prize awards for best paper in theory and research.

J. T. ROBERTSON (A'06, M'13) recently at Muscle Shoals, Ala., is now connected with the firm of J. T. Robertson and Associates at Birmingham. A graduate of Clemson College in the class of 1903, he was electrical inspector for the Southeastern Underwriters' Association, Atlanta, Ga., until 1911, when he became electrical engineer and inspector for the Mississippi Inspection and Advisory Rating Company at Vicksburg. Later he was made secretary as well as electrical engineer, a position which he held until 1925 when he became superintendent of the Abbeville (S. C.) Water and Electric Plant. In 1929 he became connected with A. H. Turner, Atlanta, as special agent and engineer.

E. L. GINZTON (Enrolled Student) has received the AIEE Pacific District prize for graduate student paper for his paper "Balanced Feed-Back Amplifiers." Mr. Ginzton is a native (1915) of Russia and an electrical-engineering graduate of the University of California in the class of 1936. Following his graduation he returned to that school to pursue graduate studies.

A. L. TURNER (M'29) chief engineer, Northwestern Bell Telephone Company, Omaha, Neb., has been appointed a member of the engineers and architects board authorized recently in a bill passed by the state legislature, which empowers the board to administer an act calling for licensing of engineers and architects in the state.

W. H. HULSWIT, JR. (A'34) who has been a fellow at Northwestern University at Evanston, Ill., now is employed in the development department of United States Rubber Products, Inc., at Passaic, N. J.

G. P. KNAPP (A'30) former field engineer with RCA Manufacturing Company, Inc., at Camden, N. J., is now service manager for the company at Baltimore, Md.

F. E. LEGGETT (A'32) recently chief draftsman for an improvement project at the University of Florida, Gainesville, is now at Tallahassee as draftsman in a highway planning survey division of the Florida State Road Department.

K. J. KRACH (A'37) who has been serving with the 34th Infantry, U.S. Army, at Fort George G. Mead, is now employed by the Pennsylvania Water and Power Company at Baltimore, Md., as electrical engineer.

L. M. SORENSON (A'34) who has been a draftsman for the Beloit Iron Works, Beloit, Wis., is now assistant electrical engineer in the inspection and development laboratory of the Western Electric Company at Chicago, Ill.

C. H. JOHNSON (M'35) who has been electrical engineer for the Idaho Maryland Mines Corporation, Grass Valley, Calif., has accepted the position of electrical engineer with the General Electric Company, San Francisco.

W. M. GILMAN (A'27) engineer for the Waterbury Tool Company, Waterbury, Conn., now is employed as an engineer for the consulting engineering firm of Jackson and Moreland, Boston, Mass.

W. F. UFFELMAN (A'34) has been transferred from the sales engineering department of the Clark Controller Company, Cleveland, Ohio, to the Detroit, Mich., offices of that company, as a district sales engineer.

J. H. PERSONS (A'31) employed in the industrial department of the General Electric Company, Atlanta, Ga., has been transferred to the Charleston, S. C., offices of that company.

L. F. PRIES (A'33) formerly development engineer for The Rudolph Wurlitzer Company, DeKalb, Ill., now is employed in the engineering department of the American Steel & Wire Company, DeKalb.

M. D. BRANE (A'28) formerly a teacher of applied electricity in the Haaren High School, New York, N. Y., now is employed by the Duquesne Light Company, Pittsburgh, Pa.

C. E. GAGNIER (A'34) formerly electrical foreman, Rotary Electric Steel Company, Detroit, Mich., now is development engineer for The DeVilbiss Company, Toledo, Ohio.

F. S. ROTHE (A'36) formerly a cadet engineer for the Metropolitan Edison Company, Reading, Pa., now is employed in the test department of the General Electric Company, Pittsfield, Mass.

W. S. GIFFORD (A'16) president, American Telephone and Telegraph Company, New York, N. Y., has been appointed chairman of the advisory committee on communication of New York World's Fair, 1939.

S. V. WADTHEKAR (A'34) formerly chief engineer of the Arrah (India) Electric Supply Co., Ltd., now is resident engineer and deputy manager of the Rewa (India) Electric Supply Co., Ltd.

E. G. HEMENWAY (A'20) district manager, Western Electric Company, Inc., of Cuba, Balboa, Canal Zone, has been transferred to the New York, N. Y., offices of Electrical Research Products, Inc.

A. R. NAHRGANG (A'24) has been transferred from the staff of Electrical Research Products, Inc., New York, N. Y., to the Kearny, N. J., plant of the Western Electric Company.

N. S. MOORE (A'17, M'19) recently was appointed a member of the sales organization of The Porcelain Insulator Corporation, Lima, N. Y., with offices at Riverside, Ill.

R. J. ABRAMSON (A'33) formerly electrical engineering draftsman with Joseph Weidenhoff, Chicago, Ill., now is industrial engineer with Max Miller Company, Chicago.

C. B. SMITH (A'35) test man with the General Electric Company as Schenectady, N. Y., has been transferred to Fort Wayne, Ind., as fractional-horsepower-motor engineer.

L. L. LATHROP (A'35) formerly with the Industrial Heater Company, New York, N. Y., now is employed by the New York Power and Light Company at Schenectady, N. Y.

L. A. GRETTUM (A'24) operating manager of the Eastern Oregon Light and Power Company, Baker, recently was elected vice-president of the Northwest Electric Light and Power Association.

NIKOLA TESLA (A'88, F'17, Edison Medalist '16, member for life) recently received the Order of the White Lion of the Republic of Czechoslovakia for his contributions to science and engineering.

T. O. SWEATT (A'33) has resigned from the staff of Gibbs and Hill, consulting engineers, New York, N. Y., and now is employed by the Public Service Electric and Gas Company, Newark, N. J.

R. S. TAYLOR (A'36) division engineer, Oklahoma Gas and Electric Company, Oklahoma City, has been transferred to the Muskogee offices of that company.

D. H. ANDREWS (A'35) who has been an experimenter in the Naval Research Laboratory, Anacostia, D. C., now is an assistant electrical engineer with the General Cable Corporation, Buffalo, N. Y.

J. W. LINDSEY (A'33) formerly electrician with the U.S. Bureau of Reclamation at Boulder City, Nev., now is electrician with the Bethlehem Shipbuilding Corporation, Ltd., San Francisco, Calif.

L. J. RICHARDS (A'34) formerly cost accountant with the East Bay Municipal Utility District, Oakland, Calif., now is employed by the Southern Pacific Railway at San Jose as signalman.

R. W. DRUSHELL (A'25, M'36) distribution engineer, The Ohio Public Service Company, Alliance, has been transferred to the Elyria, Ohio, offices of that company.

KENNETH LANNERT (A'35) formerly employed by the Sunnen Products Company, St. Louis, Mo., now is associated with the Carter Carburetor Corporation, St. Louis.

J. K. WHISTLER (A'35) recently was employed as a junior engineer for Black, Sivalls, and Bryson, Oklahoma City, Okla.

C. V. BARNHILL (A'36) formerly an engineer with the Rural Electrification Administration at Wichita, Kans., now is with The Research Service, Washington, D. C.

T. H. MAWSON (A'29) formerly with the Monsanto Chemical Company at Anniston, Ala., now is with the Commonwealth and Southern Corporation at Birmingham.

R. A. SCHOLL (A'34) formerly junior engineer with the Public Service Company of Indiana, Connersville, has been made power sales engineer at Indianapolis.

BOYD STEVENS (A'33) switchman for the Illinois Bell Telephone Company at Urbana, has been made transmission testing foreman at Danville.

E. S. HENNING (A'36) now is junior electrical engineer with the bureau of engineering of the Navy Department, Washington, D. C.

# Obituary

CLARENCE LINUS CORY (A'92, M'03, F'13, member for life) professor emeritus of electrical engineering, and formerly dean of the college of mechanics, University of California, Berkeley, died in Berkeley, August 2, 1937. Born September 4, 1872, at Lafayette, Ind., and graduated in mechanical engineering by Purdue University in 1889, Professor Cory entered Cornell University for graduate work under the late Harris J. Ryan, and was awarded the degree of master of mechanical engineering by Cornell in 1891. After teaching electrical engineering at Highland Park College in Des Moines, Iowa, for a short time, he became a member of the faculty of the University of California, serving as assistant professor of electrical engineering from 1892 to 1898, as associate professor from 1898 to 1901, and as professor of electrical engineering and dean of the college of mechanics from 1901 until his retirement from active teaching duties in 1930. In addition to his long service in the field of electrical engineering education, Professor Cory early won a prominent standing on the Pacific Coast as a consulting engineer in connection with many of the early hydroelectric and other power developments in the state of California. He also was identified with several of the early long-distance high-voltage transmission-line projects. Professor Cory was the second chairman of the Institute's San Francisco Section, serving a double term from 1905 to 1907. Later (1914–19) he was an active member of the Institute's committee on economics of electric service.

HARVEY LESTER HARRIS (A'18, M'30) president of the Automatic Electric Company, Chicago, Ill., died August 10, 1937. Mr. Harris was born at Presque Isle, Me., on August 21, 1879, and was continuously in the telephone constructing, operating, and allied manufacturing business, starting as night operator for a telephone company in Ohio in 1894. In 1907 he joined the Dean Electric Company, Elyria, Ohio, as switchboard engineer, after being employed in various capacities by several telephone companies. He remained with this company and its successors until 1917, by which time he was sales engineer for the Stromberg Carlson Telephone Manufacturing Company, Rochester, N. Y. In that year Mr. Harris became general manager of the Kansas City Telephone Company and later vice-president and general manager of the Consolidated Telephone Company, Kansas City, Mo., part of the interests of Theodore Gary and Company. Since 1924 he had been executive in general charge of Theodore Gary and Company's manufacturing interests, which include Automatic Electric Company, American Electric Company, Inc., and other companies in England, Belgium, Canada, Australia, and Japan as well as in the United States, serving as director or officer. Mr. Harris was the holder of several patents in telephony. He was a member of the board of governors of the National Electrical Manufacturers Association, and a member of the Western Society of Engineers.

FRANK DANIEL BURR (A'07, M'20) consulting power engineer, Los Angeles, Calif., was killed in an automobile accident in that city on June 30, 1937. He was born at Frederica, Del., on February 28, 1872, and received the degree of bachelor of science in electrical engineering from the University of Nebraska in 1902. For a year he was employed as electrician in coal mines at Red Lodge, Mont., and then from 1903 to 1907 was employed by the Missouri River

Power Company. For the next 2 years Mr. Burr was with the Colorado Power Company, then during 1909–10 engaged in irrigation engineering work with the Arnold Company for the Denver Reservoir and Irrigation Company and the Southern Colorado Irrigation Company. In 1910 he became power salesman for the Denver Gas and Electric Light Company at Denver, Colo., and 2 years later was made power engineer. He was made commercial representative in 1920, a position which he held until 1927, when he became power sales engineer for the Southwestern Public Service Company at Amarillo, Texas. Two years later he joined the Southern California Edison Company at Ventura as power specialist. For the past several years he had conducted a consulting practice as power engineer.

SAMUEL ERNEST MCMILLAN HENDERSON (A'09, M'12, F'14, past vice-president) central station engineer, Canadian General Electric Company, Ltd., Toronto, Ont., died September 2, 1937. Born at London, Ont., September 28, 1879, Mr. Henderson received his technical education at Toronto University, graduating in 1900 with the degree of bachelor of science in electrical engineering. Upon graduation he entered the drafting department in the switchboard division of the General Electric Company at Schenectady, N. Y., and shortly was promoted to the switchboard engineering department. In 1906 he took charge of the estimating division, and 3 years later was given full responsibility for the design and manufacture of 110,000/13,200-volt switchboards for the Hydro-Electric Power Commission of Ontario. In 1910 he joined the Canadian General Electric Company at Peterboro as engineer in charge of estimating, design, and manufacture of switchboards and other apparatus, and later was transferred to Toronto as central station engineer. Mr. Henderson was a member of the AIEE committee on protective devices from 1920 to 1926, and of the membership committee 1923–25 and 1933–34, and was vice-president representing District No. 10 during 1923–25. He was a member and president of the Engineers' Club of Toronto, and had been a member of several other organizations.

ABRAM HUSSEY (A'06, M'18) retired electrical engineer, Chester, N. J., died August 19, 1937. He had been superintendent of distribution for the Brooklyn Edison Company, Brooklyn, N. Y., for 21 years prior to his retirement in 1934. Born May 9, 1868, at Lathrop, Mo., Mr. Hussey entered electrical work as a wireman for the Western Electric Company at Chicago, Ill., in 1892. Two years later he went to Rutland, Vt., as chief electrician of the Marble City Electric Company, later the Rutland City Electric Company. In 1898 he entered the service of the Cataract Power and Conduit Company at Buffalo, N. Y., and the following year was made general foreman; during his service of 8 years with the company the plant grew from a connected load of 2,000 horsepower to 70,000 horsepower. From 1906 to 1913 he was employed by the New York Central Railroad; first until 1909, with charge of all transmission facilities in the electrified zone, and then in charge of construction and maintenance of all transmission facilities during extension of electrification to more than 150 miles of track. In 1913 he accepted the position of superintendent of distribution with the Edison Electric Illuminating Company of Brooklyn (now the Brooklyn Edison Company), where he had charge of engineering, construction, and operation of the transmission and distribution facilities.

LUTHER WILSON COPELAND (A'35) assistant manager, lubrication engineering department, Wadhams Oil Company, Milwaukee, Wis., died August 26, 1937. Mr. Copeland was born at Huntington, Ark., on August 21, 1901, and received the degree of bachelor of science in electrical engineering from Georgia Institute of Technology in 1926. For a few months following graduation he was employed by the Fort Smith Light and Traction Company at Fort Smith, Ark., then for 4 years was employed by the Sinclair Refining Company at Detroit, Mich., and Atlanta, Ga., in various capacities. In 1930 he joined the Vacuum Oil Company, which later was merged with the Wadhams Oil Company, as assistant sales manager of the industrial oil department, which position he held at the time of his death. Mr. Copeland was an active member of the Milwaukee Section of the Institute, and at the last annual meeting of the Section was elected a director for the term beginning August 1. He was chairman of the entertainment committee for the 1937 summer convention held at Milwaukee in June.

EDGAR DAVIS EDMONSTON (A'02, M'07, member for life) general superintendent of the Consolidated Gas Electric Light and Power Company of Baltimore, Baltimore, Md., died August 29, 1937. He was born at Washington, D. C., October 23, 1876, and was graduated from Lehigh University in 1898 with the degree of electrical engineer. He then obtained employment with the United States Electric Lighting Company, Washington, for a year, resigning to join the Westinghouse Electric & Manufacturing Company at East Pittsburgh, Pa. In 1900, Mr. Edmonston became electrical engineer for the Lackawanna Steel Company, which was building a large electrically equipped plant at Buffalo, N. Y., and directed the electrical engineering and construction work until he resigned in 1904. In 1905 he accepted the position of chief engineer of the American Construction Company at New Orleans, La., building a complete commercial power and lighting system in that city. Since 1908 he had been with the Consolidated Electric Light and Power Company of Baltimore, which he joined as superintendent of construction, and of which he had been general superintendent since 1911.

MAURICE COSTER (A'95, M'96, F'12, member for life) retired vice-president of the Westinghouse Electric International Company died at his residence in Magog, Que., Can., on August 31, 1937. Mr. Coster was born in the Netherlands on August 4, 1856, and was graduated from Stevens Institute of Technology, Hoboken, N. J., in 1877 with the degree of mechanical engineer. For a time he was in British Guiana, S. A., as a consulting mechancial engineer, and in 1888 he became associated with the Westinghouse Electric & Manufacturing Company as an engineer, later being transferred to the commercial department. He was sent to Paris, France, as manager of the Societe Anonyme Westinghouse, and returned to the United States in 1905. In 1919, with the formation of the Westinghouse Electric International Company, Mr. Coster became vice-president, and was appointed senior vice-president in 1922, a position which he held until his retirement in 1930. He served on the Institute's board of examiners during 1914–15. Mr. Coster was one of the original 8 founders of the American Manufacturers Export Association, one of the first 50 members of the National Foreign Trade Council, and one of the 24 incorporators of India House.

ARTHUR TOWNSEND (A'05, M'31) chief inspector, Saskatchewan Power Commission, Regina, Sask., Canada, died on August 18, 1937. Mr. Townsend was born January 7, 1875, at Southampton, England, and attended Goldsmith Technical Institute in London. Between 1891 and 1901 he was employed by various companies in England, and then he entered the electrical testing department of the British Thomson Houston Company at London. He was transferred to the technical staff at Rugby in 1903, and left the company 3 years later to move to Canada, where he installed, owned, and operated the town plant at Milestone, Sask., until 1927. In 1928 he designed and built radio station CHWC at Pilot Butte, and since 1929 had been chief inspector for the Saskatchewan Power Commission.

PAUL A. CALLIS (A'34) estimating engineer, Louisville Gas & Electric Company, Louisville, Ky., died May 11, 1937. He was born at Rosedale, Ind., December 14, 1900, and had been employed by the company since he was graduated from Purdue University in 1923 with the degree of bachelor of science in electrical engineering. He began as an estimator in the electric distribution and construction department, and since 1930 had been in charge of estimating in a supervisory capacity. During this time he aided in the development of a "unit cost" system of estimating, and in compiling drawings used as standard construction by the company.

MAURICE BARRERE (A'24) consulting engineer, Schneider and Company, Paris, France, died early in August 1937. He was born at Lourdes, France, July 28, 1891, and received his technical education at Ecole Centrale de Paris and Ecole Superieure d' Electricite. Since 1919 he had been an instructor in electrical engineering at Ecole Centrale de Paris, and in 1921 had become connected with Schneider and Company. He was a chevalier of the Legion of Honor, and had received the Croix de Guerre and the Military Cross of England.

# Membership

## Recommended for Transfer

The Board of Examiners, at its meeting on September 16, 1937, recommended the following members for transfer to the grade of membership indicated. Any objection to these transfers should be filed at once with the national secretary.

**To Grade of Fellow**

Hitchcock, H. W., chief engineer, Southern California Telephone Company, Los Angeles, Calif.

McEachron, K. B., research engineer, General Electric Company, Pittsfield, Mass.

2 to Grade of Fellow

**To Grade of Member**

Allen, C. S., design engineer, General Electric Company, Fort Wayne, Ind.

Banes, C. Raymond, electrical research engineer, Long Island Lighting Company, New York, N. Y.

Bryant, W. L., electrical engineer, Imperial Irrigation District, Imperial, Calif.

Cornelius, H. A., designing engineer, Public Service Company of Northern Illinois, Chicago.

Davis, C. L., patent department, Radio Corporation of America, Washington, D. C.

Ehrensperger, C., engineer, Brown Boveri Company, Inc., Baden, Switzerland.

Fowler, C. V., toll transmission engineer, The Pacific Telephone and Telegraph Company, San Francisco, Calif.

Gear, R. B., field engineer, Commonwealth Edison Company, Chicago, Ill.

Goodrich, J. L., electrical engineer, in care of Thomas H. Allen, Memphis, Tenn.

Hallar, K. E. V., assistant operating and maintenance engineer, Husqvarna Vapenfabriks, Huskvarna, Sweden.

Hanson, D. H., section engineer, General Electric Company, Fort Wayne, Ind.

Huntsberger, J. D., battery service engineer, Philco Radio and Television Corporation, Philadelphia, Pa.

Kilbourne, C. E., designing engineer, General Electric Company, Schenectady, N. Y.

Kilgore, L. A., design engineer, Westinghouse Electric & Manufacturing Company, East Pittsburgh, Pa.

Knoderer, C. L., technical employee, American Telephone and Telegraph Company, New York, N. Y.

Larason, G. E., extension engineer, Oklahoma Gas and Electric Company, Oklahoma City.

Mason, R. C., research engineer, Westinghouse Electric & Manufacturing Company, East Pittsburgh, Pa.

Payne, C. C., control engineer, central electricity board, Mid-East England area, Leeds, England.

Rawls, J. A., transmission engineer, Virginia Electric and Power Company, Richmond.

Swingle, R. H., patent attorney, Westinghouse Electric & Manufacturing Company, East Pittsburgh, Pa.

Wetherill, L., electrical engineer, General Electric Company, Pittsfield, Mass.

21 to Grade of Member

## Applications for Membership

Applications have been received at headquarters from the following candidates for election to membership in the Institute. If the applicant has applied for direct admission to a grade higher than Associate, the grade follows immediately after the name. Any member objecting to the election of any of these candidates should so inform the national secretary before October 31, 1937 or December 31, 1937, if the applicant resides outside of the United States or Canada.

Andrews, P. R., Tennessee Valley Authority, Wilson Dam, Ala.

Archibald, C. G., Westinghouse Elec. & Mfg. Co., New York, N. Y.

Barker, C. J. (Member), Consolidated Edison Company of New York, Inc., New York, N. Y.

Barr, J. R. (Member), General Electric Company, Pittsfield, Mass.

Becker, H. E., Westinghouse Electric & Manufacturing Company, San Francisco, Calif.

Bisson, A. J. (Member), Consolidated Edison Company of New York, Inc., New York, N. Y.

Boldt, W. F., Century Electric Company, St. Louis, Mo.

Bolton, F. D., Canadian General Electric Co., Vancouver, B. C., Canada.

Bottonari, S. A., Westinghouse Electric & Manufacturing Company, East Pittsburgh, Pa.

Brown, C. B., McCollum Laboratories, Houston, Texas.

Cattolica, J. L., Pacific Gas and Electric Company, San Francisco, Calif.

Chamberlin, J. H., Acme Electric and Manufacturing Company, Cleveland, Ohio.

Clement, P. E., Tennessee Valley Authority, Joe Wheeler Dam, Ala.

Cosentine, L. G. (Member), Wisconsin Gas and Electric Company, Fort Atkinson, Wis.

Criley, W. (Member), Rochester Telephone Corp., Rochester, N. Y.

Daugherty, C. A. (Member), Post Office Box 582, Coral Gables, Fla.

Delo, H. E., Western Electric Company, Kearny, N. J.

Edwards, P. F., Westinghouse Electric & Manufacturing Co., East Pittsburgh, Pa.

Elam, R. D., Tennessee Valley Authority, Wilson Dam, Ala.

Farmer, E. B., Electrolux Inc., New York, N. Y.

Fremo, E. C., San Diego Consolidated Gas and Electric Company, San Diego, Calif.

Garris, C. R., General Electric Company, Pittsfield, Mass.

Grethel, B. W., Public Utilities, City of San Francisco, San Francisco, Calif.

Guice, F. J. (Member), Memphis Power and Light Company, Memphis, Tenn.

Harkins, M. A., University of Tennessee, Knoxville.

Haupt, L. M., Jr., A. & M. College, College Station, Texas.

Heath, E. A., Kansas Gas & Electric Co., Wichita, Kansas.

Kelley, W. A. (Member), E. D. Jones & Sons Co., Pittsfield, Mass.

Lyons, S. E., Wilson Dam, Ala.

Mangold, A. O., Northwestern Electric Co., Portland, Oregon.

Mattison, M., Harza Engineering Company, Columbus, Nebraska.

McCarthy, E. T., Alta Electric and Mechanical Company, San Francisco, Calif.

Meinhardt, P. W., Union Electric Company of Missouri, St. Louis.

Olson, O. F., New York and Queens Electric Light and Power Company, Flushing, N. Y.

Painter, J. C., 425 Mason Street, San Francisco, Calif.

Park, C. A., Jr., Tennessee Valley Authority, Wilson Dam, Ala.

Reifsnyder, G. C., Bell Telephone Company of Pennsylvania, Allentown.

Renzi, S. E., United Shipyard Inc., Staten Island, N. Y.

Rodhouse, T. E., General Electric Company, Pittsfield, Mass.

Rodnite, F. A., Public Service Electric and Gas Company, Newark, N. J.

Ruppert, R. B., 629 Franklin Avenue, Columbus, Ohio.

Seitz, F. W., 100–112 Seeboth St., Milwaukee, Wis.

Sims, J. B., Carbide & Carbon Chemicals Corp., South Charleston, W. Va.

Smart, D. L., Detroit Edison Company, Detroit, Mich.

Smith, C. D., Ohio Edison Co., Akron, Ohio.

Strandberg, H. V. (Member), City of Seattle, Light Dept., Seattle, Wash.

Tilyou, I. B. (Member), Cooper Wire Engineering Association, Washington, D. C.

Wade, J. R., Wilson Dam, Ala.

Walker, C. D., Bell Telephone Laboratories, New York, N. Y.

Wasserman, C., Consolidated Gas Electric Light and Power Company, Baltimore, Md.

Whitaker, H. B., Underwriters' Laboratories, Inc., Chicago, Ill.

White, W. C., Northeastern University, Boston, Mass.

Wilcox, H. M. (Member), Westinghouse Electric & Manufacturing Company, East Pittsburgh, Pa.

Williams, E. A., Jr., General Electric Company, Philadelphia, Pa.

Williamson, C. A., General Electric Co., Wichita, Kans.

Wohlgemuth, M. J. (Fellow) Westinghouse Electric & Manufacturing Company, Detroit, Michigan.

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**Foreign**

Bobal, L. (Member), Bata Shoe Company, Inc., Zlin, Czechoslovakia.

Chandler, C. E., Manning & Co. Ltd., Bridgetown, Barbados, B. W. I.

Coomar, H. N., Allgemeine Electricitata-Gesellshaft, Berlin, Germany.

Fenwick, W. (Member), Victoria Falls and Transvaal Power Company, Ltd., Germiston, Transvaal, South Africa.

Sarda, B. D. (Member), Hoshiarpur Electric Supply Company, Punjab, India.

Srinivasan, R., Tinnevelly Tuticorin Electric Supply Company, Brahmin Colony, Tuticorin, India.

6 Foreign

## Addresses Wanted

A list of members whose mail has been returned by the postal authorities is given below, with the addresses as they now appear on the Institute record. Any member knowing of corrections to these addresses will kindly communicate them at once to the office of the secretary at 33 West 39th St., New York, N. Y.

Charlton, H. C., 4827 Wilson Avenue, Montreal, Que., Canada.

Evans, Maldwyn F., Canadian Comstock Company, Ltd., Toronto, Ont., Canada.

Fassett, Frank C., 100 Seward Ave., Detroit, Mich.

Gregory, G. A., 1217 Jefferson Street, Olympia, Wash.

Hall, John R., 1464 S. 74th St., West Allis, Wis.

Handy, Lee, 525 W. 113th Ave., Vancouver, B. C., Can.

Hardy, John E., 1741 Pennsylvania Avenue, Denver, Colo.

Herr, Melvin D., South 228 Lincoln St., Spokane, Wash.

Jones, K. B., Trumbull Electric Manufacturing Company, Inc., Ludlow, Ky.

Kirk, W. C., 216 E. 22nd St., Owensboro, Ky.

Koziol, Roman Joseph, 174 Farmington Ave., Hartford, Conn.

Macomber, George S., Federal Power Commission, Washington, D. C.

Matthews, Robert W., 42 St. Stephen St., Boston, Mass.

Roberts, Fred A., 2010 West Michigan Street, Indianapolis, Ind.

Sikofsky, George L., 1206 East New York Avenue Brooklyn, N. Y.

15 Addresses Wanted

# Engineering Literature

## New Books in the Societies Library

Among the new books received at the Engineering Societies Library, New York, recently are the following which have been selected because of their possible interest to the electrical engineer. Unless otherwise specified, books listed have been presented gratis by the publishers. The Institute assumes no responsibility for statements made in the following outlines, information for which is taken from the preface of the book in question.

La FATIGUE des MÉTAUX. By R. Cazaud and L. Persoz. Paris, Dunod, 1937. 190 p., illus., 10x7 in., paper, 75 frs.; bound, 95 frs. Analyzes the principal studies of the fatigue of metals and discusses theories, methods of testing, fatigue limits, the factors that affect fatigue, and the resistance of welded and riveted joints.

BEIHEFTE zum GESUNDHEITS-INGENIEUR, Reihe 1, Heft 86. Die heiztechnischen Neuanlagen des Städtischen Krankenhauses Bad Cannstatt, by H. Wolfer. Munich and Berlin, R. Oldenbourg, 1937. 24 p., illus., 13x9 in., paper, 4.80 rm. Describes the power plant of a large German hospital and reports the results of an operating test.

Der ULTRASCHALL. By L. Bergmann. Berlin, VDI-Verlag, 1937. 230 p., illus., 8x6 in., cloth, 18.50 rm. An account of the present state of supersonics, with emphasis upon the scientific and technical uses of supersonic waves.

YEAR BOOK on COAL MINE MECHANIZATION. Washington, D. C., American Mining Congress, 1936. 362 p., illus., 9x6 in., lea., $2.00. Contains extracts from the reports of various district committees and papers presented at the 1936 convention.

DIESEL ENGINES. By P. E. Biggar. Toronto and New York, Macmillan Co., 1936, 165 p., illus., 9x6 in., cloth, $3.25. Condensed information in the Diesel field covering many particular points and the probable future development of the Diesel type.

MACHINE DESIGN. By P. H. Hyland and J. B. Kommers. 2 ed. New York and London, McGraw-Hill Book Co., 1937. 598 p., illus., 9x6 in., cloth, $4.50. A comprehensive elementary textbook on machine design, arranged to be studied simultaneously with mechanics of materials courses.

TEXTBOOK of THERMODYNAMICS. By P. S. Epstein. New York, John Wiley & Sons, 1937. 406 p., illus., 10x6 in., cloth, $5.00. Thermodynamics is treated from the physicist's point of view, and mainly as apart from statistical mechanics.

(The) SCIENCE of VALUATION and DEPRECIATION. By E. B. Kurtz. New York, Ronald Press Co., 1937. 221 p., illus., 9x6 in., cloth, $4.50. Offers scientific solutions, based on life experience tables, to basic problems in valuation and depreciation estimating and accounting.

# Industrial Notes

**Arc Welding Forges Ahead.**—True to the predictions that were made for it a decade ago, the electric arc welding process has been making tremendous strides in extending its fields of usefulness. The growth in volume in the past five years is shown by the NEMA reports of electric welding wire consumption, from 18.8 millions of pounds in 1932 to 111 millions of pounds in 1936. It is thought in some quarters that there will be recorded a further 50 per cent increase when the total for 1937 is known. That this progress is not all due to the general revival of industrial activity is shown by the steady increase in volume of consumption in the early thirties, before any real revival had started. A more graphic proof is the increasing amount of electrodes being used for each ingot ton of steel poured. In 1932 the figure was 1.4 lbs. of electrode for each ingot ton; in 1936 this figure had reached 2.4 pounds, an increase of 71 per cent.

**Electric Appliance Sales Mount.**—Retail sales of electric household washers in the first seven months of 1937 amounted to $80,531,874. Machines shipped in this period totalled over one million and their average retail price was $73.39. Ironer shipments for the same period totalled 109,270, compared to 102,988 for the same months of 1936. Vacuum cleaner sales aggregated 1,083,170 during the period, a total which was not reached until October last year. According to the Air Conditioning Manufacturers' Association, sales of air conditioning equipment of its members to the end of July amounted to $68,306,175, which was 37 per cent higher than the volume for all of last year.

**Cutler-Hammer Appointments.**—A new district office in New Orleans, was opened recently by Cutler-Hammer Inc., with Joseph Gardberg in charge. W. E. Ragsdale has been appointed manager of the Dallas office.

**Allegheny Steel Appointment.**—Charles H. McKnight has been appointed special sales representative by the Allegheny Steel Co., of Brackenridge, Pa. Since 1912 he was in the employ of the General Electric Co. During the past few years he devoted his time to special cost reduction activities.

**American Steel & Wire Promotion.**—John May has been elected vice-president in charge of sales of the American Steel & Wire Co., a subsidiary of the U. S. Steel Corp., according to a recent announcement by C. F. Blackmer, president of the wire company. Mr. May has been connected with the company since 1909.

**G-E Employees' Service Records.**—More than 40 per cent of the employees of the General Electric Company have worked with the company for 10 or more years, according to a recent survey. Those employed more than 5 years number 42,875 and those with 10 or more years of service 32,019. 53 employees have been with the company 45 or more years; more than 200 for 40 years or more; more than 1000 for 35 or more years; 11,705 have worked 20 or more years and 19,773 have been employed 15 or more years.

**Westinghouse Appointments.**—R. R. Davis, formerly apparatus advertising manager of the Westinghouse Electric & Mfg. Co., has been appointed assistant to the general advertising manager, according to a recent announcement by S. D. Mahan, general advertising manager. J. M. McKibbin, Jr., associated with the company since 1922, has been appointed apparatus advertising and sales promotion manager. Walter Thompson, formerly Eastern sales manager of the radiotron division, R.C.A. Mfg. Co., is now director of utility sales for the Westinghouse merchandising division at Mansfield, Ohio. Angus G. Scott, formerly superintendent of power distribution for Cleveland Railways, has been appointed manager of line material activities at East Pittsburgh.

# Trade Literature

**Steam Turbine Units.**—Bulletin, 28 pp. Describes in considerable detail reaction type turbo-generator units of 1500- to 5000-kw capacity. Allis-Chalmers Mfg. Co., Milwaukee, Wis.

**Capacitors.**—Bulletin 143, 4 pp. Describes a new line of capacitors for power factor correction on electric distribution systems. Cornell-Dubilier Electric Corp., South Plainfield, N. J.

**Neutral Clamp and Thimble.**—Bulletin 629-H, 2 pp. Describes and gives catalog information on a clamp for grounding the neutral conductor on primary and secondary systems of distribution lines, and on a thimble for dead-ending conductors. Ohio Brass Co., Mansfield, O.

**Time Switches.**—Catalog. Describes Sauter synchronous and electrically-wound time switches. Types for all time switch applications are listed. R. W. Cramer & Co., Inc., 67 Irving Place, New York.

**A-C Generators.**—Bulletin 1158-A, 8 pp. Describes a-c bracket bearing type generators, built in standard ratings from 30 to 1000 kva, suitable for coupled service to high speed steam or internal combustion engines. Allis-Chalmers Mfg. Co., Milwaukee, Wis.

**Suspension Insulator Tests.**—Bulletin 623-H, 8 pp. Describes tests of dynamic characteristics of cap-pin insulators; explains what factors influence insulator life, and shows how test data are used in correlating insulator design with field performance. Ohio Brass Co., Mansfield, O.

**Vibration Elimination.**—Bulletin, 16 pp., "Eliminating Vibration Losses." Describes the application of various methods and materials, such as cork, rubber, etc., for eliminating vibration in the operation of many types of heavy machinery. Korfund Co., Inc., Long Island City, N. Y.

**Transformers.**—Bulletin GEA 2206C, 4 pp. Describes rural-line distribution transformers in ratings of 1 and 3 kva, which meet the need for inexpensive units designed for application to lines of 13,200 Y volts and below, where a solidly grounded common neutral is used for both high-voltage and low-voltage circuits. General Electric Co., Schenectady, N. Y.

**New Constant Level Oiler.**—Bulletin. Describes a new line of inexpensive constant level oilers for automatically maintaining an accurate level of oil in ring and ball bearings of motors, line shafts, pumps, and other machinery having oil wells. Trico Fuse Mfg. Co., Milwaukee, Wis.

**Arc Welder.**—Folder, "The Characteristics of a Modern Arc Welder." Includes volt-ampere curve analysis for general welding, heavy welding and light-gauge welding; describes single-current control, self-excitation and other features in the design and construction of the Hansen Smootharc welding generators. Harnischfeger Corp., 4400 W. National Ave., Milwaukee, Wis.

**Mercury Switches.**—Catalog 603, 12 pp. Describes the complete line of Kon-nec-tor mercury switches. Full-size illustrations of the twelve common types of mercury-to-mercury and mercury-to-metal switches are included, as well as a table giving the capacity and electrical specifications of each type. A section is devoted to desirable applications of mercury switches. General Electric Vapor Lamp Co., Hoboken, N. J.

**Watthour Meters.**—A series of bound, loose-leaf bulletins. Bulletin No. GEA-615E, 4 pp., General Information and Index to Contents. No. GEA-2668, 16 pp., Single-Phase, Type I-20. No. GEA-2669, 12 pp., Two-Element, Types V-2 and V-3. No. GEA-1046A, 8 pp., Polyphase, Types D-14 and D-15. No. GEA-1093B, 8 pp., Switchboard A-C Meters, Types IS-8, DS-19, DS-20, DS-21 and DS-23. No. GEA-2670, D-C Meters, 8 pp. No. GEA-1350A, 4 pp., Portable Standards. No. GEA-2671, 12 pp., Accessories and Supplies, describes protective cases, autotransformers, jewels, tool kits, etc. General Electric Co., Schenectady, N. Y.

**Modified Schering Bridge.**—Catalog E-54 (2), 8 pp. Describes a modified form of Schering bridge for determining the characteristics of samples of both liquid and solid dielectrics. High voltage is applied only to the test samples and to the standard air capacitor. A method of compensation for residual capacitance is used which enables results to be calculated from simple equations. In the case of low power factors, the result is read directly. Capacitances ranging from 40 mmf to 0.020 mf and power factors from 0.0001 to 0.70 can be accurately determined. The bridge is intended for use on 60-cycle circuits and the standard air capacitor and sample holders listed are rated at 10 kv. Leeds & Northrup Co., 4962 Stenton Ave., Philadelphia, Pa.

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Registered U. S. Patent Office

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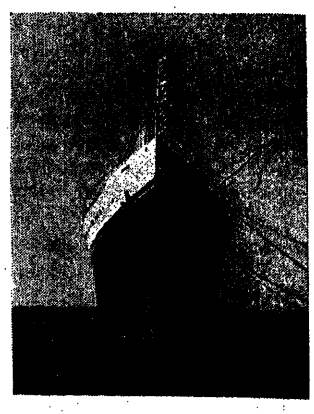


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## The Cover

**The completely electrified liner, S.S. "President Coolidge," powered by 2 13,250-horsepower 133-rpm synchronous motors each supplied from an individual turbogenerator set**

Westinghouse Photo



# High Lights

**D-C Transformers.** Various methods have been proposed for transforming voltage on d-c systems without using a motor-generator set. Although little practical use has been made of the device, the d-c transformer using grid-controlled mercury-arc rectifiers for commutating the direct current is one of the more promising of the systems thus far devised. The general theory of d-c transformers is discussed in a paper in this issue, and 2 new types of d-c transformers using grid-controlled mercury-arc rectifiers are described (*pages 1372–8*).

**Grand Coulee Dam.** Irrigating more than a million acres of land is one of the functions of the dam being built as part of the Columbia Basin project in the State of Washington. Pumps motor-driven by power generated at the dam will draw water from the river for distribution through hundreds of miles of canals; millions of kilowatt-hours of firm power will be produced annually. Construction of the dam is being accompanied by new accomplishments and records (*pages 1339–45*).

**ECPD Annual Meeting.** At the fifth annual meeting of Engineers' Council for Professional Development, additional engineering curricula were accredited, making a total of 442 curricula now so recognized in 127 educational institutions. Reports of committees and election of officers constituted the other principal items of business (*pages 1416–19*).

**Correction.** In the article "Engineering Income and Earnings, 1929–34," published in ELECTRICAL ENGINEERING for September 1937, the second sentence in the second paragraph under the heading "Earned Annual Income," page 1092, should read "Some 479 reported incomes less than $800 per year, while 295 earned more than $19,000 a year."

**New Committee Chairmen.** As usual, the newly appointed chairmen of AIEE committees are being introduced to the Institute membership through the "Personal Items" section. Items on the first group of chairmen were published in the October issue; items on the remainder are included in this issue (*pages 1424–6*).

**Short Circuits.** Water-wheel generators that are without damper windings and connected to a capacitive load such as an open transmission line can produce abnormally high voltages during unsymmetrical short circuits because of resonance or near resonance of the capacitance of the load and the reactance of the machine (*pages 1385–95*).

**Load Loci.** The method of circular loci may be applied to the solution of a circuit containing 2 transformers operating in parallel. The variation of current in either transformer or the ratio of the 2 currents is said to be obtainable as a function of the load impedance or the ratio of transformation without much involved computation (*pages 1379–84*).

**Important developments** in publication policy and procedure just approved by the board of directors, affecting both ELECTRICAL ENGINEERING and the TRANSACTIONS, are outlined on *page 1409* by Chairman I. Melville Stein of the AIEE publication committee.

**Noise in Small Motors.** Careless or inaccurate manufacturing methods sometimes are responsible for flaws such as uneven air gaps, loose bearings, or loose rotor bars, which contribute to noisy operation of small electric motors. Some of this noise can be minimized by proper design procedure (*pages 1359–67*).

**Akron District Meeting.** A strong and well received industrial flavor characterized the busy program of the recent Middle Eastern District Meeting. Of the 464 persons included on the registration list, approximately a third were students. A comprehensive report of activities will be found in this issue, beginning on *page 1410*.

**Engineers' Income.** Data derived from reports of 52,589 engineers tend to show that engineers engaged in technical work reach their maximum earning capacity later than those in nonengineering endeavors, but that this disadvantage is offset after a certain age (*pages 1353–8*).

**Insulation Research.** Principal advances in insulation research made during the past year were summarized in the report of the chairman of the committee on electrical insulation of National Research Council, presented during the 10th annual meeting of that body (*pages 1346–52*).

**NRC Subcommittee Meets.** At the recent annual meeting of the American Chemical Society held at Rochester, N. Y., the chemistry subcommittee of the National Research Council insulation committee held a symposium on insulation materials (*page 1420*).

**Winter Convention.** A "general" session has been scheduled tentatively on the program of the Institute's 1938 winter convention to be held January 24–28 in New York, N. Y. Preliminary plans for the convention are now under way (*page 1415*).

**Nominations for Offices.** For the guidance of the national nominating committee, suggestions for nominations for election to AIEE offices in 1938 are invited from the Institute membership (*page 1415*).

**Letters to the Editor.** Engineering education and democracy, and synchronous motor effects on induction machines are the subjects discussed in the "Letters" columns of this issue (*pages 1422–3*).

**New AIEE Section.** A new Institute Section recently was organized at Wichita, Kans. This increases the total number of AIEE Sections to 63 (*page 1414*).

**Transformer Reactance.** A mathematical formula for computing the reactance of the interleaved component of transformers has been derived (*pages 1368–71*).

# DISCUSSIONS

Appearing in this issue are discussions of the following papers:

## Education


A Suggested Course on Industrial Economics and Business Methods—Hellmund 1396

Per-Unit Quantities—Travis . . . . . 1399

Fundamental Concepts of Synchronous Machine Reactances—Prentice 1400


## Instruments and Measurements


A New Magnetic Flux Meter—Smith . . . . 1400

A New High-Speed Cathode-Ray Oscillograph—Kuehni and Ramo 1401

Sixty-Cycle Calibration of the 50-Centimeter Sphere Gap—Sprague and Gold 1405


## Insulation Co-ordination


Basic Impulse Insulation Levels—EEI-NEMA Joint Committee Report 1405

Insulation Strength of Transformers—AIEE Subcommittee Report 1406

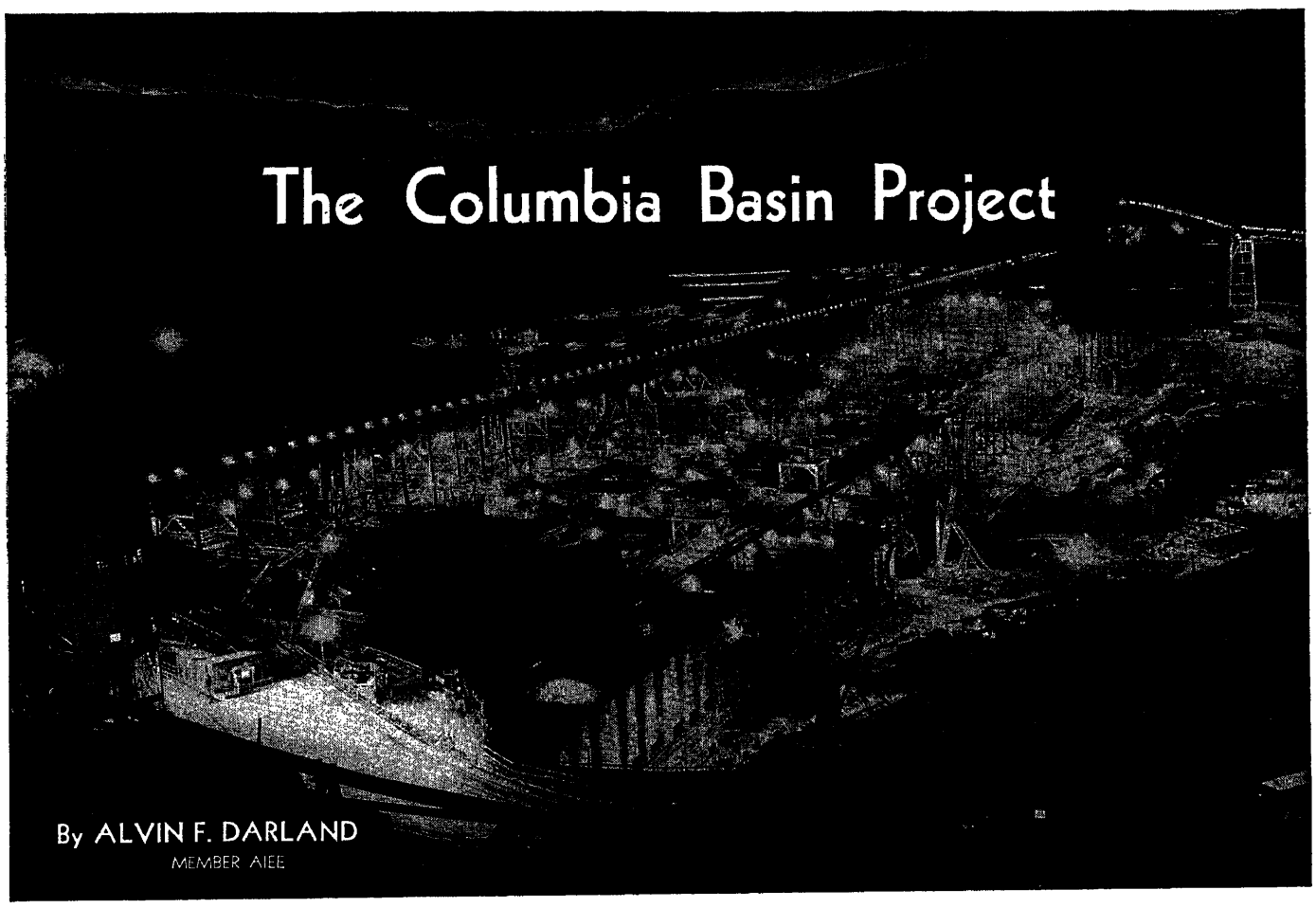
Application of Arresters and the Selection of Insulation Levels—Foote and North 1407

Insulation Co-ordination—Sporn and Gross . . 1407

Application of Spill Gaps and Selection of Insulation Levels—Melvin and Pierce 1408



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# The Columbia Basin Project

By ALVIN F. DARLAND
MEMBER AIEE

**Grand Coulee Dam, now under construction on the Columbia River in the State of Washington, will create a 150-mile lake from which irrigation water for more than a million acres of land will be pumped by part of the power to be generated at the dam. This article describes the purposes of the project, which will not be completed in its entirety for half a century, and the present status of construction of the dam.**

NEAR THE CENTRAL PART of the State of Washington is a pear-shaped body of semiarid land, approximately 85 miles long and 60 miles wide, containing $1^1/_4$ million acres of highly fertile soil, having a long growing season and a moderate climate, but without sufficient rainfall to support agricultural activities. This land, now largely covered with a determined growth of sagebrush and tumbleweed, was settled a generation ago by dry-land farmers who attempted to grow grain. Only a few relatively small areas have succeeded in maintaining anything approaching a successful farming venture. In those areas the key to success is water, available by pumping from a limited subterranean supply or an adjoining lake, or by enough rainfall to enable the harvest of an occasional crop.

Fifty miles to the north of the northern end of the irrigable area, and bordering its full length on the west, the Columbia River flows through a granite and basalt gorge from 300 to 1,500 feet below the level of the parched lands adjoining. The Columbia is the second largest river in the United States in the quantity of runoff, and the largest on the American continent in potential water power. Strangely enough, the Columbia at one time, diverted by a glacier choking its ancient gorge, was forced to carve from basalt rock a new channel some 50 miles long, from 2 to 5 miles wide, and from 600 to 1,000 feet deep, now known as the Grand Coulee. At the lower end of the Grand Coulee the diverted Columbia spread over the lands where the subsequent farming efforts failed because of the lack of water, and these lands today are known as the Columbia Basin. The river returned to its original channel after the glacial barrier melted, leaving the floor of the Grand Coulee 600 feet high and dry above its own restored level, and quitting at the same time its great lake-like channels in the Columbia Basin.

## Preparation of Plans

Two plans proposed for the irrigation of the Columbia Basin were: first, gravity flow from the Clark Fork of the river by way of a long aqueduct; and second, damming the

Essential substance of an address presented at Coulee Dam, Wash., on September 3, 1937, on the occasion of an all-day inspection trip during the AIEE Pacific Coast convention.

ALVIN F. DARLAND is a native of Tacoma, Wash., and received the degree of bachelor of science in electrical engineering from the University of Washington in 1914. In 1923 he became superintendent of electrical construction and design in the public utilities department of the City of Tacoma, and was in responsible charge of the design and construction of 2 hydroelectric plants built by the city. Since 1935 he has been field engineer with the United States Bureau of Reclamation at Coulee Dam, Wash.

river near the head of the Grand Coulee to form a lake back of the dam, and pumping water from this lake into the Grand Coulee, whence it could flow by gravity to the land.

The United States Engineers, acting under authority of Congress, in 1932 submitted a report of a thorough study of these plans as one phase of the report on a comprehensive plan for the economic development of the river for power, irrigation, and navigation, from its crossing of the international boundary between Canada and the United States to its mouth at the Pacific Ocean, a river distance of 750 miles, through which there is a difference in elevation of the river of 1,300 feet. This report recommended the building of the Grand Coulee Dam as the key structure to the development of the power of the Columbia River, and the irrigation of the Columbia Basin by pumping from the lake formed by the dam. The ultimate building of 10 hydroelectric projects on the river having an aggregate capacity of 10,000,000 prime horsepower was recommended. Of these, the Rock Island Dam and power plant already have been built by private capital, while the Grand Coulee and Bonneville dams, the headwater and tidewater projects, are now under construction by the United States Government.

Outstanding attributes of the dam at Grand Coulee were cited as the doubling of the low-water flow of the river, an increase of from 50 to 100 per cent in the output of downstream power developments at low water because of the great storage afforded by the dam, and a reduction (from 635 feet to 295 feet) in the pumping lift necessary to divert water through the Grand Coulee to the Columbia Basin lands. The building of the dam was authorized by President Franklin D. Roosevelt in the fall of 1933 as a public works project, and work was started shortly thereafter under the direction of the United States Bureau of Reclamation; plans for the project previously had been prepared by the Bureau, following investigations and studies extending over a period of years.

## Plan of Development

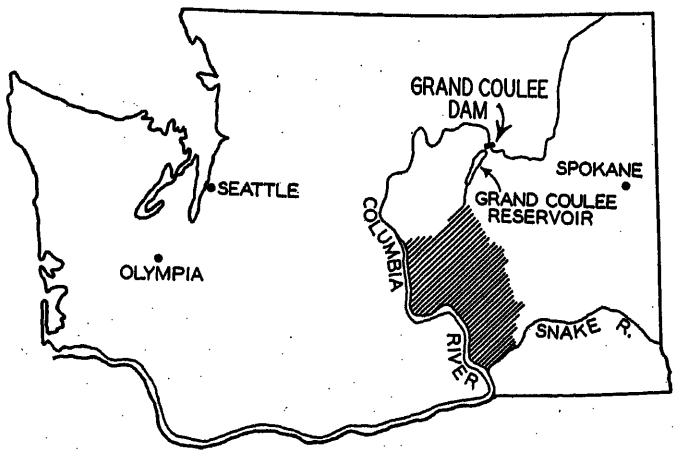
Fundamentally, the plan of development of the Columbia Basin project consists of: a dam across the Columbia River at the head of the Grand Coulee; 2 power plants adjacent to the dam utilizing the hydraulic head created thereby; a pumping plant to lift water from the lake created by the dam to a reservoir approximately 23 miles long, to be developed in the Grand Coulee by the construction of 2 dams, each about 90 feet high and crossing relatively narrow sections of the floor of the coulee; and a distribution system to convey the water from the reservoir to the 1,200,000 acres of land in the Columbia Basin that are to be irrigated.

The dam and power plant are estimated to cost $179,000,000 and to have an annual output capacity of 8,100,000,000 kilowatt-hours of firm power and 5,000,000,000 kilowatt-hours of secondary power. The sale of this power is expected to repay to the United States Government the cost of the dam and power plant, and half the cost of the irrigation system. Irrigation, including the pumping plant, will cost $198,000,000 and will be repaid, half by the revenue surplus from the sale of power, and half by the settlers of the land. The total annual cost to the farmer for the contemplated irrigation is now estimated to be about $5 per acre.

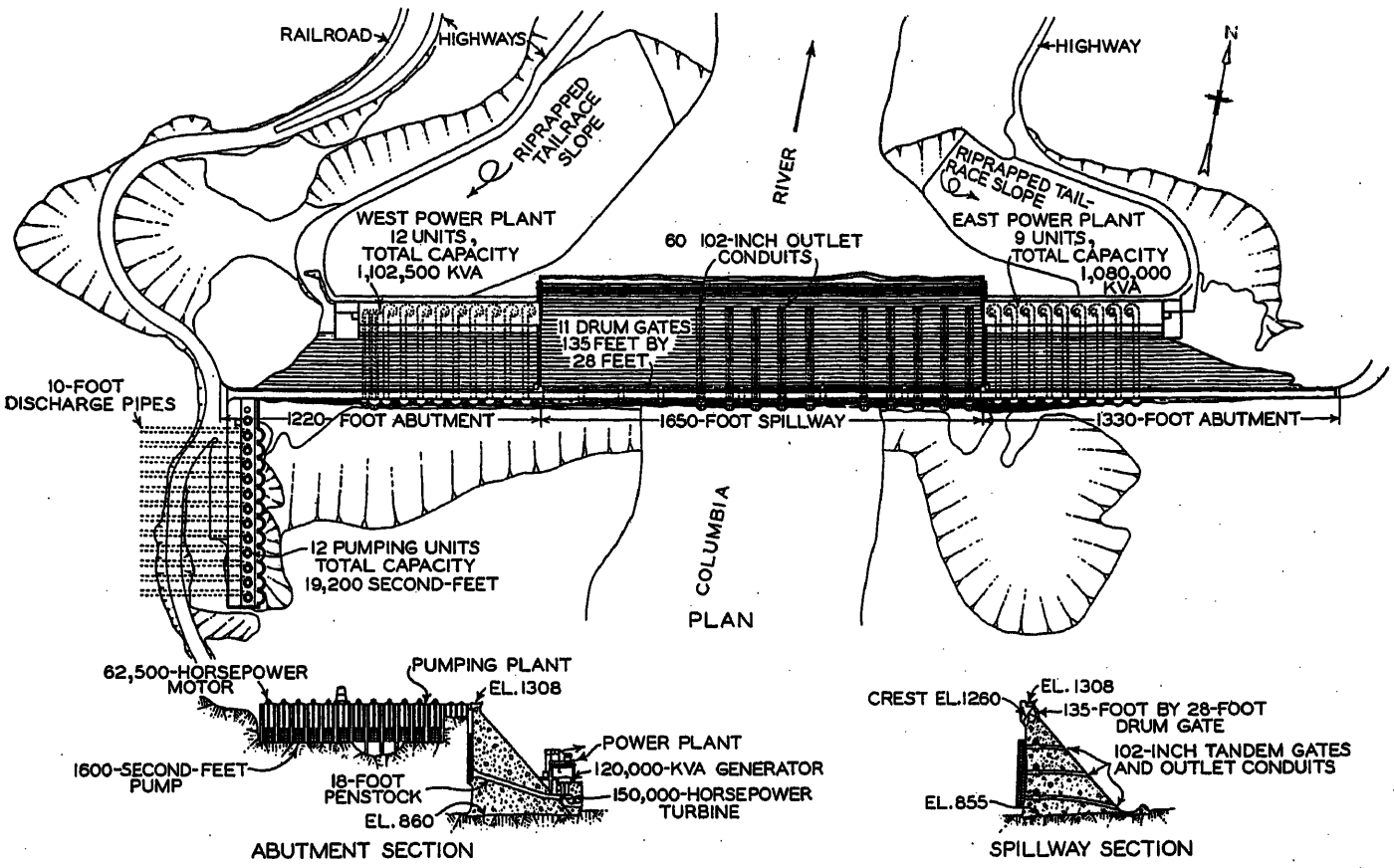
### Dam and Power Plant

Grand Coulee Dam is being constructed upon the granite floor and abutments of the river gorge within a mile downstream from the point where the river was forced to make its glacial detour through the Grand Coulee. The structure, a straight gravity-type dam, will rise 550 feet above the lowest bedrock, will be approximately 4,300 feet long and 500 feet thick at the base, and will raise the river 335 feet, creating a lake 150 miles long reaching the Canadian border and providing 5,000,000 acre-feet of useful storage in the upper 80 feet of the reservoir. The average flow of the river is 109,000 second-feet at the dam site, but during an exceptionally high flow in 1894 is estimated to have reached 725,000 second-feet. A spillway 1,650 feet long with a capacity of 1,000,000 second-feet, and designed to dissipate without damage to the structure 30,000,000 horsepower of hydraulic energy, will be provided in the channel section of the dam. For the construction of the dam and power houses, $11\frac{1}{4}$ million cubic yards of concrete will be required.

A power plant having 18 120,000-kva main generating units and 3 7,500-kva station-service units is contemplated for the ultimate development, 9 main generating units to be in a power house to be constructed adjacent to the dam at its easterly downstream face, and the rest to be in a similar power house at the west end of the dam. The initial installation will consist of 3 main generating units and 2 station-service units. Additional units will be installed as irrigation and power-market requirements justify them. It is anticipated that power generating capacity of the project over and above that required for pumping of irrigation water will be absorbed within a 15-




**Outline map of the State of Washington, showing the location of Grand Coulee Dam; the cross-hatched portion is the approximate area to be irrigated**




**Grand Coulee Dam and appurtenant works**

year period after completion of the dam and initial power development, but the development of the irrigation phase of the project is expected to continue for a much longer period.

IRRIGATION SYSTEM

The pumping plant, which will lift the irrigation water from the lake to the reservoir in the Grand Coulee, will be constructed on a granite bedrock shelf upstream from the west end of the dam. The plant will have a rated capacity of 16,000 second-feet of water, and an installed capacity of 19,200 second-feet in 12 pumping units. Each pump will be rated at 1,600 second-feet and will be driven by a 62,-500-horsepower motor, 2 such pumping units to be operated by the output of one main generating unit at the west power plant. The irrigation water diversion will amount to slightly more than a seventh of the average flow of the river, and will require the power output of 5 main generating units totaling 600,000 kva for pumping. The flood stage of the river is during the irrigation season, a fact of importance to this project.

Water from the pumping plant will be conducted through penstocks to a canal, which will connect with the irrigation reservoir in the Grand Coulee. Two relatively small dams will be constructed to close the 2 ends of the upper 23 miles of the Grand Coulee, so that water may be stored to a depth of about 70 feet and in a useful amount of 339,000 acre-feet above the elevation of the outlet to the distribution system.

A main canal from the southerly end of the irrigation reservoir at a point 11 miles farther south, will branch into a main east canal and a main west canal, the former to be 156 miles long and the latter 101 miles long. These 2 canals practically will encompass the irrigable lands of the basin. A system of lateral and distribution canals will finally convey water to 40-acre units of the project. During the irrigation season, it is estimated that an average of 40 inches of water can be supplied to the land, whereas the mean annual precipitation for the area is but 8.2 inches, and the rainfall during the irrigation season is only 3.6 inches.

## Construction

During somewhat more than $3\frac{1}{2}$ years since the fall of 1933, work accomplished on the project represents a cost equal to approximately half the expenditure necessary to construct the dam (not including power development). The base of the dam has been built out from the west abutment to the original west bank of the river, and within this portion of the dam have been left multiple channels through which the river now flows while the building of the dam from the east abutment proceeds out across the old channel of the river to join that portion of the structure on the west side of the stream. This work has necessitated the building of 2 systems of cofferdams, the excavation of earth overburden amounting to 20,000,000 cubic yards, foundation rock excavation of 1,000,000 cubic yards, and

the placing of more than 3,900,000 cubic yards of concrete to October 1937. Incidental to the principal work of the project has been the building of the towns, both on the project and adjacent thereto, for the housing, care, and entertainment of more than 6,000 workmen, who with their families have brought approximately 15,000 people

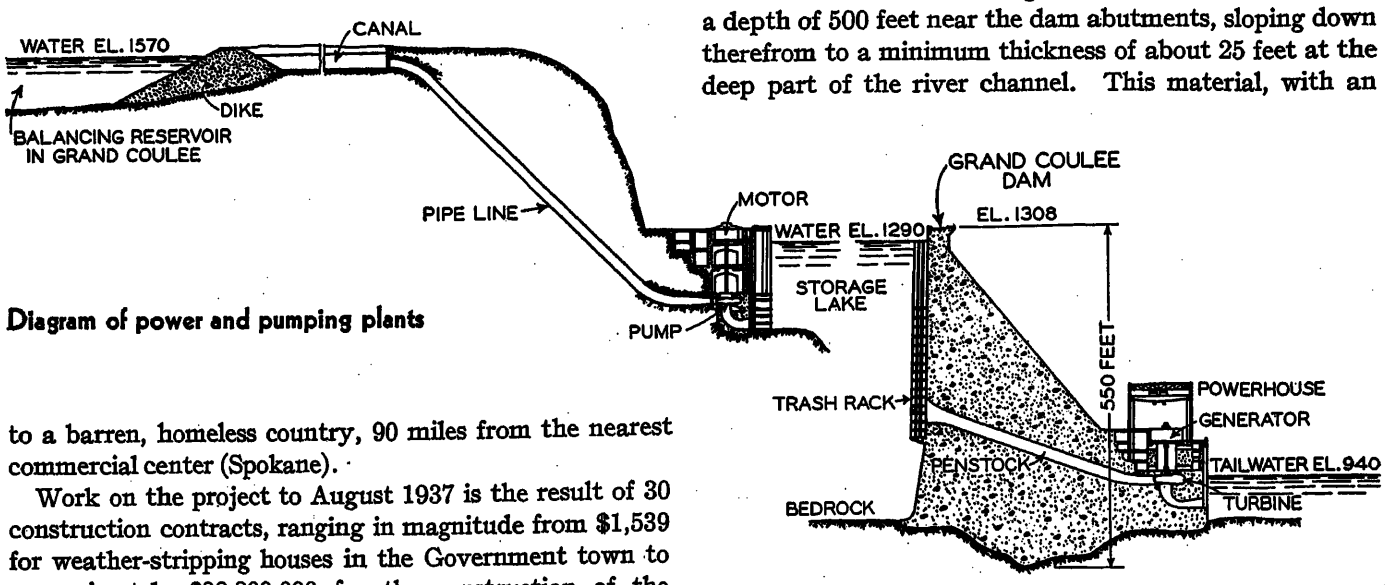



**Diagram of power and pumping plants**

to a barren, homeless country, 90 miles from the nearest commercial center (Spokane).

Work on the project to August 1937 is the result of 30 construction contracts, ranging in magnitude from $1,539 for weather-stripping houses in the Government town to approximately $38,800,000 for the construction of the base of the dam and foundations for the 2 power houses. This latter, the principal contract of the project and the only one not yet completed, is held by the Mason-Walsh-Atkinson-Kier Company, a company organized by 3 previously independent contracting firms for the purpose of providing financing and equipment adequate to conduct operations on the large scale necessary at Grand Coulee Dam. In addition to the construction contracts, many others have been made for construction materials, the Government furnishing materials and equipment that become a permanent part of the dam and power plants.

The Mason-Walsh-Atkinson-Kier Company is within a few months of the completion of work included under its contract, which comprises briefly the building of the electrically heated Mason City, the contractor's town; most of the excavation required for the dam and power houses; the diversion of the river; and the manufacture and placing of about 4,500,000 cubic yards of concrete, which represents about 40 per cent of the concrete required for the completed dam.

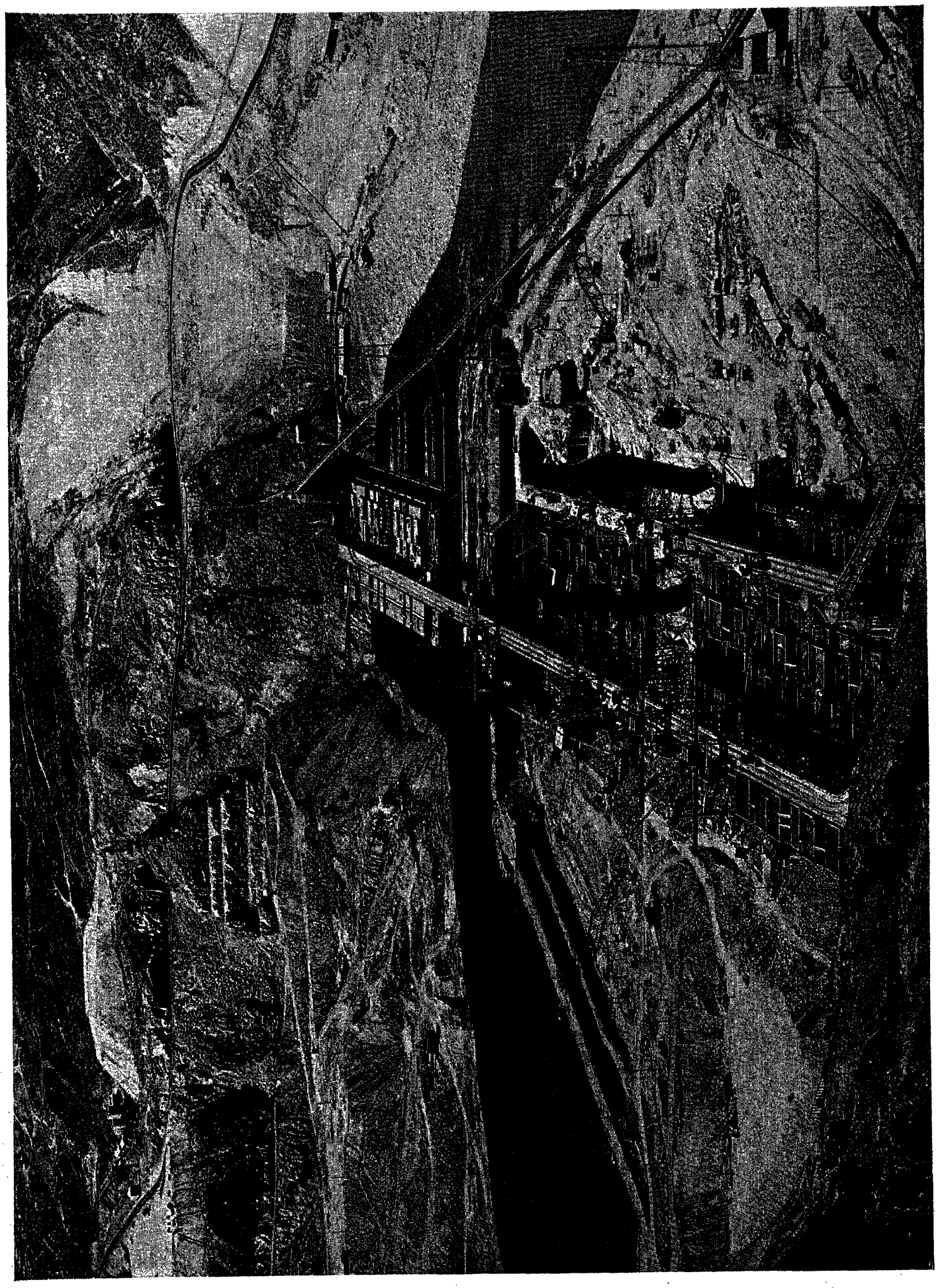
Mason City at present has a population of 300 families and 1,200 single men in semipermanent houses and dormitories, and a population of 400 men in tents. The homes and dormitories, general store, recreation hall, hotel, theater, messhalls, and company office buildings are all electrically heated, comprising a connected electrical load of 8,500 kw, all of which is active during the cold-weather months. When this condition occurs, however, weather conditions are so severe that the electrical load from construction activities is greatly reduced, and an almost uniform power demand results. Peak power demand of the project has been 14,000 kw. Power is supplied by the Washington Water Power Company at a 110-kv switching station in Coulee City, 30 miles from the project, and is transmitted therefrom by the contractor to the site of the work over a single-circuit 110-kv line.

### Excavation for the Foundation

The silt bed on the granite floor of the river gorge, placed during the existence of the glacial lake at the time of the diversion of the river through the Grand Coulee, reached a depth of 500 feet near the dam abutments, sloping down therefrom to a minimum thickness of about 25 feet at the deep part of the river channel. This material, with an occasional glacial deposit of sand and gravel, was removed by a battery of electrically operated power shovels, dumping into trucks and tractor-drawn buggies which ranged in capacity from 12 to 30 cubic yards; these in turn dumped onto a system of belt conveyers, likewise electrically operated, reaching to a canyon a mile away from the dam site and having a daily capacity of 48,000 cubic yards of excavated material. Operation of these belts required 5,000 horsepower of electric energy.

Bedrock excavation necessary to remove weathered rock and shape the granite floor and abutments in a manner suitable for foundation purposes has required excavation of about 1,000,000 cubic yards of rock over an area of 38 acres. Blasting of bedrock was permitted only with light charges of dynamite in relatively shallow, closely spaced holes, in order to minimize disturbance to sound bedrock uncovered by the removal of weathered rock. The excavated rock was hauled by trucks since the belt conveyers were unsuited to this type of material, and

**(Right). A view of the dam, looking west. High- and low-level construction trestles each have a battery of 5 traveling cranes. The suspension bridge carries a belt conveyer that delivers sand and gravel to a concrete-mixing plant at the west end, and a pipe line that delivers cement to a mixing plant at the east end. A 50,000-barrel cement storage and blending plant may be seen at the upper left, where 60 carloads of cement are unloaded daily and blown by air through pipe lines to the mixing plants. The completed dam will reach the elevation of the highway in the background**

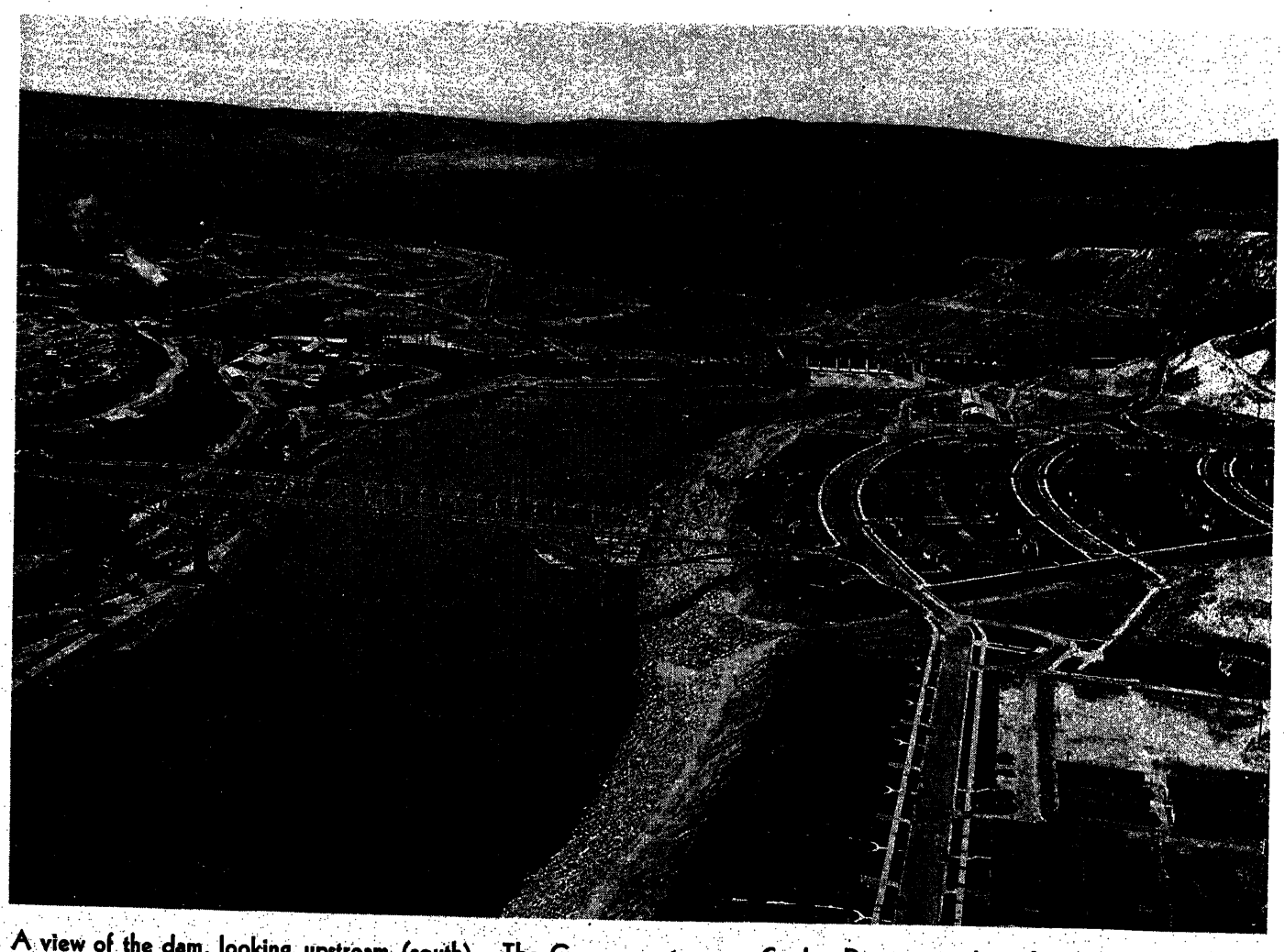


much of it used in riprapping the tailrace and river slopes downstream from the dam. The granite floor of the dam is generally quite level, except for 3 secondary gorges across its floor that reach depths of 100 feet below the general level. The quality of the final foundation rock ranges from good to excellent granite, superior in all cases to the best concrete that can be produced. A curtain of cement grout to seal the contraction and structural joints in the bedrock will be injected in an approximately vertical plane parallel to the axis of the dam and under its upstream portion throughout the full length of the structure to depths as great as 300 feet, and with a thickness at right angles to the axis of about 100 feet.

### Diversion of the River During Excavation

The excavation on both the east and west sides of the river was carried to bedrock elevations as much as 200 feet below the water surface of the river. Two cofferdams were built to enable this excavation. The first of these, constructed during the winter of 1934–35 on the west bank of the river, was a bow-shaped structure, about a half mile long, with a central section parallel to the river channel, and the wings cutting into the silt banks of the stream. This structure employed in its building 17,000 tons of interlocking steel piling, and attained a height of 100 feet, sufficient to safeguard operations for a river rise of 55 feet above the low-water flow of the stream. The second cofferdam was constructed during the fall of 1935 on the east side of the river, and was of a shape similar to the west cofferdam, but employed timber rather than steel piling and was built only to an elevation sufficient to withstand a river rise of 30 feet above low water. This structure was topped by the river as anticipated, and work within the east cofferdam was suspended during a period of 3 months in the summer of 1936. Both the west and east cofferdams were unusually tight and but little pumping because of leakage was necessary, a condition resulting from the adequate designs by the contractor and the generally tight nature of the silt deposits over the old lake bottom.

Following completion of bedrock excavation within the west cofferdam, construction of the dam and west power house was started in the fall of 1935. About 1,500,000 cubic yards of concrete has been placed in this portion of the structure. This section of the dam contains the temporary diversion channels through which to detour the river from its original channel, and was completed to a stage of construction necessary to enable opening of the west cofferdam to the river in November 1936. In the



A view of the dam, looking upstream (south). The Government camp, Coulee Dam, is on the right side of the river; the highway bridge leads to Mason City. The river is shown at about the stage of average flow

meantime, construction had been started on the shore arms of the upstream and downstream main river cofferdams to close the river channel and enable its unwatering for construction purposes. These 2 structures were built of timber cribs rock filled and armored with a single row of interlocking steel piling driven to refusal. The cross-river cofferdams were joined to useful portions of the original west cofferdam, which portions were joined in turn to the upstream and downstream faces of the west section of the dam in such a manner that the diversion channels were west of the junction points. This arrangement exposed the east end of the west section of the dam within the enclosure formed by the main river cofferdams. Completion of these structures and the full diversion of the river through the west section of the dam were accomplished in December 1936. Removal of overburden and foundation-rock excavation had advanced from the east abutment within the area enclosed by the east cofferdam and concreting operations had been started prior to the diversion of the river. When the diversion was accomplished, and the old river channel unwatered, these operations successively advanced across the channel to meet the west section.

### Improved Methods

The successful conduct of construction work on the huge scale demanded by the physical and economic factors at Grand Coulee Dam has naturally resulted in superlative accomplishments. Here during the excavation period, for instance, was the world's largest conveyer system; now there are in operation the largest concrete aggregate preparation plant, the largest concrete mixing plants, and the greatest assembly of concrete placing equipment ever on a single construction job. The acceleration of construction rates has been accompanied by the adoption of improved methods with more consistent and uniform results than heretofore have generally been achieved. An illustration of this is the high quality of the concrete going into the dam. The average compressive strength of 3,214 28-day test cylinders, 6 by 12 inches, taken at the mixing plants from mass concrete for the dam and dry screened to $1^1/_2$-inch maximum aggregate, was 5,545 pounds per square inch, with a very high uniformity factor. Mass concrete contains one barrel of cement per cubic yard. Concrete has been placed at a rate of 15,500 cubic yards per day and it seems probable that this record may be extended to 18,000 cubic yards per day before work is completed under the present contract.

### Control of Slides

Unexpected difficulties have been experienced because of landslides of the lake-bed silt deposits from the granite side walls of the river gorge into the excavation area of the dam and power plants. Two major slides have occurred, one on the west side where about 1,000,000 cubic yards of material moved toward the power house and tailrace sites, and a second on the east side of the gorge, that moved into the forebay and dam excavation. The additional excavation occasioned by these slides amounted to 1,500,000 cubic yards of material and necessitated the construction in the west slide area of a drainage system and a rock barrier at the toe of the slide to a height of 120 feet above the level of bedrock, with a ballast blanket consisting of 225,000 cubic yards of gravel spread on the slopes of the slide above the barrier. A complete cure was necessary to prevent the slide moving into the tailrace and turbine discharge outlets of the power house.

The east slide was directly into the largest depression crossing the granite floor forming the foundation of the dam. Although movement of the slide subsequent to the construction of the dam could do no damage, about 500,000 cubic yards of slide material had to be removed to enable the complete excavation of the depression and the placement of concrete. Considerable additional excavation was avoided by the construction of a temporary barrier across a neck of the depression at a point just outside the upstream limit of the dam, to prevent further movement of the slide during the time required to fill this depression with concrete.

Before this land slide started, a concrete arch about 25 feet high, topped by a timber crib 15 feet high, had been constructed across the neck of the depression. As the slide became active, these structures were buried under the toe of the slide, which at this point was about 100 feet deep above bedrock. The slide was temporarily stabilized by the removal of the surcharge from its fan-shaped upper portion. A refrigeration plant of 80 tons capacity was rented and erected at a nearby site, and pipes through which brine could be circulated were driven into the slide. An earth-ice arch 100 feet long, from 20 to 25 feet thick, and from 42 to 50 feet deep was frozen directly over the concrete arch and timber crib submerged by the slide, and this composite structure of concrete, timber, and ice proved to be an adequate barrier to further movement of the slide and enabled the necessary excavation for the dam to be completed, and subsequent phases of the work to proceed without interruption. The dam was frozen in September 1936 and was abandoned in April 1937.

## Plans for Completion of the Project

Plans and specifications are now being prepared in anticipation of a contract to provide for the completion of the dam and west power plant building, funds to continue with the construction program having been appropriated by Congress. If future appropriations are adequate to continue at the construction rate established for the work now accomplished, the dam could be completed and the initial power-plant installation ready for operation by 1941. Surveys are in progress in the irrigable area to enable the planning of the system of canals and aqueducts necessary to convey Columbia River water to the lands of the Columbia Basin. There is a growing and insistent demand for irrigated land, and it now appears likely that the 50-year period for combined irrigation construction and land settlement originally contemplated for this project may be materially shortened. The lands, when irrigated, will provide from 30,000 to 40,000 new farm homes and an equal number of homes forming urban communities of the project.

# Recent Progress in Insulation Research

By J. B. WHITEHEAD
PAST PRESIDENT AIEE

**Another in a series of annual reports presented by the chairman of National Research Council's committee on electrical insulation, this article summarizes some of the principal advances in research work on gaseous, liquid, and solid dielectrics during the past year. References are included to both fundamental scientific studies and practical research under service conditions.**

RESEARCH in the field of dielectrics and insulation is broadly speaking of 2 general types. The first is that of fundamental scientific character in the fields of chemistry and physics. There is a constant flow of the results of studies of this type in the field of dielectrics, gaseous, liquid, and solid; and as related to their various properties, dielectric constant, electric conductivity, and breakdown. Intense interest attaches to the slow but steady unfolding of the picture of atomic and molecular structures, and of the phenomena associated with the movements therein of electric ions of various character. Unfortunately, however, it is not always possible, by reason of our inability to control the forces and extend the laws so discovered to large-scale conditions, to apply the results of this type of research to the construction and behavior of everyday insulation.

The second type of research is that in which effort is made to develop directly under the conditions of normal service improved materials and methods for insulation. Such efforts watch more or less distantly the progress of fundamental scientific research and are quick to grasp and try out on a practical plane any new discovery or suggestion. Thus, while they often have a cut-and-try character, and in this sometimes suffer criticism in comparison with more fundamental types of research, it nevertheless remains a fact that a large proportion of the advances that have been made in the improvement of electrical insulation have been through researches of this character.

Obviously both types of research are very much the concern of the committee on electrical insulation, of the National Research Council, and this review includes notices of the principal advances during the past year which have come to the writer's attention. It includes reference to a number of researches of the first type in which there is a definite interest as related to the problems of insulation, even though sometimes remote. On the other hand, the review makes no pretense of covering completely the large volume of important research of the first type which has appeared.

## Gases

From the standpoint of insulation, first interest for gases attaches to conductivity and breakdown. Most of the new work during the year has been on breakdown in air. Some of it is purely practical in character, other continues the study of the process leading from initial ionization to self-supporting spark or arc discharge. This problem continues to hold the interest of both physicists and engineers; of the former because of the light thrown on gaseous structure and submolecular behavior; of the latter because of the obvious bearing on the mechanism of the spark and arc and of various types of protective equipment.

The use of the spark gap in its various forms as voltmeter is reviewed by W. M. Thornton.[1] Best methods and empirical formulas are suggested for needle gaps, sphere gaps, plane electrodes, the corona voltmeter, the attracted-disk electrometer, the ellipsoid voltmeter, the capacitance divider, etc. K. Potthoff[2] continues a series of papers developing the relationship between corona loss as measured on laboratory equipment and the losses which occur in overhead lines. Comparative results on the laboratory equipment, consisting of wire and coaxial cylinders, and those observed on 3-phase open lines show fairly good agreement. E. Horst[3] reports an extensive study of the time constant of capacitors. The time constant in general decreases with increasing voltage, and a wide range of values is found for commercial capacitors. This author believes that the residual phase difference in air capacitors is due principally to leakage over the insulating supports rather than to radiation and electrode surface phenomena.

Of more fundamental character are a number of studies on the breakdown of gaps of various lengths and under different conditions. R. Strigel[4] reports (from the Siemens laboratories) studies on the spark lag in a uniform field and in the field between points. From the same laboratories is a study by Von Engel and Steenbeck[5] on the rôle of the positive ions in a gas discharge. All of these papers discuss the mechanism of the setting up of preliminary and then final complete discharge, with particular reference to the influence of the space charges due to the more rapidly moving electrons and the sequence of happenings leading up to the avalanche of electrons. A clear picture is drawn of the growth of the electronic avalanche introducing as new element the electrostatic force

Part of the annual report of the chairman of the committee on electrical insulation, division of engineering and industrial research, National Research Council, presented during the 10th annual meeting at New York, N. Y., November 4–5, 1937.

J. B. WHITEHEAD, professor of electrical engineering and, since 1919, dean of the school of engineering at The Johns Hopkins University, Baltimore, Md., has been a member of the faculty of that university since he was appointed associate professor of electrical engineering in 1904. He received his first degree in engineering from Johns Hopkins in 1893, and subsequently received those of bachelor of arts and doctor of philosophy. Doctor Whitehead was the founder of the Institute's Baltimore Section, and was its chairman for 19 years. A Life Member, he has served on many committees and on the board of directors, and was president during 1933–34. He is now a junior past president and a member of the committees on code of principles of professional conduct, Edison Medal, and Institute policy, and representative on the John Fritz Medal board of award and National Research Council, division of industrial and engineering research. He has been chairman of National Research Council's committee on electrical insulation since 1923.

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on the electron caused by space charge, and the setting up of an accelerating force greater than that caused by the external field. The necessity for such additional force is shown by measurements indicating very high ionic mobilities. A. Köhler[6] studies the impulse breakdown at pressures between 100 and 760 millimeters of mercury in uniform fields. He shows that for both alternating and impulse voltages down to 4 milliseconds duration, Paschen's law is confirmed down to 100 millimeters for dry air, but not for air containing moisture. The cathode-ray oscillograms clearly indicate a break in the descending voltage curve after breakdown, which is attributed to the passage from spark to glow discharge. E. Finkelmann[7] studies the breakdown of different gases at high pressures up to 20 atmospheres; in homogeneous fields in gaps up to 2 centimeters, and in coaxial cylinders in gaps up to 4 centimeters. The gases studied are oxygen, carbon dioxide, air, and hydrogen. The departures from Paschen's law already recognized for small gaps are also found for large gaps. They begin at higher voltages, the greater the gap; and for different gap lengths at approximately the same field intensity, the value of the latter varying with the gas. The departures are attributed to space charges and consequent electron emission from the cathode. On account of the smaller increase of breakdown voltage of oxygen, as compared with that of carbon dioxide, the latter is to be preferred as an insulator in high-voltage practice. H. Böcker[8] studies the well-known lowering of breakdown voltage at high frequencies. The commonly accepted cause is that at a certain critical frequency during a reversal of the electrode voltage, positive ions accumulate as space charge. A limitation of the space charge is set by the rate of diffusion. Starting from this condition, the author computes the density of space charge necessary to account for the actual field distortion and derives a formula for the lowering of voltage at higher frequencies. This formula is closely similar to that for the lowering of static continuous voltage as computed by Rogowski and Wallraff.[5a] The decrease of breakdown voltage with frequency above the critical value so computed is in good agreement with the experimental results.

Outstanding contributions in this country to our knowledge of all forms of gaseous discharge are made by L. B. Loeb and co-workers.[9] In an admirable review of the mechanism of static spark discharge Loeb not only reports much work of himself and co-workers, but makes a comparative study of the significance of the results of others. The beginning of any type of discharge at ordinary air pressure is due to the collision of electrons with molecules and the liberation of further electrons, in accordance with Townsend's theory. The presence of electrons is necessary and there is always a sufficient number due to external causes to start matters. This is called by Loeb the primary process of ionization. The resulting current of itself does not usually lead to a spark, but as the applied field is increased the increase in current may become very rapid. An unstable condition results in which the current readjusts itself so as to become self-maintaining, that is, it changes to glow discharge, brush, spark, or arc. In order to reach this self-maintaining condition the ionization current must develop a mechanism by which new electrons are generated in sufficient number; that is, some new or secondary ionization process must arise. Loeb lists at least 5, and including very low pressure, 6 mechanisms of self-maintaining character by which spark discharge can occur. Among these are, in the gas itself, ions and atomic excitation by electron impact, ionization by positive-ion impact in the gas, photoelectric action in the gas, and at the cathode electron bombardment, positive-ion bombardment, photoelectric effects, and the so-called field currents, all leading to increased electron emission. Of special interest is the conclusion that under ordinary conditions ionization in a gas by positive-ion impact, as first suggested by Townsend, does not enter into the sparking equations. The most common secondary influences are the liberation of electrons at the cathode by positive-ion impact, and with photoelectric electron liberation at the cathode and in the gas. An influence of metastable atoms is noted in certain special cases, for example, low-pressure corona; also with sufficient initial ionization high local fields may be caused by space charge, leading directly to spark. The essential conclusion of Loeb's analysis is that there is no single definite secondary process which occurs universally in all discharge phenomena, but that depending on the particular circumstances, usually one or 2 of the secondary influences mentioned predominate to the exclusion of others. Other interesting experimental studies from the same laboratories, some of which are utilized in Loeb's analysis, are those of R. R. Wilson[10] on very short time lag in sparking, that of D. Q. Posin[11] on the Townsend coefficients, that of Cravath and Loeb[12] on the mechanism of the high velocity of the lightning discharge. In connection with the latter, one of the difficulties has been that the leader lightning stroke moves faster than any possible electronic velocity. "Calculations based on justified assumptions concerning the conditions known to exist in a lightning stroke show that if the field just ahead of the tip averages $10^5$ volts per centimeter for about one centimeter, ionization by collision by the electrons already present in the gas before the stroke would be great enough to advance the tip at the observed rate. In this way a propagation of the leader stroke at a velocity many times higher than the velocity of the electrons can be attained."

## Liquids

As is usual, work in this field is very voluminous. Liquids are more readily controlled, purified, and offer more uniform molecular structure than solids, and so offer themselves more readily for fundamental research. Entering as they do into many types of insulation, they also appeal to the research engineer.

To the engineer, the most interesting properties are dielectric strength and conductivity; to the physicist and chemist, dielectric constant is more important for the study of molecular structure. Theories of dielectric strength and breakdown take a wide range. The Schumann-Nikuradse theory of breakdown ties in the current-voltage characteristic in much the manner as now accepted for gases, and sees failure as an internal collision

ionization phenomenon. Koppelmann and Gyemant invoke an electrode layer of high stress due to space charge acting on a layer of adsorbed gas, thus creating gas pockets or filaments leading to gaseous ionization and breakdown. Pure electric breakdown is apparently due to electronic collision ionization and is recognized only in the purest liquids. Thermal breakdown on the other hand, due to the liberation of gases by heating in impure liquids, is also evident in many cases. From the variety of conditions which are suggested in the work supporting these several theories it may be easily seen that the approach to pure electric breakdown occurs only under conditions in which the liquid and electrodes are most carefully purified, conditions which cannot be approached for large scale use. Breakdown in liquids prepared under the best manufacturing conditions is commonly of thermoelectric character, with gas evolution and gas breakdown as the final stage. The following brief notices of recent work in this field for the most part support this view. W. Bahre[13] reports a careful series of observations on the breakdown strength of liquid and solid benzol. The outstanding feature is the extreme elaboration, over a period of months, of methods of purification. Under the final test conditions breakdown strength of the liquid reached the high value of 1,870 kilovolts per centimeter and solid benzol 1,000 kilovolts per centimeter. In each case the peak value of a wave was the determining factor, indicating electric breakdown. The very smallest amounts of added impurities lowered the dielectric strength and increased the influence of the effective rather than the maximum value of voltage, indicating entrance of thermoelectric influence. Careful studies of the influence of drying and degassing supported in general the Koppelmann theory. Working in the same field, R. Bredner[14] studies toluol, chloric benzol, nitrobenzol, and benzol, as regards both dielectric strength and loss. Similar care was exercised for purification and similar evidence adduced that for toluol in this state, breakdown cannot be thermal in character. It is shown to be independent of the rapidity of voltage increase and independent of the pressure. On the other hand, the values for chloric benzol and nitrobenzol were much lower and gave evidence of thermoelectric failure, although breakdown was still independent of pressure. Here then is a case in which thermoelectric failure seems to take place without special reference to gas formation, thus indicating the Nikuradse type of breakdown. A. Walther and O. Tscheljustkino[54] conclude that the characteristic dependence of electric strength on pressure in liquids occurs only when the gas is in emulsified form. Liquids in which the gas is completely dissolved have electric strength independent of pressure.

Of special interest as related to the foregoing are 2 papers by E. Conradi[15,16] on the breakdown behavior of commercial insulating oils. He finds the following behavior: (*a*) As delivered, from 25 to 50 kilovolts per centimeter; (*b*) after filtration, from 75 to 125 kilovolts per centimeter; (*c*) 3 millimeters vacuum, 100 degrees centigrade, 12 hours, from 120 to 150 kilovolts per centimeter; (*d*) special filtration and 3 millimeters vacuum, 100 degrees centigrade, 12 hours, from 160 to 200 kilovolts per centimeter; (*e*) 3 millimeters vacuum, 240 degrees centigrade, and direct distillation, from 200 to 245 kilovolts per centimeter. Rotating a commercial oil in a circular channel between high-voltage electrodes, at a certain velocity dust and fiber particles are swept out and a breakdown stress of 150 kilovolts per centimeter is reached, an increase of upward of $33^1/_3$ per cent, and the spread of test points is reduced to 7 per cent or 8 per cent. Combined with a specially constructed electric filter, this method increased the low breakdown strength of badly deteriorated oil to 150 kilovolts per centimeter. Fibers and dust particles cause breakdown; thermal breakdown pertains to intermediate ranges of purification; and the pure electric breakdown enters only under extreme purification. Further interesting data are presented by F. M. Clark[17] on the properties of noninflammable synthetic insulating oils of the chlorinated diphenyl type. An advantage in favor of the synthetic liquids and insulation treated therewith of at least 20 per cent over corresponding mineral-oil values is claimed.

## Oxidation

Studies of the oxidation process in insulating liquids have also continued. A. Gemant[18] proposes a rapid and simple approximate method for relative oxidation rates, based on the decrease of volume of the gas over the oil in a closed vessel. The claim is that for the better oils the contribution of volatile products of oxidation may be neglected. J. F. Gillies and J. B. Black[19] reach the conclusion that dielectric strength and power factor of transformer oil are not affected in the early stages of oxidation, nor until heavier asphaltine products begin to be formed. Similar conclusion by different methods is reached by J. B. Whitehead and T. B. Jones[20] as reported at the present meeting of this committee. G. M. L. Sommerman[21] reports results of tests on 9 viscous mineral oils of various types and their mixtures with 8 rosins. Interesting correlations between physical and electrical properties, stability in oxidation, with the viscosity index and chemical composition are reported. J. B. Whitehead and F. E. Mauritz,[22] working with a single insulating oil of high quality, have shown important correlations between changes in electrical properties, and those of several oxidation products. P. J. Haringhuizen and D. A. Was[23] report welcome quantitative measurements of the catalytic action of metals on oils. The samples were treated for 1,000 hours at 90 degrees centigrade in the presence of thin layers of copper, lead, and tin. Copper formed the most sludge, lead next, and tin least. In two of the oils contact with tin gave less sludge formation than in a blank specimen, thus suggesting an antioxidizing value. Studies of the acid number indicate that the action of copper is at first the most rapid, but that after a time the acid number becomes constant while that caused by lead finally rises above those of both copper and tin, approaching a constant value of 7. It is suggested that catalytic action in all these cases is limited, due to the accumulation of protective products on the metals. T. Itoh and Y. Hyraki[24] report methods for the recovery of badly deteriorated oils by evacuation and distillation. Claim is made that the

recovered oils were superior to the original oils, and that the volume recovered is better than 93 per cent.

Results by A. Lasarev and J. Raschektaev[25] conclude that the electric conductivity of oils polymerized by oxidation depends only on the mobilities of the ions and on changes in the macroscopic viscosity. The effect of increased temperature is to increase the decomposition of secondary associated complexes. It is stated that the Debye dipole theory adequately accounts for the temperature changes of the dielectric losses of those polymers and oxides examined, and other interesting suggestions are made.

### Gas Generation

The generation and absorption of gas in insulating oils subjected to electric discharge has been studied by Nederbragt,[26] whose results show a wide variation in volume of gas liberated over a range of oils. Of special interest is the reduction of the amount of gas evolved by the addition of selected aromatic compounds. No general formula is proposed, but the author concludes that the volume of gas generated depends on the nature of the most volatile components of the oil, and that in general the gas evolved may be substantially reduced by small percentages of aromatics, more volatile than the oil itself. In these experiments the gasifying agency is merely the layer of ionized gas or vapor over the oil, the field being roughly parallel to the surface of the oil. The nature of the action is not suggested, and should be a promising problem for further study.

### Conduction

Studies of conductivity at high stress in insulating liquids are as follows: In experiments on carefully distilled toluene, E. B. Baker and H. A. Boltz[27] claim to have demonstrated the presence of thermionic emission at ordinary temperatures from cathodes in contact with dielectric liquids. The current-voltage relations found obey, in the upper range of field strength, a law which is interpreted as being a modification of the Schottky law in vacuum. Differences are found amongst curves for adsorbed oxygen and hydrogen on electrodes of several metals and explanations offered on the basis of variations in the work function of the metal. They contrast their results with the commonly accepted view that residual conduction in dielectric liquids is due to ions initially present, formed by some ionizing agent or electrolytic dissociation. An interesting feature of the results is that the slope of the current-voltage curve of the liquid becomes less steep in the upper range. The theory of secondary ionization, as described by Nikuradse, calls for log $I$ increasing directly as the field whereas the Schottky law calls for a log $I$ variation as the (field)$^{1/2}$.

Closely related to the foregoing is the work of K. H. Reiss,[28] on ionization by intense ultraviolet radiation in highly refined liquids. The author concludes that the rise in the current-voltage characteristic of highly refined insulating liquids above the saturation value is not due to ionization by collision, as proposed by Nikuradse, nor to cold thermionic emission, as proposed by Baker and Boltz.[27] The chief experimental evidence against ionization by collision is in the observation of the increase of current over normal saturation and rising current regions, as between the nonirradiated and the irradiated conditions. The increase in conductivity due to the ionization by ultraviolet radiation was found to be constant up to 200 kilovolts per centimeter, that is, well above saturation. In other words, the large increase in the number of ions due to ultraviolet radiation did not cause any increase in the ionization by collision. Cold electron emission was eliminated by experiments with the electrode irradiated by ultraviolet radiation. A very small increase of current was noted at low field strengths, but for increasing voltage the increasing curve merged with the normal curve of the liquid. The increase of conductivity with stress is attributed by the author to the phenomenon discovered by Wien and Schiele of an increase of field strength in weak electrolytes, arising in dissociation at higher voltages. Particular support for this view is found in measurements on the mobilities of the ions which are found to be much lower than those of electrons involved in avalanche and secondary ionization processes. The author concludes that breakdown in insulating liquids at values below 400 kilovolts per centimeter can be caused only by the liberation of gas, thus supporting the Koppelmann view. Ionization phenomena in liquid hydrocarbons are also studied by C. Bialobjeski[29] utilizing X rays. He shows 3 kinds of ions, of which two are positive and the other negative. He makes studies of mobility and coefficients of recombination. Commenting upon Nikuradse's theory of the relation between the current-voltage characteristic of a liquid, and its approach to breakdown, Y. Toriyama and U. Shinohara[30] have measured the impulse breakdown voltage of distilled water and several aqueous solutions. In particular, they point to the case of a solution of $NH_4OH$, in which the breakdown voltage is greater than that for distilled water, although the conductivity of the solution is 7.5 times greater. They claim, therefore, no direct relation between the current-voltage characteristic and breakdown and that the latter is an electronic rather than an ionic conduction phenomenon.

## Solids

Owing to the complexity and wide range of type of conduction processes in solids, and to the difficulty of securing strict uniformity in bulk, research in the field of solids, as directed to their properties as insulators, is still of a broadly general character. Nevertheless much progress has been made, some of it recently, and in certain classes of materials general correlations are to be found between chemical composition, physical properties, and electrical constants and behavior. Thus in the case of the glasses, one of the most baffling groups, certain constituents are now recognized as related to conductivity and dielectric loss. The particular way in which moisture remains in fibrous materials is recognized and certain methods of control have been developed. There has been much study of the molecular polar properties of liquids when passing into the solid state and some grouping of materials as to the polar

variation of dielectric constant and dielectric loss. Studies of synthetic materials have been particularly successful in indicating wide changes in electrical properties associated with well recognized chemical variations. Examples of this are the thermoplastic rosin, poly-styrene, and the chlorinated diphenyl compounds. Similar studies have been made in the ceramic field, notably the steatite and rutile groups, the latter affording, when compounded with suitable binders, the possibility of a very wide range of value of dielectric constant. An excellent survey of some of these relationships has been presented during the year by W. Jackson.[31] In the experimental study of the dielectric strength of various types of solid materials, J. C. Dowell and C. M. Foust[32] present an important assembly of curves and data showing the impulse and 60-cycle breakdown voltages of various gaps, bushings, insulator strings, creepage paths in both liquid and solid materials. The data are presented in 33 sets of curves and 5 tables, and constitute a valuable reference source. An analytical study of the results of many workers on the breakdown of solids is given by S. Whitehead[33] in an effort to determine the figures for the breakdown strength inherent in the materials themselves. He attributed failure in practice (1) to the properties of the ambient medium, (2) to imperfections of macroscopic order in the solid material itself, (3) to the presence of foreign materials, moisture, etc. The present study looks away from these causes and analyzes the results of many workers for a determination of the limiting electric strength as determined by (*a*) thermal instability, (*b*) internal ionization, (*c*) ultimate electric strength. The author concludes that evidences of failure due to internal ionization are not very definite, and that the figures indicated for ultimate or pure electric strength, as studied by Rogowski and Von Hippel, are far above the values of present practice. Thermal breakdown is the most frequent and the values indicated for this by known material constants are also well above those of practice. The author states that there is no reason why, with a closer control of materials, field strengths of from 500 to 1,000 kilovolts per centimeter should not be possible on the basis of thermal instability alone.

Recent studies of conduction, absorption, and dielectric loss are as follows: A. Walther and Lydia Inge[34] have studied the conductivity of rock salt and glass at field strengths up to 2,000 kilovolts per centimeter. The conductivity increases as much as tenfold at high field strengths. From the conductivity-temperature relations, it is concluded that the increase of conductivity with field strength is largely due to an increase in ionic conductivity. Breakdown at room temperatures is shown to be thermal as well as electric. R. W. Sillars[35] attempts a model of Maxwell's complex dielectric, and Wagner's extension thereof, in a model of wax containing water drops. The theory is not supported by the results. Conclusion is reached that a minute amount of impurity in the form of fine needles can produce a serious alternating loss, while the effect of the same volume in spherical form would be negligible. W. A. Yager[36] also contributes in this field an exhaustive analysis of the distribution of relaxation times in complex dielectrics. The work is a careful examination of Wagner's proposal, which the results confirm, together with a somewhat extended explanation as to how the results of experiment can be utilized for determining the statistical distribution of relaxation times. The work tacitly assumes the Maxwell theory as the basis of dielectric absorption. G. A. Albert[37] measured dielectric losses parallel to the laminations of impregnated materials, showing values from 2 to 10 times the losses with field normal to laminations, depending upon the condition of the material. Thiessen, Winkel, and Herrmann[38] and Frei and Groetzinger[39] have studied the volumetric electric charges to be found in the rosin wax mixtures known as electrets. Evidence is presented that these are space charges which may have opposite signs, depending on the value of the stress applied during cooling. Thus not all of the behavior of the electret is due to dipolar orientation and fixation. Data as regards some of the new materials referred to in the first paragraph of this section are presented by M. Hagedorn[40] showing that polystyrol and similar substances can be prepared as foils with thickness from 0.02 millimeters up. Electrical properties vary with the material and proposal is made that these substances may be used in capacitors and cables. Standard Telephones and Cables[41] report new studies of the control of moisture in cellulose papers and fibers by esterification. Results on impregnated paper indicate acetic-acid values up to 30 per cent as about the limit to which this process can be extended without serious lowering of necessary physical properties of the paper.

A valuable paper is reported by C. Schmelzer[42] on the absolute measurement of dielectric losses at very high frequencies ($3 \times 10^7$) with the capacitor-thermometer. The loss is measured as the heat liberated in a small cylindrical capacitor (maximum length, 0.5 centimeter) in a glass cell. An accuracy within 5 per cent is claimed. W. J. Shutt and H. Rogan[43] made a critical experimental investigation of the oscillation or "force" method of determining the dielectric constant of slightly conducting liquids. With the improved method described, results are reported indicating an accuracy of $\pm 0.2$ per cent for solutions of electrolytes having conductivities less than 0.005 mhos. J. A. Weh[44] describes methods of measuring the thermal conductivity of sheet materials, with a maximum inaccuracy of $\pm 10$ per cent. W. D. Buckingham[45] describes an experimental method for determining the equivalent resistance and capacitance network for an absorptive capacitor, at different frequencies and voltages. The method consists of an a-c bridge with the absorptive capacitor in one arm and an air capacitor in the opposite arm. To this capacitor are added series or shunt resistances adjusted by experiment to give complete balance. Balance is determined by complete disappearance of current as indicated by amplifier and cathode ray oscillograph. Value of the method is claimed in the construction of phantom circuits and in the operation of long communication cables. H. A. Thomas[46] presents an extensive study of the causes of relatively small variations in the capacitance of capacitors with solids and with air as dielectric. Special methods for the accurate measurement of capaci-

tance are given, and methods proposed for controlling variations due to temperature.

## High-Voltage Cables

The causes of instability and deterioration continue to occupy chief attention. In recent years we appear to have passed through a series of fashions in our ideas of the principal causes of cable deterioration. We have noted as chief suspect in successive periods, high inherent power factor and loss, gaseous ionization due to temperature cycles, wax formation, and oxidation. At the moment we appear to be leaving the oxidation period and reverting to that of gaseous ionization, through new methods for studying free gas spaces in the cable.

Physical structure and dielectric loss of impregnated paper, as related to the amount of contained air and under changes of voltage, temperature, frequency, and pressure, are reported in an analytical and speculative study by P. Junius.[47] The conclusions are that the shape of the power factor-voltage curves at different temperatures changes very little in a dielectric containing large amounts of air. On the other hand, the shape of these curves varies noticeably in well-impregnated cable. In the latter case the change of power factor due to temperature change may be much steeper than that for a cable containing air. An overpressure of one atmosphere is sufficient to cause a flat loss curve in a cable which contains much air. Thus comparison between the loss curves of a pressure cable and an ordinary cable not under pressure, should not be used as a basis of the relative excellence of the 2 cables. Since gas in a dielectric may be either above, at, or below atmospheric pressure, power-factor variation with pressure and temperature are better criteria than the variation with voltage. J. Lawton[48] presents a good review and analytical study of all American research on wax formation, and also a clear classification of oils as regards correlation between chemical structure and gas evolution. The properties of the 2 broad divisions of petroleum oil, the aliphatics and the carbocyclics, are well described, and the differences between polymerization and condensation, and the relation of these to molecular structure under ionic bombardment pointed out. Two papers from French sources have appeared on the leakage of oil from oil-filled cables in service, one by P. Capdeville,[49] and the other by M. R. Laroche.[50] These methods depend on differences in pressure caused by the leaks. They are very sensitive to temperature and pressure changes. Measuring apparatus and connections are described, a few test results are given, and a maximum inaccuracy of 3 per cent is claimed. P. Dunsheath[51] describes manufacturing equipment for the continuous extrusion of lead cable sheaths.

Of most recent interest is the work of K. S. Wyatt[52] and associates on the mechanical uniformity of cable insulaton. A new method is described for the examination of the cross section of the cable. Oil is extracted from a short length, which is then impregnated with styrene and then heated so as to solidify the latter. It is stated that in this condition an undistorted wafer, as thin as 5 mils can be cut from the cable. As the styrene is highly translucent, the wafer so prepared, when viewed against a light, affords a remarkably clear picture of the laminated structure of the cable, accentuating sharply all regions of separation or voids between layers, conductors, and sheath. In somewhat similar manner longitudinal sections may also be prepared. Complete publication of the results of these interesting studies are not yet available, but we are fortunate in having a paper on the subject from Mr. Wyatt at the annual meeting of this committee this year.

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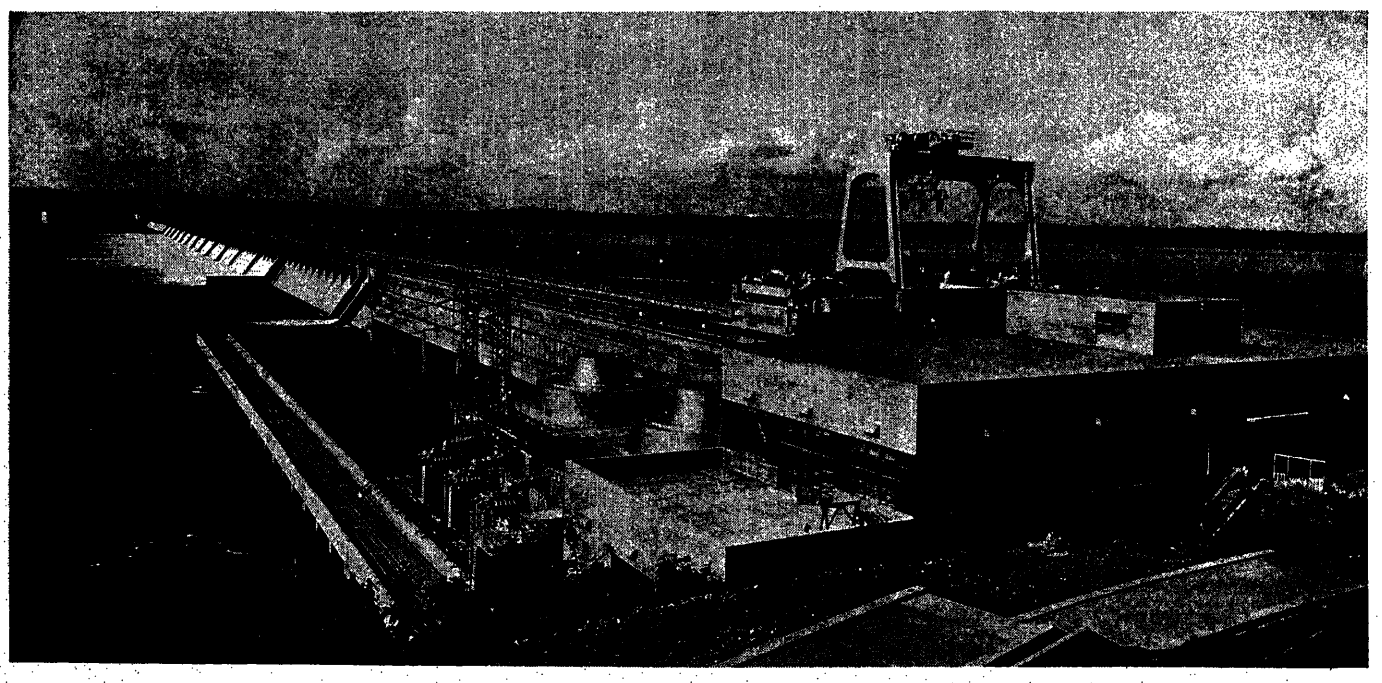
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**Downstream face of the Tennessee Valley Authority's Wheeler Dam, the $37,000,000 project named after General Joseph Wheeler and dedicated formally September 10, 1937, on the 101st anniversary of the general's birth, although actually completed early in the year. The dam is some 15 miles upstream from the "war baby" Wilson Dam at Muscle Shoals (which has been deeded to the TVA by the government) and is intended to extend Tennessee River navigation some 74 miles upstream to the Guntersville Dam which is now under construction. This view shows the power house in the immediate foreground with the 2 45,000-horsepower outdoor-type generating units just beyond. Above at the right is the frame of the movable gantry crane, while across the river the outlines of the navigation lock and the high arched bridge over it may be seen. The dam is 72 feet high and 6,502 feet long, with a reservoir area of 67,100 acres**

# Sources of Engineering Income, 1929–34

**Dealing with the annual incomes of engineers engaged in both engineering and nontechnical work, this sixth article[1] of a series reporting a survey of engineering employment conducted by the United States Bureau of Labor Statistics presents data, derived from reports of 52,589 engineers, tending to show that engineers engaged in technical work reach their maximum earning capacity later than those in nonengineering endeavors.**

IN 1929 there was greater spread in the earnings of engineers engaged in nonengineering work than in those obtained from engineering work. Thus, among engineers 40 to 47 years of age, 10 per cent of those engaged in nonengineering earned more than $12,424 and 10 per cent earned less than $2,420 per year. The respective annual incomes of similar proportions of all those engaged in engineering work were $9,615 and $2,705; and of graduates in engineering $10,088 and $2,936.

The age of maximum earning power for engineers arrives more quickly for nonengineering than for engineering work. At 48 to 55 years of age, however, those college graduates who stayed in engineering were doing as well as those who had gone into nonengineering work. This was true even at the highest income levels.

Despite the fact that in 1929 the tendency was for average annual incomes of engineers engaged in nonengineering to exceed slightly those from engineering work, the opportunities in the former field did not embrace more than 7 per cent of the total in any one age classification.

Over the period 1929–34 the relationship changed between the jobs engineers took in engineering and nonengineering work. On the whole it appears that in 1929 nonengineering work was an alternative to engineering work, but from 1929 to 1934 many nonengineering jobs were accepted as an alternative to unemployment or work relief.

The extent to which earning opportunities from nonengineering work depreciated between 1929 and 1934 differs at the various age levels. The average earnings of 2 groups in nonengineering who were 28 to 40 years in 1929 declined by almost one-third from 1929 to 1934. As between the groups that were over 48 years in 1929 the average income of the 1934 group is only one-half the average of the 1929 group. Similarly at each of the other income levels a greater fall is found in the average income of older men in nonengineering.

Those who were able to stay in engineering fared better. Furthermore the changes which occurred in the earnings from engineering work, as reported by all engineers and by graduates only, were consistently uniform.

The relative changes as between nonengineering earnings and those for engineering work of engineers, with advancing age and experience, are also found to be the same for men with comparable periods of experience.

It was among those newcomers who were trying to force their way into the profession that the greatest fall in income occurred. Thus average earnings in engineering in 1934, 2 years after graduation, were 37 per cent less than in 1929. The earnings of those who had been out of college 10 years were 31 per cent lower in 1934 than in 1929. At higher ages all groups averaged a decrease of 26 per cent.

In 1934 almost one-tenth of the engineers were unemployed or on work relief at the end of the year. The low level of earnings of this group during 1934 contributed to lowering the average earnings of all engineers. Thus of those engineers who were unemployed at the end of 1934 the average earnings for the preceding 12 months of those who were less than 28 years of age ranged from $700 to $950. Engineers of 40 to 50 years averaged $1,350. Only about 10 per cent of the unemployed, even though they were in those ages at which engineering earnings reached a peak, had made as much as $2,000 in the preceding 12 months. Ten per cent made less than $300 a year.

## Scope and Method

The earned annual-income data used in the preceding analysis were those reported for personal services of all classes of engineers, irrespective of whether or not they were engaged primarily in engineering or nonengineering work. They related, in other words, to the incomes of engineers, not to the incomes of men engaged in engineering. Consideration is here given to the annual incomes, classified by age, as related to the professional engineers' employment status.

While income was reported for the year, the type of employment was reported only as of December 31, 1929, 1932, and 1934. Consequently it has been necessary to assume that the kind of engineering or nonengineering employment engaged in at the end of the year was the source of the income for that year. This assumption makes possible valid general comparisons of the earnings of engineers in these 2 types of employment. But in that section dealing with the annual incomes of engineers who were unemployed, or who were employed on relief projects at the end of the year, it must not be assumed that they reflect the source of income. They are merely the incomes which had accrued during the year to those who were unemployed at the end of the year.

Before presenting the annual incomes from all kinds of engineering work and nonengineering work attention is di-

1. An article prepared by Andrew Fraser, Jr., of the Division of Hours, Wages, and Working Conditions, Bureau of Labor Statistics, United States Department of Labor, which article was published in the September 1937 issue of *Monthly Labor Review*. Articles reporting other phases of this survey were published in ELECTRICAL ENGINEERING as follows: "Professional Aspects of Engineering Education," August 1936, pages 863–7; "Unemployment in the Engineering Profession," February 1937, pages 216–23; "Employment in the Engineering Profession," May 1937, pages 524–31; "Security of Engineering Employment," June 1937, pages 655–61; "Engineering Income and Earnings," September 1937, pages 1089–1104. A detailed report of the survey will be published later in bulletin form by the Bureau of Labor Statistics.

rected to the following: It must be noted that the requirements of editing the questionnaires caused the selection of a relatively large proportion of the engineers engaged in nonengineering work in 1929 who had college degrees in engineering. Thus, elsewhere it has been shown that the general movement from 1929 to 1934 was out of engineering work either into unemployment or into work not in the engineering field. Consequently, a substantial number of those who were in pursuits other than engineering in 1929 would also have so reported in 1932 and 1934. Such returns from nonengineering graduates and "other" engineers were, in general, discarded. Therefore, the tabulations for nonengineering work in 1929 tend to be those of graduate engineers. On the other hand, a number of nongraduates who were practicing their profession in 1929 passed into nonengineering employment in 1932 and 1934. The schedules for such engineers were retained. Clearly the situation which prevailed in 1929 was less true in 1932 and 1934. Hence it is as well to compare the earnings for nonengineering both with the earnings of graduates and with those of all persons reporting who were engaged in engineering. These data are presented in table I.

Caution should be exercised in comparing earnings with various types of employment in 1929, 1932, and 1934. The earnings of all engineers in engineering work reflect best the changes in what was being paid for engineering services. Both sets of figures of engineering earnings do reflect changes in the rates for given kinds and qualities of work. This is not true of the earnings from nonengineering; they indicate merely what individual engineers were able to earn in miscellaneous employments called "nonengineering." Conceivably such persons might all have been managers of industrial establishments in 1929 and gasoline-station attendants in 1932. Obviously a decrease in earnings from nonengineering employment would not

**Table I. Comparison of 5 Levels of Annual Earnings From Nonengineering and Engineering Work Reported in 1929, 1932, and 1934**

| Age | Year of Graduation | Years After Graduation | Proportion With Annual Earnings of More Than Specified Amount as Derived From— | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | 10 Per Cent | | | 25 Per Cent | | | 50 Per Cent | | | 75 Per Cent | | | 90 Per Cent | | |
| | | | Nonengineering Work by All Engineers[1] | Engineering Work by— | | Nonengineering Work by All Engineers[1] | Engineering Work by— | | Nonengineering Work by All Engineers[1] | Engineering Work by— | | Nonengineering Work by All Engineers[1] | Engineering Work by— | | Nonengineering Work by All Engineers[1] | Engineering Work by— | |
| | | | | All Engineers[1] | All Graduates | | All Engineers[1] | All Graduates | | All Engineers[1] | All Graduates | | All Engineers[1] | All Graduates | | All Engineers[1] | All Graduates |
| **1929 Income (in Dollars)** | | | | | | | | | | | | | | | | | |
| 64 years and over | Prior to 1889 | 41+ | (2) | 9,937 | 10,148 | (2) | 6,917 | 7,346 | 2,400 | 4,476 | 4,971 | (2) | 3,060 | 3,469 | (2) | 1,957 | 2,413 |
| 56–63 years | 1889–96 | 33–40 | (2) | 12,625 | 13,516 | 7,155 | 7,500 | 7,955 | 4,400 | 4,979 | 5,590 | 2,893 | 3,422 | 3,760 | (2) | 2,420 | 2,624 |
| 48–55 years | 1897–1904 | 25–32 | 12,495 | 11,709 | 12,478 | 7,867 | 7,108 | 7,610 | 5,057 | 4,912 | 5,232 | 3,494 | 3,481 | 3,777 | 2,280 | 2,661 | 3,020 |
| 40–47 years | 1905–12 | 17–24 | 12,424 | 9,815 | 10,088 | 8,106 | 6,407 | 6,747 | 5,346 | 4,562 | 4,876 | 3,408 | 3,405 | 3,624 | 2,420 | 2,705 | 2,936 |
| 36–39 years | 1913–16 | 13–16 | 10,140 | 7,751 | 8,294 | 6,620 | 5,680 | 6,099 | 4,347 | 4,102 | 4,353 | 3,013 | 3,210 | 3,354 | 1,998 | 2,582 | 2,756 |
| 32–35 years | 1917–20 | 9–12 | 8,052 | 6,480 | 6,578 | 5,502 | 4,814 | 4,988 | 3,685 | 3,672 | 3,822 | 2,792 | 3,010 | 3,146 | 1,945 | 2,458 | 2,581 |
| 28–31 years | 1921–24 | 5–8 | 5,460 | 4,753 | 4,842 | 4,099 | 3,776 | 3,847 | 3,042 | 3,145 | 3,207 | 2,349 | 2,577 | 2,664 | 1,642 | 2,150 | 2,258 |
| 26–27 years | 1925–26 | 3–4 | 4,170 | 3,618 | 3,641 | 3,075 | 3,104 | 3,124 | 2,331 | 2,558 | 2,582 | 1,821 | 2,164 | 2,200 | 1,308 | 1,850 | 1,891 |
| 24–25 years | 1927–28 | 1–2 | 2,910 | 3,043 | 2,992 | 2,344 | 2,501 | 2,477 | 1,786 | 2,105 | 2,095 | 1,407 | 1,834 | 1,831 | 889 | 1,476 | 1,493 |
| 23 years | 1929 | 0 | 2,496 | 2,356 | 2,165 | 1,973 | 1,933 | | 1,500 | 1,322 | 1,168 | 936 | 888 | 862 | 446 | 502 | 449 |
| **1932 Income (in Dollars)** | | | | | | | | | | | | | | | | | |
| 67 years and over | Prior to 1889 | 44+ | (2) | 9,009 | 9,386 | (2) | 6,032 | 6,363 | 3,000 | 3,846 | 4,100 | (2) | 2,242 | 2,469 | (2) | 1,145 | 1,233 |
| 59–66 years | 1889–96 | 36–43 | (2) | 9,020 | 9,643 | 5,000 | 6,252 | 6,589 | 2,550 | 4,126 | 4,689 | 1,200 | 2,640 | 3,143 | (2) | 1,300 | 1,571 |
| 51–58 years | 1897–1904 | 28–35 | 9,146 | 8,405 | 9,008 | 5,069 | 5,892 | 6,163 | 3,011 | 4,046 | 4,411 | 1,395 | 2,823 | 3,119 | 525 | 1,807 | 1,989 |
| 43–50 years | 1905–12 | 20–27 | 9,188 | 7,567 | 7,979 | 5,528 | 5,242 | 5,557 | 3,129 | 3,742 | 4,007 | 1,528 | 2,720 | 2,968 | 736 | 1,903 | 1,999 |
| 39–42 years | 1913–16 | 16–19 | 7,450 | 6,387 | 6,700 | 4,980 | 4,643 | 4,990 | 2,800 | 3,490 | 3,711 | 1,602 | 2,604 | 2,854 | 809 | 1,926 | 2,090 |
| 35–38 years | 1917–20 | 12–15 | 5,486 | 5,579 | 5,858 | 3,675 | 4,191 | 4,400 | 2,320 | 3,223 | 3,381 | 1,276 | 2,475 | 2,664 | 587 | 1,851 | 1,999 |
| 31–34 years | 1921–24 | 8–11 | 4,290 | 4,332 | 4,415 | 3,007 | 3,457 | 3,546 | 1,963 | 2,790 | 2,885 | 1,123 | 2,195 | 2,299 | 490 | 1,619 | 1,728 |
| 29–30 years | 1925–26 | 6–7 | 3,301 | 3,501 | 3,565 | 2,465 | 2,934 | 2,799 | 1,639 | 2,411 | 2,455 | 964 | 1,942 | 1,990 | 454 | 1,468 | 1,533 |
| 27–28 years | 1927–28 | 4–5 | 2,463 | 3,005 | 3,021 | 1,908 | 2,504 | 2,521 | 1,319 | 2,103 | 2,128 | 765 | 1,702 | 1,751 | 306 | 1,257 | 1,310 |
| 26 years | 1929 | 3 | 2,034 | 2,518 | 2,504 | 1,585 | 2,140 | 2,134 | 1,045 | 1,871 | 1,878 | 570 | 1,523 | 1,546 | 228 | 1,119 | 1,169 |
| 25 years | 1930 | 2 | 1,930 | 2,167 | 2,155 | 1,465 | 1,946 | 1,941 | 1,069 | 1,662 | 1,658 | 585 | 1,325 | 1,324 | 234 | 937 | 927 |
| 24 years | 1931 | 1 | 1,766 | 2,039 | 2,014 | 1,348 | 1,742 | 1,725 | 921 | 1,394 | 1,381 | 470 | 1,024 | 1,008 | 188 | 539 | 515 |
| 23 years | 1932 | 0 | 1,689 | 1,910 | 1,826 | 1,240 | 1,335 | 1,243 | 814 | 766 | 716 | 406 | 383 | 358 | 163 | 153 | 143 |
| **1934 Income (in Dollars)** | | | | | | | | | | | | | | | | | |
| 69 years and over | Prior to 1889 | 46+ | (2) | 7,867 | 7,570 | (2) | 5,155 | 5,513 | 2,500 | 3,292 | 3,700 | (2) | 1,861 | 2,225 | (2) | 1,050 | 1,229 |
| 61–68 years | 1889–96 | 38–45 | (2) | 8,460 | 9,372 | (2) | 5,700 | 6,264 | 2,200 | 3,793 | 4,280 | (2) | 2,294 | 2,625 | (2) | 1,105 | 1,160 |
| 53–60 years | 1897–1904 | 30–37 | 7,848 | 7,951 | 8,548 | 4,147 | 5,443 | 5,841 | 2,523 | 3,745 | 4,095 | 1,305 | 2,520 | 2,751 | 631 | 1,558 | 1,711 |
| 45–52 years | 1905–12 | 22–29 | 9,171 | 7,230 | 7,665 | 5,426 | 4,980 | 5,271 | 3,040 | 3,524 | 3,788 | 1,579 | 2,526 | 2,688 | 921 | 1,826 | 1,893 |
| 41–44 years | 1913–16 | 18–21 | 7,293 | 6,221 | 6,542 | 4,576 | 4,518 | 4,863 | 2,892 | 3,319 | 3,540 | 1,667 | 2,471 | 2,655 | 1,042 | 1,829 | 1,966 |
| 37–40 years | 1917–20 | 14–17 | 5,560 | 5,393 | 5,656 | 3,667 | 4,058 | 4,278 | 2,414 | 3,101 | 3,271 | 1,514 | 2,379 | 2,525 | 848 | 1,839 | 1,960 |
| 33–36 years | 1921–24 | 10–13 | 4,101 | 4,323 | 4,405 | 3,055 | 3,387 | 3,499 | 1,992 | 2,676 | 2,801 | 1,276 | 2,113 | 2,219 | 694 | 1,625 | 1,752 |
| 31–32 years | 1925–26 | 8–9 | 3,560 | 3,554 | 3,601 | 2,468 | 2,892 | 2,949 | 1,700 | 2,380 | 2,442 | 1,123 | 1,929 | 2,002 | 526 | 1,513 | 1,581 |
| 29–30 years | 1927–28 | 6–7 | 2,658 | 3,066 | 3,120 | 2,028 | 2,507 | 2,533 | 1,439 | 2,106 | 2,141 | 1,015 | 1,745 | 1,806 | 500 | 1,298 | 1,362 |
| 28 years | 1929 | 5 | 2,209 | 2,635 | 2,658 | 1,764 | 2,209 | 2,227 | 1,296 | 1,929 | 1,946 | 934 | 1,593 | 1,621 | 431 | 1,244 | 1,266 |
| 27 years | 1930 | 4 | 2,149 | 2,370 | 2,371 | 1,621 | 2,044 | 2,044 | 1,224 | 1,789 | 1,797 | 889 | 1,431 | 1,443 | 408 | 1,083 | 1,093 |
| 26 years | 1931 | 3 | 2,028 | 2,155 | 2,146 | 1,536 | 1,900 | 1,895 | 1,171 | 1,578 | 1,571 | 835 | 1,265 | 1,261 | 352 | 954 | 949 |
| 25 years | 1932 | 2 | 1,798 | 2,002 | 1,999 | 1,442 | 1,701 | 1,693 | 1,113 | 1,396 | 1,392 | 815 | 1,107 | 1,104 | 336 | 837 | 835 |
| 24 years | 1933 | 1 | 1,664 | 1,911 | 1,895 | 1,325 | 1,562 | 1,551 | 991 | 1,272 | 1,265 | 606 | 960 | 954 | 242 | 526 | 520 |
| 23 years | 1934 | 0 | 1,388 | 1,391 | 1,811 | 1,093 | 976 | 939 | 744 | 642 | 617 | 372 | 321 | 309 | 149 | 128 | 123 |

[1] That is, includes all graduates and all "other" engineers. [2] Between 50 and 100 engineers reported. [3] Between 10 and 50 engineers reported.

**Table II. Comparison of 5 Levels of Annual Earnings From Engineering Work, for 5 Age Groups of Older Graduates[1] Reporting in 1929, 1932, and 1934**

| Per Cent of Specified Income Level | Engineers With Annual Earnings of More Than Specified Amount, Whose Ages Were— | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 60 in 1929 | 63 in 1932 | 65 in 1934 | 38 in 1929 | 41 in 1932 | 43 in 1934 | 30 in 1929 | 33 in 1932 | 35 in 1934 | 25 in 1929 | 28 in 1932 | 30 in 1934 |
| 10 per cent | 13,516 | 9,643 | 9,372 | 8,294 | 6,700 | 6,542 | 4,842 | 4,415 | 4,405 | 2,992 | 3,021 | 3,120 |
| 25 per cent | 7,955 | 6,589 | 6,264 | 6,099 | 4,990 | 4,863 | 3,847 | 3,546 | 3,499 | 2,477 | 2,521 | 2,533 |
| 50 per cent | 5,590 | 4,689 | 4,280 | 4,353 | 3,711 | 3,540 | 3,207 | 2,885 | 2,801 | 2,095 | 2,128 | 2,141 |
| 75 per cent | 3,760 | 3,143 | 2,625 | 3,354 | 2,854 | 2,655 | 2,664 | 2,299 | 2,219 | 1,831 | 1,751 | 1,860 |
| 90 per cent | 2,624 | 1,571 | 1,160 | 2,756 | 2,090 | 1,966 | 2,258 | 1,728 | 1,752 | 1,443 | 1,310 | 1,362 |

| | Percentage Increase or Decrease | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 1929–34 | 1929–32 | 1932–34 | 1929–34 | 1929–32 | 1932–34 | 1929–34 | 1929–32 | 1932–34 | 1929–34 | 1929–32 | 1932–34 |
| 10 per cent | −31 | −29 | − 3 | −21 | −19 | −2 | − 9 | − 9 | (2) | +4 | + 1 | +3 |
| 25 per cent | −21 | −17 | − 5 | −20 | −18 | −3 | − 9 | − 8 | −1 | +2 | + 2 | (2) |
| 50 per cent | −23 | −16 | − 9 | −19 | −15 | −5 | −13 | −10 | −3 | +2 | + 2 | +1 |
| 75 per cent | −30 | −16 | −16 | −21 | −15 | −7 | −17 | −14 | −3 | −1 | − 4 | +3 |
| 90 per cent | −56 | −40 | −26 | −29 | −24 | −6 | −23 | −24 | +1 | −9 | +12 | +4 |

[1] Includes postgraduates, nonengineering graduates, and first-degree engineering graduates who were professionally active prior to 1930.
[2] Less than one per cent.

then measure the fall in earnings of industrial managers. Actually the changes reflect the composite effect of a lowering of pay for various types of nonengineering work and a lowering of the quality of nonengineering work that was accepted as an alternative to unemployment.

Finally, among those reported at the end of the year as engaged in both engineering and nonengineering, there were some who suffered unemployment during part of the year. Inasmuch as unemployment was far more common in 1932 and 1934 than in 1929, this accounts for part of the decreases in annual incomes previously noted for both engineering and nonengineering. As regards engineering, rate change alone will be more fully analyzed later when monthly earnings from engineering employment are presented.[2]

## Incomes From Engineering and Nonengineering Work

The first significant point of comparison between the incomes in 1929 of engineers engaged in engineering and those in nonengineering work is that the earnings of the latter showed greater dispersion. Thus, among engineers 40 to 47 years of age, 10 per cent of those engaged in nonengineering earned more than $12,424 and 10 per cent earned less than $2,420 per year. The respective annual incomes for similar proportions of all those in engineering work were $9,815 and $2,705; and of graduates in engineering $10,088 and $2,936. It seems apparent from these figures and others for 1929, that on the one hand many engineers were attracted out of engineering jobs by favorable opportunities, whereas, on the other hand, an almost equally large proportion dropped out of engineering work and were forced to find alternative employment.

2. In the present article it must be borne in mind that the influence of unemployment in decreasing annual income was probably somewhat more important among those who reported nonengineering work as the source of income. It has been stated that the major direction of flow was from engineering work into nonengineering work. While some such transfers were made without an intervening period of unemployment, there must have been unemployment for many who lost an engineering job and went into nonengineering work after failure to find work of an engineering nature.

This point appears to be substantiated by a consideration of the variation in the relationship between engineering and nonengineering earnings in moving from the lowest to the highest of the 5 income levels.

Only at the lowest 10-per-cent income group or level did engineering incomes exceed those from nonengineering work at all ages for which comparison can be made. At the middle levels the engineering incomes were greater than nonengineering by only 10 per cent at 25 and 27 years of age, and by only 5 per cent at age 30. From this point the more rapid advance in average nonengineering earnings to a maximum at age 44 brought about an equalization of the incomes near to age 34 at a value of $3,700 per year. They again equalized at 54 years. That is, between 44 and 54 years, while the average returns from nonengineering had declined from $5,346 to $4,900, those from engineering had advanced from $4,562 to $4,900. The advance in the latter continued to age 60, attaining a value of $4,979 per year, as against $4,400 for nonengineering at the same age. At the upper 10- and 25-per-cent income groups or levels engineering work ceased to have an advantage over nonengineering near age 26. Thereafter the latter diverged upward from the former to reach a maximum of $12,495 at age 52 at the highest level, and of $8,106 at age 44 in the case of the next lowest level. The corresponding values of engineering earnings were $11,709 and $6,407 per annum. The steady advance in engineering earnings, together with the declines in nonengineering earnings, brought about an equalization of incomes at age 58.

A second point of significance is that in 1929 engineering work as such ultimately offered rewards as high as engineers were able to find in nonengineering. This arose primarily from the fact that the age of maximum earning power for engineers arrived more quickly for nonengineering than for engineering work. For at 48 to 55 years of age those college graduates who stayed in engineering were doing proportionately as well as those who had gone into nonengineering. This was true even at the highest income levels. The earnings of the upper 10 per cent of

## Table III. Comparison of 5 Levels of Annual Earnings, for Corresponding Years After Graduation, in 1929, 1932, and 1934

| Age of Engineers | Years After Graduation | Proportion With Annual Earnings of More Than Specified Amount | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 10 Per Cent | | | 25 Per Cent | | | 50 Per Cent | | | 75 Per Cent | | | 90 Per Cent | | |
| | | 1929 | 1932 | 1934 | 1929 | 1932 | 1934 | 1929 | 1932 | 1934 | 1929 | 1932 | 1934 | 1929 | 1932 | 1934 |
| Nonengineering work—all engineers: | | | | | | | | | | | | | | | | |
| 23½ years | ½ | $2,496 | $1,689 | $1,388 | $1,973 | $1,240 | $1,093 | $1,500 | $814 | $744 | $936 | $406 | $372 | $446 | $163 | $149 |
| 25 years | 2 | 2,910 | 1,850 | 1,710 | 2,344 | 1,380 | 1,365 | 1,786 | 990 | 1,040 | 1,407 | 520 | 685 | 889 | 210 | 275 |
| 28 years | 5 | 4,560 | 2,463 | 2,160 | 3,320 | 1,908 | 1,680 | 2,525 | 1,319 | 1,250 | 1,995 | 765 | 910 | 1,410 | 306 | 420 |
| 33 years | 10 | 7,320 | 4,290 | 3,770 | 5,060 | 3,007 | 2,640 | 3,500 | 1,963 | 1,790 | 2,670 | 1,123 | 1,170 | 1,840 | 490 | 575 |
| 43 years | 20 | 11,950 | 7,950 | 7,293 | 7,780 | 5,140 | 4,576 | 5,100 | 2,880 | 2,892 | 3,390 | 1,580 | 1,667 | 2,340 | 785 | 1,042 |
| 53 years | 30 | (1) | 9,130 | 8,400 | 7,730 | 5,200 | 4,770 | 4,970 | 3,050 | 2,775 | 3,420 | 1,425 | 1,435 | (1) | 570 | 760 |
| 60 years | 37 | (1) | (1) | (1) | 7,155 | 5,020 | (2) | 4,400 | 2,725 | 2,400 | 2,893 | 1,270 | (2) | (1) | (1) | (1) |
| Engineering work—all engineers: | | | | | | | | | | | | | | | | |
| 23½ years | ½ | 2,356 | 1,910 | 1,391 | 1,933 | 1,335 | 976 | 1,322 | 766 | 642 | 888 | 383 | 321 | 502 | 153 | 128 |
| 25 years | 2 | 3,043 | 2,100 | 1,960 | 2,501 | 1,840 | 1,610 | 2,105 | 1,520 | 1,310 | 1,834 | 1,150 | 1,020 | 1,476 | 690 | 650 |
| 28 years | 5 | 3,910 | 3,005 | 2,470 | 3,320 | 2,504 | 2,115 | 2,750 | 2,103 | 1,840 | 2,280 | 1,702 | 1,490 | 1,940 | 1,257 | 1,150 |
| 33 years | 10 | 5,940 | 4,332 | 3,800 | 4,480 | 3,457 | 3,020 | 3,520 | 2,790 | 2,470 | 2,890 | 2,195 | 2,000 | 2,385 | 1,619 | 1,550 |
| 43 years | 20 | 9,400 | 6,660 | 6,221 | 6,250 | 4,800 | 4,518 | 4,440 | 3,580 | 3,319 | 3,400 | 2,660 | 2,471 | 2,690 | 1,920 | 1,829 |
| 53 years | 30 | 11,900 | 8,230 | 7,620 | 7,060 | 5,640 | 5,180 | 4,900 | 3,990 | 3,620 | 3,460 | 2,790 | 2,530 | 2,650 | 1,840 | 1,680 |
| 60 years | 37 | 12,625 | 8,800 | 8,150 | 7,500 | 6,130 | 5,550 | 4,979 | 4,070 | 3,750 | 3,422 | 2,710 | 2,440 | 2,420 | 1,470 | 1,370 |
| Engineering work—graduates only: | | | | | | | | | | | | | | | | |
| 23½ years | ½ | 2,165 | 1,826 | 1,311 | 1,858 | 1,243 | 939 | 1,168 | 716 | 617 | 862 | 358 | 309 | 449 | 143 | 123 |
| 25 years | 2 | 2,992 | 2,100 | 1,940 | 2,477 | 1,840 | 1,610 | 2,095 | 1,510 | 1,310 | 1,831 | 1,150 | 1,015 | 1,493 | 690 | 650 |
| 28 years | 5 | 4,030 | 3,021 | 2,470 | 3,360 | 2,521 | 2,110 | 2,800 | 2,128 | 1,840 | 2,375 | 1,751 | 1,505 | 2,010 | 1,310 | 1,170 |
| 33 years | 10 | 6,100 | 4,415 | 3,860 | 4,660 | 3,546 | 3,110 | 3,680 | 2,885 | 2,530 | 3,040 | 2,299 | 2,110 | 2,495 | 1,728 | 1,640 |
| 43 years | 20 | 10,350 | 7,100 | 6,542 | 6,620 | 5,140 | 4,863 | 4,770 | 3,865 | 3,540 | 3,600 | 2,890 | 2,655 | 2,910 | 2,060 | 1,966 |
| 53 years | 30 | 12,500 | 8,820 | 8,100 | 7,620 | 5,980 | 5,560 | 5,270 | 4,320 | 3,910 | 3,780 | 3,030 | 2,710 | 2,960 | 1,980 | 1,790 |
| 60 years | 37 | 13,516 | 9,400 | 8,850 | 7,955 | 6,400 | 5,980 | 5,590 | 4,580 | 4,150 | 3,760 | 3,080 | 2,690 | 2,624 | 1,710 | 1,460 |

| Age of Engineers | Years After Graduation | Per Cent of Increase or Decrease | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 1929–34 | 1929–32 | 1932–34 | 1929–34 | 1929–32 | 1932–34 | 1929–34 | 1929–32 | 1932–34 | 1929–34 | 1929–32 | 1932–34 | 1929–34 | 1929–32 | 1932–34 |
| Nonengineering work—all engineers: | | | | | | | | | | | | | | | | |
| 23½ years | ½ | −44 | −32 | −18 | −45 | −37 | −12 | −50 | −46 | − 9 | | | | | | |
| 25 years | 2 | −41 | −36 | − 8 | −42 | −41 | − 1 | −42 | −45 | + 5 | −51 | −63 | +32 | −69 | −76 | +31 |
| 28 years | 5 | −53 | −46 | −12 | −48 | −43 | −12 | −50 | −48 | − 5 | −54 | −62 | +19 | −70 | −78 | +37 |
| 33 years | 10 | −48 | −41 | −12 | −50 | −41 | −16 | −49 | −44 | − 9 | −56 | −58 | + 4 | −69 | −73 | +17 |
| 43 years | 20 | −39 | −33 | − 8 | −41 | −34 | −11 | −43 | −44 | (3) | −51 | −53 | + 6 | −55 | −66 | +33 |
| 53 years | 30 | | | − 8 | −38 | −33 | − 8 | −44 | −39 | − 9 | −58 | −58 | + 1 | | | +33 |
| 60 years | 37 | | | | −30 | | | −45 | −38 | −12 | | −56 | | | | |
| Engineering work—all engineers: | | | | | | | | | | | | | | | | |
| 23½ years | ½ | −41 | −19 | −27 | −50 | −31 | −27 | −51 | −42 | −16 | | | | | | |
| 25 years | 2 | −36 | −31 | − 7 | −36 | −26 | −13 | −38 | −28 | −14 | −44 | −37 | −11 | −56 | −53 | − 6 |
| 28 years | 5 | −37 | −23 | −18 | −36 | −25 | −16 | −33 | −24 | −13 | −35 | −25 | −12 | −41 | −35 | − 9 |
| 33 years | 10 | −36 | −27 | −12 | −33 | −23 | −13 | −30 | −21 | −11 | −31 | −24 | − 9 | −35 | −32 | − 4 |
| 43 years | 20 | −34 | −29 | − 7 | −28 | −23 | − 6 | −25 | −19 | − 7 | −27 | −22 | − 7 | −32 | −29 | − 5 |
| 53 years | 30 | −36 | −31 | − 7 | −27 | −20 | − 8 | −26 | −19 | − 9 | −27 | −19 | − 9 | −37 | −31 | − 9 |
| 60 years | 37 | −35 | −30 | − 7 | −26 | −18 | − 9 | −25 | −18 | − 8 | −29 | −21 | −10 | −43 | −39 | − 7 |
| Engineering work—graduates only: | | | | | | | | | | | | | | | | |
| 23½ years | ½ | −39 | −16 | −28 | −49 | −33 | −24 | −47 | −39 | −14 | | | | | | |
| 25 years | 2 | −35 | −30 | − 8 | −35 | −26 | −13 | −37 | −28 | −13 | −45 | −37 | −12 | −56 | −54 | − 6 |
| 28 years | 5 | −39 | −25 | −18 | −37 | −25 | −16 | −34 | −24 | −14 | −37 | −26 | −14 | −42 | −35 | −11 |
| 33 years | 10 | −37 | −28 | −13 | −33 | −24 | −12 | −31 | −22 | −12 | −31 | −24 | − 8 | −34 | −31 | − 5 |
| 43 years | 20 | −37 | −31 | − 8 | −27 | −22 | − 5 | −26 | −19 | − 8 | −26 | −20 | − 8 | −32 | −29 | − 5 |
| 53 years | 30 | −35 | −29 | − 8 | −27 | −22 | − 7 | −26 | −18 | − 9 | −28 | −20 | −11 | −40 | −33 | −10 |
| 60 years | 37 | −35 | −30 | − 6 | −25 | −20 | − 7 | −26 | −18 | − 9 | −28 | −18 | −13 | −44 | −35 | −15 |

[1] Between 50 and 100 engineers reported. [2] Between 10 and 50 engineers reported. [3] Less than one per cent.

the college graduates continued to advance from $10,088 at age 44 to $13,516 at 60. The average at these ages rose from $4,876 to $5,590, whereas the average from nonengineering fell from $5,346 to $4,400 between these ages.

From the preceding analysis, therefore, it appears that in 1929 the tendency was for average annual incomes of engineers who engaged in nonengineering work to exceed slightly those from engineering work. Notwithstanding, it should be noted that the opportunities outside the engineering field did not embrace more than 7 per cent of the total reporting in any one age classification. Furthermore, since there is no knowledge of the basis of selection, it cannot be said that nonengineering earnings would have been greater or less for the engineer had he stayed in engineering work. The only justifiable assumption is that in 1929 there was a preference to remain in engineering by those in the 2 lower income groups or levels and a definite tendency to accept attractive openings in nonengineering work at the 2 higher income levels. The turning point in this movement occurred near to the middle levels of income reported.

## Changes in Income, 1929 to 1934

In an earlier article the changes from 1929 to 1934 in the incomes of all engineers were analyzed on an age basis. The decreases noted were due partly to salary reductions

## Table IV. Comparison of 5 Levels of Earned Annual Income in 1932 and 1934, for All Engineers Reporting Unemployment, on an Age Basis

Without Regard to Type of Education

| Age | Year of Graduation | Years After Graduation | Proportion Earning More Than Specified Amount | | | | |
|---|---|---|---|---|---|---|---|
| | | | 10 Per Cent | 25 Per Cent | 50 Per Cent | 75 Per Cent | 90 Per Cent |
| | | | 1932 Income | | | | |
| 67 years and over | Prior to 1889 | 44 and over | (1) | (1) | (1) | (1) | (1) |
| 59–66 years | 1889–96 | 36–43 | (2) | (2) | $720 | (2) | (2) |
| 51–58 years | 1897–1904 | 28–35 | $2,453 | $1,477 | 793 | $396 | $159 |
| 43–50 years | 1905–12 | 20–27 | 2,790 | 1,867 | 1,105 | 528 | 211 |
| 39–42 years | 1913–16 | 16–19 | 2,497 | 1,574 | 1,008 | 494 | 198 |
| 35–38 years | 1917–20 | 12–15 | 2,420 | 1,417 | 1,057 | 559 | 223 |
| 31–34 years | 1921–24 | 8–11 | 2,150 | 1,416 | 932 | 462 | 185 |
| 29–30 years | 1925–26 | 6–7 | 1,754 | 1,250 | 761 | 380 | 152 |
| 27–28 years | 1927–28 | 4–5 | 1,690 | 1,178 | 751 | 375 | 150 |
| 26 years | 1929 | 3 | 1,232 | 925 | 605 | 303 | 121 |
| 25 years | 1930 | 2 | 1,280 | 907 | 581 | 290 | 116 |
| 24 years | 1931 | 1 | 1,233 | 891 | 588 | 294 | 118 |
| 20–23 years | 1932 | 0 | (3) | 754 | 503 | 251 | (3) |
| | | | 1934 Income | | | | |
| 69 years and over | Prior to 1889 | 46 and over | (3) | (3) | $1,000 | (3) | (3) |
| 61–68 years | 1889–96 | 38–45 | (3) | $1,300 | 688 | $344 | (3) |
| 53–60 years | 1897–1904 | 30–37 | $2,349 | 1,700 | 1,080 | 542 | $217 |
| 45–52 years | 1905–12 | 22–29 | 2,546 | 1,943 | 1,357 | 748 | 299 |
| 41–44 years | 1913–16 | 18–21 | 2,151 | 1,730 | 1,357 | 867 | 353 |
| 37–40 years | 1917–20 | 14–17 | 2,250 | 1,780 | 1,316 | 769 | 308 |
| 33–36 years | 1921–24 | 10–13 | 1,959 | 1,684 | 1,304 | 836 | 340 |
| 31–32 years | 1925–26 | 8–9 | 2,138 | 1,746 | 1,243 | 716 | 287 |
| 29–30 years | 1927–28 | 6–7 | 1,796 | 1,495 | 1,045 | 546 | 219 |
| 28 years | 1929 | 5 | 1,805 | 1,417 | 893 | 449 | 180 |
| 27 years | 1930 | 4 | 1,638 | 1,374 | 948 | 534 | 214 |
| 26 years | 1931 | 3 | 1,545 | 1,210 | 836 | 419 | 167 |
| 25 years | 1932 | 2 | 1,548 | 1,200 | 716 | 358 | 143 |
| 24 years | 1933 | 1 | 1,460 | 1,107 | 756 | 378 | 151 |
| 20–23 years | 1934 | 0 | 1,257 | 881 | 571 | 285 | 114 |

[1] Less than 10 persons reported. [2] Between 10 and 50 persons reported. [3] Between 50 and 100 persons reported.

on given jobs. They were also due to the fact that incomes were reduced by extended periods of unemployment and by the necessity for accepting poorer jobs. That article described what happened between 1929 and 1934 on the average, for example, to engineers 40 to 47 years of age.

From the data presented in table I it is now possible to trace more precisely the influence of these several factors on the incomes of engineers. The first point to be noted is that the relationship changed between the jobs that engineers took in engineering and nonengineering work. In 1929 the essential elements of the story are to be found in the similarities of earnings in the 2 fields, rather than in the differences. On the whole it appears that nonengineering work was an alternative to engineering work. But from 1929 to 1934 many nonengineering jobs were accepted as an alternative to unemployment or work relief. Thus, the average earnings of those who were 40 to 47 years of age in 1929 and were in nonengineering work were $5,346. In 1934 a larger number of men from this age class were in nonengineering, and the average of this larger group was $3,040, a decline of 43 per cent. By way of contrast the average annual income of graduates in engineering work of from 40 to 47 years of age was $4,876 in 1929. A smaller number still in engineering in 1934 averaged $3,788, a decrease of only 23 per cent.

The extent to which earning opportunities from nonengineering work depreciated between 1929 and 1934 differed at the various age levels. The average earnings of 2 groups in nonengineering whose ages were 28 to 40 in 1929 declined by almost one-third from 1929 to 1934. As between the groups of those who were over 48 in 1929, the average income of the 1934 group was only half the average of the 1929 group. Similarly at each of the other income levels there was a greater fall in the average income of older men in nonengineering.

Those who were able to stay in engineering fared better. As illustrating this point, table II is presented, covering graduates of advancing age and experience, who were engaged in engineering work. A similar table based on the data in table I might be presented for all engineers. Essentially, however, the changes which occurred in the earnings from engineering work, as reported by all engineers and by graduates only, were consistently uniform.

In the period from 1929 to 1934 the average earnings of graduates in engineering who were 60 years old in 1929 declined 23 per cent. There was a smaller decrease for the middle-aged groups, and among those averaging 30 years of age in 1929 the decline amounted to 13 per cent. For the youngest groups shown in the table—those who were 25 in 1929 and 30 in 1934—the 5 years of added experience resulted in an actual increase in the average earnings of those who remained in engineering in 1934, as against the average for the larger numbers in the profession in 1929. The nature and extent of these changes in the averages of graduate earnings from engineering work were closely paralleled by those which occurred at the 2 upper income groups or levels. The increase in average earnings that was noted at 25 and 30 years did not occur for this age group at the 2 lower levels of income for the period 1929

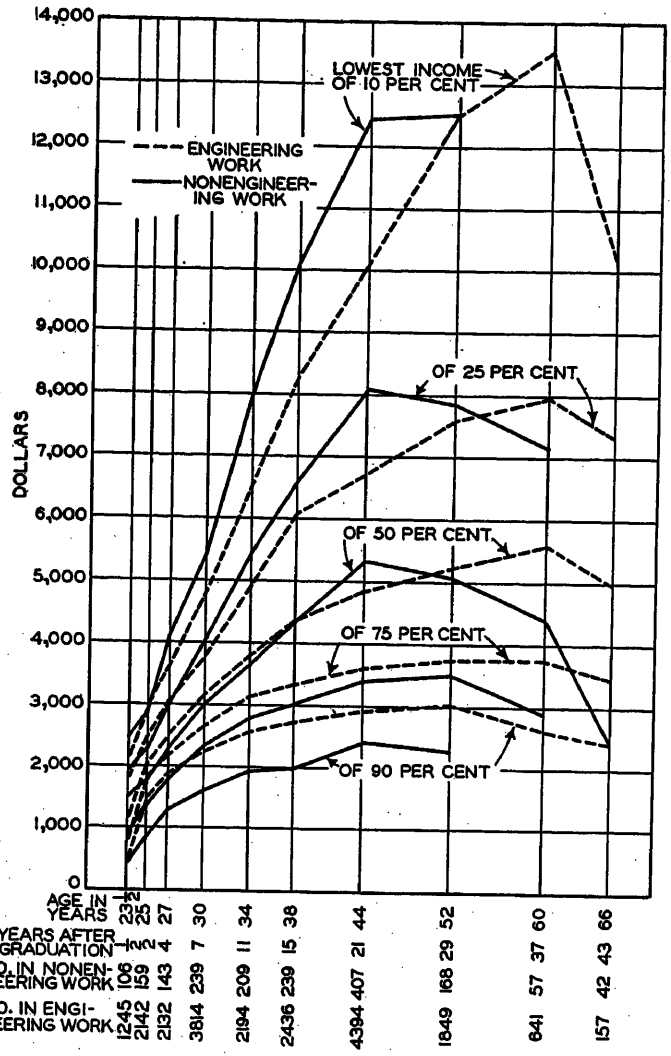



**Figure 1. Earned annual income of professional engineers in engineering and nonengineering work by age in 1929**

Primarily income reported by graduate engineers in either full- or part-time employment

to 1934. Furthermore, the declines in earnings for the lowest 10 per cent in each of the 3 older groups were greater than the average.

The relative changes as between nonengineering earnings and those for engineering work of engineers with advancing age and experience are also found to be the same for men with comparable periods of experience (table III).

As far as the comparison of nonengineering and engineering earnings is concerned, this table merely reenforces the evidence already advanced as to the severe fall of income that occurred when engineers were forced out of the profession. However, the table sets forth more clearly than table II the picture of the fall of earnings from engineering. It was among those newcomers who were trying to force their way into the profession that the greatest fall of income occurred. Thus, average earnings in engineering in 1934, 2 years after graduation, were 37 per cent less than in 1929. The earnings of those who had been out of college 10 years were 31 per cent lower in 1934 than in 1929. At higher ages all groups averaged a decrease of 26 per cent. A similar movement occurred in the level of earnings of the upper and lower 25 per cent of those in engineering, but at the level of the upper 10 per cent the declines were greater for the older engineers.

## Income of Unemployed Engineers

In 1934 almost one-tenth of the reporting engineers were unemployed or on work relief at the end of the year. The low level of earnings of this group during 1934 contributed to lowering the average earnings of all engineers.

The distribution of the earnings of this group has significance only as indicating the income which a group, unemployed in December 1934, had earned in the preceding 12 months. Some were probably men who had had a few months' work at a good rate, and a long period of unemployment. Others may have worked quite steadily at a low rate and become recently unemployed. All were unemployed at the end of the year. They could look back on average earnings for the preceding 12 months of $700 to $950 if they were less than age 28, while those of 40 to 50 had averaged $1,350. Only about 10 per cent of the unemployed, even though they were in those ages at which engineering earnings reach a peak, had made as much as $2,000 in the preceding 12 months. Ten per cent had made less than $300 a year.

**Correction.** In the previous article of this series, September issue, page 1092, sentence beginning in line 11, right-hand column should read: "Some 479 reported incomes less than $800 per year, while 295 earned more than $19,000 per year.

# Steel Structures Identified Magnetically

A PAPER "Steel Structures Identified and Flaws Located by Means of Balancing Wave Tests" was presented by Carl Kinsley (A'97, F'35, member for life), consulting engineer, New York, N. Y., at the annual meeting of the American Society for Testing Materials held in New York, N. Y., June 28–July 2, 1937. The fundamental assumption of the method is that magnetic hysteresis loops uniquely characterize any ferromagnetic material with respect to its structure and physical condition. The magnetic "finger print" is standardized and recorded by using a simple sine wave of magnetizing force which produces a cyclical magnetic flux in the material which, in turn, causes a complex induced electromotive force in a secondary testing circuit. This is quantitatively analyzed by the testing apparatus into its equivalent Fourier series of harmonic terms which are then recorded as the complete characterization of the material.

It has not been found possible to make any change in the material without having a corresponding change in one or more of the constants of its characteristic series of terms. No different combination of analysis, metallurgical structure, or physical condition has been found that would produce a duplicate of the characteristic equation of the specimen.

The correctness of the fundamental assumption was questioned in the discussion at the meeting, and the author indicated that it had been verified in every case examined throughout the whole range of laboratory investigations.

# The Cause and Elimination of Noise in Small Motors

By W. R. APPLEMAN
MEMBER AIEE

## Common Causes of Noise

MUCH OF the noise present in electrical motors is due to poor manufacture. Careless or inaccurate manufacturing methods often show up in some manner as uneven air gaps, loose bearings, brush noise, or loose rotor bars.

It is beyond the scope of this article to discuss either the various production problems or special noise insulating mountings. We shall rather confine ourselves to a discussion of the electrical design features as the selection of the proper slot combinations, winding distribution, and skew.

## Slot Combinations

The number of stator slots is usually fairly well set, or at least the selection is limited because of the number of poles and phases. We shall confine ourselves, therefore, to the proper selection of the number of rotor bars after the number of stator slots is decided upon.

An interesting example of the method used by one electrical manufacturer with an excellent reputation shows what work can be saved. About 17 different type rotors all using different numbers of bars were made up. The 3 or 4 quietest were selected and the head of the department chose the quietest one as the standard. A couple of years later one rotor was calculated which would decrease the harmonics. This rotor was quieter than the rotor selected after 17 attempts. I realized then that elimination of noise was not just the lucky finding of a good *combination* after many trials, but calculations were worthwhile. Had 3 or 4 quiet rotors been calculated and the best one selected much money and time would have been saved and better results secured. This same company received a number of complaints concerning a noisy 4-pole motor with a 17-bar rotor. As soon as the motors were used a short time by critical customers they were returned because of noisy bearings. Actually the bearing fits were still close and the noise was caused by a magnetic force.

If 2 fields exist which differ by 2 poles a rotor vibration will be set up. The unbalanced pull will be proportional to the product of the magnitude of the 2 fields. This noise will increase with the load because the magnitude of both fields increases with the load. This vibration will sound very much like a loose bearing condition. If 2 fields exist which differ by 4 poles a rotating elliptical field will be set up. A heavy or rigid yoke section will prevent this. Polarity differences of more than 4 poles will seldom cause any trouble. In fact 2 fields differing by 4 poles seldom give rise to very much noise. Our next step then is to list the harmonics present, determine whether there are some with fields with a 2-pole difference and if so, eliminate them. The harmonics caused by the slot openings have $2(P/2 \text{ plus } m)$ and $2(P/2 \text{ minus } m)$ poles. These must be figured for the following values of $m$:

$m$ = number stator slots. (These particular harmonics will show up in the winding calculations and cannot be eliminated or even altered by the winding distribution)

$m$ = number rotor slots

$m$ = difference between number of stator and rotor slots

$P$ = number of poles

In the example cited with a 24-slot stator and 17- and 26-bar rotors for 4 poles we have:

| | |
|---|---|
| 24 slots (stator) | $2(2 + 24) = 52$ poles |
| | $2(2 - 24) = -44$ poles |
| 17 slots (rotor) | $2(2 + 17) = 38$ poles |
| | $2(2 - 17) = -30$ poles |
| 7 slots (difference) | $22(2 + 7) = 18$ poles |
| | $2(2 - 7) = -10$ poles |
| 26 slots (rotor) | $2(2 + 26) = 56$ poles |
| | $2(2 - 26) = -48$ poles |
| 2 slots (difference) | $2(2 + 2) = 8$ poles |
| | $2(2 - 2) = 0$ poles |

Next the field harmonics set up by the stator winding were calculated from the formula $N = \pm (2\phi g \pm 1)$, in which

$N$ = order of the harmonic
$\phi$ = number of phases
$g$ = any positive integer

It will be noted from the formula that all odd harmonics can be present on single phase and all odd except thirds and multiples of thirds on 3 phase. The number of poles present in the harmonic field is equal to the order of the harmonic multiplied by the number of poles of the fundamental.

The number of poles of the stator field harmonics present are therefore as shown in table I.

The strength of these fields and the direction of rotation

**Table I**

| N (Harmonics) | Number Poles |
|---|---|
| 1 | 4 |
| 3 | 12 |
| 5 | 20 |
| 7 | 28 |
| 9 | 36 |
| 11 | 44 |
| 13 | 52 |
| 15 | 60 |

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## Table II

| | 2-Pole Motor | 4-Pole Motor | 6-Pole Motor | 8-Pole Motor |
|---|---|---|---|---|
| 24 slots | 50 | 52 | 54 | 56 |
| | −46 | −44 | −42 | −40 |
| 33 slots | 68 | 70 | 72 | 74 |
| | −64 | −62 | −60 | −58 |
| 9 slots | 20 | 22 | 24 | 26 |
| | −16 | −14 | −12 | −10 |
| 34 slots | 70 | 72 | 74 | 76 |
| | −66 | −64 | −62 | −60 |
| 10 slots | 22 | 24 | 26 | 28 |
| | −18 | −16 | −14 | −12 |

## Table III

| N | Number Poles | Number Poles | Number Poles | Number Poles |
|---|---|---|---|---|
| 1 | 2 | 4 | 6 | 8 |
| 3 | 6 | 12 | 18 | 24 |
| 5 | 10 | 20 | 30 | 40 |
| 7 | 14 | 28 | 42 | 56 |
| 9 | 18 | 36 | 54 | 72 |
| 11 | 22 | 44 | 66 | 88 |
| 13 | 26 | 52 | 78 | 104 |
| 15 | 30 | 60 | 90 | 120 |
| 17 | 34 | 68 | 102 | 136 |
| 19 | 38 | 76 | 114 | 152 |
| 31 | 62 | | | |
| 33 | 66 | | | |
| 35 | 70 | | | |
| 37 | 74 | | | |

can be calculated as shown in another chapter of this paper.

Note then that the 17-slot rotor has 30 poles and the field 28 (seventh harmonic), also that the 17-slot rotor has 38 poles and the field 36 (ninth harmonic). Note again that the 7-slot difference has 10 poles and the field 12 (third harmonic), also 18 poles and the field 20 (fifth harmonic).

If, however, we use a 26-slot rotor which we did try, and adopt as standard there is a 4-pole difference and at no point a 2-pole difference. The increased quietness due to the use of a larger number of rotor bars, elimination of the 2-pole harmonic difference, and proper skew showed a marked decrease in noise, not only under load but also with no load.

Another motor with 33 rotor bars worked satisfactorily on 6 poles, but was not very quiet on 4 poles. Let us analyze the motor from the standpoint of harmonic fields with a 2-pole difference for the various numbers of fundamental poles. Also check a 34-bar rotor with the 24-slot stator. The results are shown in table II.

The number of poles of the stator field harmonics present are therefore as shown in table III.

From these tables we gather this information:

1. To avoid a difference of 2 poles between the harmonic fields it is necessary to use a rotor with an even number of rotor slots for 2- and 4-pole motors.

2. The 33-slot rotor is very good for a 6-pole motor having a difference of 6 poles between all the harmonic fields.

3. The 34-bar rotor is satisfactory for 6 poles having a minimum difference of 4 poles.

4. The 33-slot is not good for 8 poles as a 2-pole difference exists.

5. The 34-slot is satisfactory for 8 poles as it has a minimum difference of 4 poles.

Probably the most commonly used stator punching is one in approximately a 6-inch diameter with 36 slots. A very satisfactory rotor for this stator is one with 44 slots. This can be readily checked by the method just illustrated. A further check will eliminate such rotors as 39- or 41-bar for general purpose work.

It is very evident from the preceding work that it would be of great help to have 2 sets of tables for rapid checking of rotors. One of these tables consists of the number of poles present caused by stator field harmonics. Since all odd harmonics are present this will be the order of each odd harmonic multiplied by the number of poles of the fundamental. The other table is for the harmonics caused by slot openings and the difference existing due to slot openings.

More recent investigation and articles have added still more to our fund of knowledge on the selection of the number of rotor bars which will let us design our motor still quieter and eliminate some that we would still retain if we tried all those without a 2-pole difference.

Kron states: "Vibration and noise are liable to be present as follows:

1. When the slots differ by one or by the number of poles plus or minus one, transverse vibration and noise may occur.

## Table IV. Pitch Fractions

| Decimal Fraction | Slot Value | See Table |
|---|---|---|
| 1.00 | 18/18 15/15 etc. | V |
| 0.9445 | 17/18 | XIV |
| 0.9333 | 14/15 | XIII |
| 0.9166 | 11/12 | XII |
| 0.9 | 9/10 | XI |
| 0.889 | 8/9 | X |
| 0.875 | 7/8 | IX |
| 0.8667 | 13/15 | XIII |
| 0.833 | 5/6 | VIII |
| 0.8 | 8/10 | XI |
| 0.778 | 7/9 | X |
| 0.75 | 3/4 | VII |
| 0.7333 | 11/15 | XIII |
| 0.7222 | 13/18 | XIV |
| 0.7 | 7/10 | XI |
| 0.667 | 2/3 | VI |
| 0.625 | 5/8 | IX |
| 0.6112 | 11/18 | XIII |
| 0.6 | 6/10 | XI |
| 0.5833 | 7/12 | XII |
| 0.556 | 5/9 | X |
| 0.533 | 8/15 | XIII |
| 0.5 | 1/2 | V |
| 0.4667 | 7/15 | XIII |
| 0.444 | 4/9 | X |
| 0.4166 | 5/12 | XII |
| 0.4 | 4/10 | XI |
| 0.3889 | 7/18 | XIV |
| 0.375 | 3/8 | IX |
| 0.333 | 1/3 | VI |
| 0.3 | 3/10 | XI |
| 0.2778 | 5/18 | XIV |
| 0.2667 | 4/15 | XIII |
| 0.25 | 1/4 | VII |
| 0.222 | 2/9 | X |
| 0.2 | 2/10 | XI |
| 0.1667 | 1/6 | VIII |
| 0.1333 | 2/15 | XIII |
| 0.125 | 1/8 | IX |
| 0.111 | 1/9 | X |
| 0.1 | 1/10 | XI |
| 0.0833 | 1/12 | XII |
| 0.0667 | 1/15 | XIII |
| 0.0556 | 1/18 | XIV |

2. When the slots differ by half the number of poles, torsional vibration and noise may occur.

3. When the slots differ by the number of poles, torsional vibration and noise may occur and also rumbling noise unaccompanied by critical vibrations.

"The chance that the noise occurs in the working range is greater with smaller number of poles, higher speed, and with small transverse or torsional critical speeds. When these noises do occur the motor is practically useless."

The reader has probably already noticed by rule 2 torsional vibration and noise may occur in our example of the 24-slot stator and 26-bar rotor. Probably partly due to the relatively heavy yoke section this did not occur. Had we, however, avoided 26 and 28 slots because of rules 2 and 3 and avoided 30- and 32-slot because of fear of locking in points on starting we would probably have tried a 34-bar rotor. Actual experience with another firm has showed us that a 24-slot stator and a 34-bar rotor makes a quiet 4-pole motor. All combinations falling under rule 1 have a 2-pole difference, and should therefore be avoided for a double reason.

## Table V

| 2 Slots Per Pole | | |
|---|---|---|
| Pitch | Full (1.00) | 1/2 (0.5) |
| $m$ = 1 | 127.32 | 90.03 |
| 3 | 42.45 | −30.01 |
| 5 | 25.47 | −18.01 |
| 7 | 18.19 | 12.86 |
| 9 | 14.15 | 10.00 |
| 11 | 11.58 | − 8.184 |
| 13 | 9.795 | − 6.925 |
| 15 | 8.488 | 6.002 |
| 17 | 7.49 | 5.296 |
| 19 | 6.702 | − 4.739 |
| 21 | 6.064 | − 4.287 |
| 23 | 5.536 | 3.914 |
| 25 | 5.094 | 3.601 |
| 27 | 4.716 | − 3.335 |
| 29 | 4.39 | − 3.104 |
| 31 | 4.108 | 2.905 |
| 33 | 3.859 | 2.728 |

## Table VI

| 3 Slots Per Pole | |
|---|---|
| 2/3 | 1/3 |
| 0.667 | 0.3333 |
| 110.27 | 63.66 |
| 0.00 | −42.45 |
| − 22.06 | 12.73 |
| − 15.75 | 9.095 |
| 0.00 | −14.15 |
| 10.02 | 5.787 |
| 8.48 | 4.897 |
| 0.00 | − 8.488 |
| − 6.487 | 3.745 |
| − 5.805 | 3.351 |
| 0.00 | − 6.064 |
| 4.795 | 2.768 |
| 4.411 | 2.547 |
| 0.00 | − 4.716 |
| − 3.803 | 2.195 |
| − 3.558 | 2.054 |
| 0.00 | − 3.859 |

## Table VII

| 4 Slots Per Pole | | |
|---|---|---|
| Pitch | 3/4 | 1/4 |
| $m$ = 1 | 117.63 | 48.72 |
| 3 | 16.24 | −39.22 |
| 5 | − 9.744 | 23.53 |
| 7 | − 16.81 | − 6.96 |
| 9 | − 13.07 | − 5.414 |
| 11 | − 4.429 | 10.694 |
| 13 | 3.748 | − 9.05 |
| 15 | 7.843 | 3.248 |
| 17 | 6.92 | 2.866 |
| 19 | 2.564 | − 6.192 |
| 21 | − 2.32 | 5.602 |
| 23 | − 5.115 | − 2.118 |
| 25 | − 4.706 | − 1.949 |
| 27 | − 1.804 | 4.357 |
| 29 | 1.68 | − 4.056 |
| 31 | 3.795 | 1.572 |
| 33 | 3.565 | 1.476 |

## Table VIII

| 6 Slots Per Pole | |
|---|---|
| 5/6 | 1/6 |
| 0.833 | 0.1667 |
| 122.96 | 32.95 |
| 30.01 | −30.01 |
| 6.59 | 24.6 |
| − 4.707 | −17.57 |
| − 10.00 | 10.00 |
| − 11.18 | − 2.995 |
| − 9.46 | − 2.535 |
| − 6.002 | 6.002 |
| − 1.938 | − 7.234 |
| 1.734 | 6.472 |
| 4.287 | − 4.287 |
| 5.346 | 1.433 |
| 4.919 | 1.318 |
| 3.335 | − 3.335 |
| 1.136 | 4.24 |
| − 1.063 | − 3.967 |
| − 2.728 | 2.728 |

It is advisable for the designer to also bear rules 2 and 3 in mind as the discussion so far would not eliminate some undesirable combinations. For a 2-pole design rule 2 would again eliminate rotors which would cause a 2-pole difference.

A general statement, subject to all the limitations of a general statement follows:

Any rotor with a number of rotor slots divisible by the number of pairs of poles of the fundamental and which differs from the number of stator slots by more than the number of poles will probably be a quiet rotor.

This does not apply to 2-pole motors as the above rule will give a motor with a difference between the number of harmonic poles equal to the number of poles of the fundamental. This rule does not cover all possibilities as it does not include rotors that would have a 4-pole difference on a 6- or 8-pole motor or a 6-pole difference on an 8-pole motor, etc. It might also be mentioned before leaving the subject that small slot openings will give rise to less violent flux disturbance than large slot openings. Rotors with closed slots should be machined accurately to keep the same thickness of steel outside the various bars. Care must also be taken in the selection of the number of rotor slots to prevent locking in at starting.

## Winding Distribution for Sinusoidal Wave Form

In our section on the selection of the number of rotor bars we showed how to calculate which harmonics could be present in the field. There are 2 ways to reduce the strength of the harmonics and consequently reduce the noise. One is to design the stator punching with heavy teeth at the center of the pole and lighter teeth toward the outside of the pole, and the other is to distribute the winding to decrease the harmonic. The former method is patented and each punching is applicable to but one given number of poles. It is well for each manufacturing company to have on hand a set of tables showing the harmonic strength for the various fractions of the pole pitch based on 100 turns. A discussion of how these may be calculated will be explained later. I am including with this thesis blue prints of the table I use. Often, the designer has little interest in knowing the strength of the various harmonics provided he has his winding distributed in the best way. The author has worked out 2 simple methods for calculating this which as far as he knows are original.

**Table IX**

| | 8 Slots Per Pole | | | |
|---|---|---|---|---|
| Pitch | 7/8 | 5/8 | 3/8 | 1/8 |
| | 0.875 | 0.625 | 0.375 | 0.125 |
| $m$ = 1 | 124.86 | 105.86 | 70.73 | 24.84 |
| 3 | 35.23 | − 8.28 | −41.63 | −23.58 |
| 5 | 14.15 | − 24.98 | 4.969 | 21.14 |
| 7 | 3.549 | − 10.1 | 15.12 | −17.84 |
| 9 | − 2.76 | 7.859 | −11.74 | 13.87 |
| 11 | − 6.43 | 11.35 | − 2.258 | − 9.608 |
| 13 | − 8.13 | 1.911 | 9.605 | 5.44 |
| 15 | − 8.325 | − 7.046 | 4.715 | − 1.656 |
| 17 | − 7.345 | − 6.218 | − 4.161 | − 1.461 |
| 19 | − 5.563 | 1.307 | 6.572 | 3.723 |
| 21 | − 3.368 | 5.946 | − 1.183 | − 5.032 |
| 23 | − 1.08 | 3.075 | − 4.595 | 5.429 |
| 25 | 0.9936 | − 2.829 | 4.228 | − 4.995 |
| 27 | 2.62 | − 4.625 | 0.92 | 3.915 |
| 29 | 3.644 | − 0.8565 | − 4.305 | − 2.438 |
| 31 | 4.028 | 3.41 | 2.282 | 0.8014 |
| 33 | 3.784 | 3.203 | 2.143 | 0.753 |

**Table X**

| | 9 Slots Per Pole | | | | | |
|---|---|---|---|---|---|---|
| Pitch | 8/9 | 7/9 | 5/9 | 4/9 | 2/9 | 1/9 |
| | 0.889 | 0.778 | 0.556 | 0.444 | 0.222 | 0.111 |
| $m$ = 1 | 125.38 | 119.64 | 97.53 | 81.84 | 43.55 | 22.11 |
| 3 | 36.76 | 21.22 | −21.22 | −36.76 | −36.76 | −21.22 |
| 5 | 16.37 | − 4.422 | −23.93 | − 8.71 | 25.08 | 19.51 |
| 7 | 6.222 | − 13.93 | 3.159 | 17.92 | −11.69 | −17.09 |
| 9 | 0.00 | − 14.15 | 14.15 | 0.00 | 0.00 | 14.15 |
| 11 | − 3.959 | − 8.866 | 2.01 | −11.4 | 7.44 | −10.88 |
| 13 | − 6.295 | − 1.701 | − 9.204 | 3.35 | − 9.65 | 7.502 |
| 15 | − 7.35 | 4.244 | − 4.244 | 7.35 | 7.35 | − 4.244 |
| 17 | − 7.377 | 7.038 | 5.738 | − 4.815 | − 2.562 | 1.301 |
| 19 | − 6.6 | 6.297 | 5.133 | − 4.308 | − 2.292 | 1.164 |
| 21 | − 5.25 | 3.031 | − 3.031 | 5.25 | 5.25 | − 3.031 |
| 23 | − 3.558 | − 0.9612 | − 5.202 | 1.893 | − 5.45 | 4.24 |
| 25 | − 1.742 | − 3.90 | 0.884 | − 5.02 | 3.274 | − 4.785 |
| 27 | 0.00 | − 4.716 | 4.716 | 0.00 | 0.00 | 4.716 |
| 29 | 1.501 | − 3.362 | 0.762 | 4.325 | − 2.822 | − 4.125 |
| 31 | 2.64 | − 0.715 | − 3.86 | − 1.405 | 4.046 | 3.146 |
| 33 | 3.84 | − 1.929 | − 1.929 | − 3.84 | − 3.84 | − 1.929 |

### Method *A*

Let us assume a 36-slot stator to be wound 4 poles or 9 slots per pole. We want to make all the harmonics small or in other words approach a sine wave.

If the stator pole were wound with a single coil the wave form would be a rectangle. If more than one coil per pole were used the wave form would be a series of rectangles above each other, giving a resultant wave with a number of steps. Figures 1 and 2 illustrate this. As the number of slots per pole and the number of coils per pole are increased the shape of the wave will approach that of a sine wave. Since in actual practice neither is infinity nor any where near it, it is necessary that we allot the proper number of turns to each coil to make the wave as nearly a sine wave as possible. The following method of calculation is not empirical but theoretically sound. Figure 4 is the layout for a winding over 2, 4, 6, and 8 teeth for 9 slots per pole and figure 3 is its flux wave. The point of zero flux is at the center of the teeth between adjacent poles. There will be 180/9 equals 20 electrical degrees between adjacent teeth. The ordinates of the sine wave at the various teeth are as follows:

sine 20 degrees = 0.342 at teeth *B*
sine 40 degrees = 0.643 at teeth *D*
sine 60 degrees = 0.866 at teeth *F*
sine 80 degrees = 0.985 at teeth *H*

Since the wave will actually have a flat top and the maximum flux will be in teeth *B* let us call this point 100 per cent. The percentage of flux in the various teeth which is also the percentage of the total turns in all coils which surround these teeth is as follows:

tooth *B:* 0.342/0.985 = 0.347
tooth *D:* 0.643/0.985 = 0.653
tooth *F:* 0.866/0.985 = 0.879
tooth *H:* 0.985/0.985 = 1.000

Since all the flux in teeth *B* is caused by the coils in slots *A* then 0.347 of the total turns per pole lie in slots *A*. The flux in teeth *D* is caused by the coils in both slots *A* and *C*. The turns in slots *C* must therefore be 0.653 minus 0.347

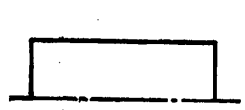


Figure 1



Figure 2

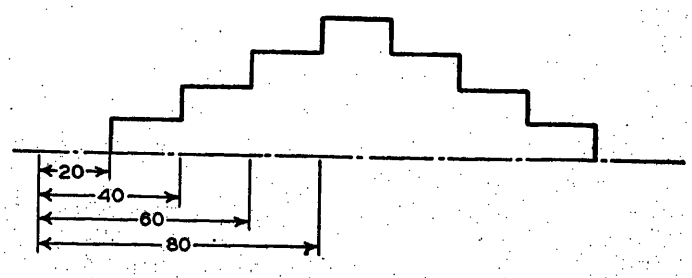



Figure 3. Flux wave

## Table XI

10 Slots Per Pole

| Pitch | 9/10 0.9 | 8/10 0.8 | 7/10 0.7 | 6/10 0.6 | 4/10 0.4 | 3/10 0.3 | 2/10 0.2 | 1/10 0.1 |
|---|---|---|---|---|---|---|---|---|
| $m$ = 1 | 125.76 | 121.1 | 113.45 | 103.00 | 74.84 | 57.8 | 39.346 | 19.916 |
| 3 | 37.82 | 24.95 | 6.64 | −13.11 | −40.37 | −41.92 | −34.34 | −19.27 |
| 5 | 18.01 | 0.00 | −18.01 | −25.47 | 0.00 | 18.01 | 25.47 | 18.01 |
| 7 | 8.258 | −10.69 | −17.97 | −5.62 | 17.3 | 2.845 | −14.71 | −16.21 |
| 9 | 2.213 | −13.46 | −6.422 | 11.445 | −8.316 | −12.61 | 4.372 | 13.974 |
| 11 | −1.8105 | −11.01 | 5.254 | 9.363 | −6.804 | 10.31 | 8.577 | −11.43 |
| 13 | −4.446 | −5.757 | 9.674 | −3.027 | 9.316 | −1.532 | −7.922 | 8.728 |
| 15 | −6.002 | 0.00 | 6.002 | −8.488 | 0.00 | −6.002 | 8.488 | −6.002 |
| 17 | −6.674 | 4.403 | −1.171 | 2.314 | −7.124 | 7.399 | −6.06 | 3.4 |
| 19 | −6.62 | 6.374 | −5.972 | 5.422 | 3.939 | −3.042 | 2.071 | −1.048 |
| 21 | −5.99 | 5.767 | −5.402 | 4.905 | 3.564 | −2.752 | 1.874 | −0.948 |
| 23 | −4.933 | 3.254 | −0.866 | 1.711 | −5.266 | 5.468 | −4.479 | 2.513 |
| 25 | −3.601 | 0.00 | 3.601 | −5.093 | 0.00 | −3.601 | 5.093 | −3.601 |
| 27 | −2.141 | −2.772 | 4.658 | −1.452 | 4.486 | −0.7377 | −3.815 | 4.202 |
| 29 | −0.6868 | −4.176 | 1.993 | 3.552 | −2.58 | 3.912 | 1.357 | −4.337 |
| 31 | 0.6426 | −3.907 | −1.865 | 3.323 | −2.415 | −3.66 | 1.27 | 4.058 |
| 33 | 1.752 | −2.268 | −3.811 | −1.192 | 3.67 | 0.6036 | −3.121 | −3.438 |

equals 0.306 of the turns per pole. The turns in slots $E$ will be 0.879 minus 0.653 equals 0.226 and in slots $G$ will be 1.00 minus 0.879 equals 0.121. This method is fundamentally sound and I recommend it to anyone interested in an exact derivation. It too is quite simple involving only 3 steps namely:

1. Looking up the sine values of the angles.
2. Correcting to a percentage basis using the maximum sine value of the particular wave as 100 per cent.
3. Subtracting from each value the value listed directly above it.

There is another type of distribution which includes the use of a full-pitch coil. We know that in practice we cannot get 2 full coils in this slot so it will be interesting to see what we should have for nearly sinusoidal wave form. We shall again use 9 slots per pole with the winding distributed over 3, 5, 7, and 9 teeth as shown in figures $E$ and $F$.

sine 10 degrees = 0.174 = 18.5 per cent.
sine 30 degrees = 0.500 = 53.2 per cent.
sine 50 degrees = 0.766 = 81.5 per cent.
sine 70 degrees = 0.940 = 100.0 per cent.

Percentage of turns over 3 teeth = 18.5 per cent
Percentage of turns over 5 teeth = 53.2 per cent
Percentage of turns over 5 teeth = 53.2 per cent
−18.5 per cent = 28.3 per cent
Percentage of turns over 7 teeth = 81.5 per cent
−53.2 per cent = 34.7 per cent
Percentage of turns over 9 teeth = 100.0 per cent
−81.5 per cent = 18.5 per cent

100.0 per cent

### Method B

Another method of calculating the percentage of turns in each coil and which involves no subtraction is still simpler. The ratio of the number of teeth spanned by the particular coil to the total number of teeth per pole is first calculated. The sine of this fraction times 90 degrees is calculated for each coil and the sum of these sines considered to be 100 per cent. The various sines expressed as a percentage of the sum of the sines is the percentage of the total number of turns per pole in the individual coil. Assume again the 36-slot stator with the winding over 2, 4, 6, and 8 teeth.

sine 2/9 × 90 degrees = sine 20 degrees = 0.342/2 teeth.
sine 4/9 × 90 degrees = sine 40 degrees = 0.643/4 teeth.
sine 6/9 × 90 degrees = sine 60 degrees = 0.866/6 teeth.
sine 8/9 × 90 degrees = sine 80 degrees = 0.985/8 teeth.

Total turns per pole equals 100 per cent = 2.836

The percentage of the total turns per pole allotted to the particular coil is then in direct proportion to the ratio of the sine of that particular angle to the sum of the sines of the angles. This expressed in percentage of the total turns per pole is:

Over 2 teeth = 0.121 or 0.342/2.836
Over 4 teeth = 0.227 or 0.643/2.836
Over 6 teeth = 0.306 or 0.866/2.836
Over 8 teeth = 0.346 or 0.985/2.836

1.000 = 100 per cent

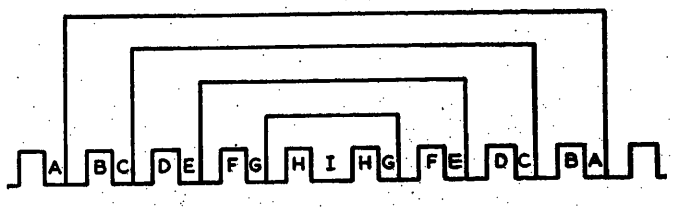



**Figure 4. Winding distribution, 9 slots per pole wound over 2, 4, 6, and 8 teeth**

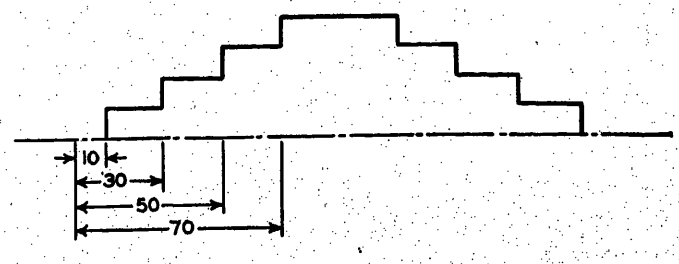



**Figure 5. Flux wave**

## Table XII

12 Slots Per Pole

| | Pitch | 11/12 0.9166 | 7/12 0.5833 | 5/12 0.4166 | 1/12 0.0833 |
|---|---|---|---|---|---|
| $m$ = | 1 | 126.23 | 101.00 | 77.5 | 16.616 |
| | 3 | 39.22 | − 16.24 | −39.22 | −16.24 |
| | 5 | 20.20 | − 25.25 | − 3.323 | 15.50 |
| | 7 | 11.07 | − 2.374 | 18.035 | −14.43 |
| | 9 | 5.414 | 13.07 | − 5.414 | 13.07 |
| | 11 | 1.51 | 7.046 | − 9.18 | −11.476 |
| | 13 | − 1.278 | − 5.962 | 7.769 | 9.712 |
| | 15 | − 3.248 | − 7.843 | 3.248 | − 7.843 |
| | 17 | − 4.56 | 0.9775 | − 7.427 | 5.941 |
| | 19 | − 5.316 | 6.644 | 0.874 | − 4.08 |
| | 21 | − 5.602 | 2.32 | 5.602 | 2.32 |
| | 23 | − 5.488 | − 4.391 | − 3.37 | − 0.7224 |
| | 25 | − 5.049 | − 4.04 | − 3.10 | − 0.6645 |
| | 27 | − 4.357 | 1.805 | 4.357 | 1.805 |
| | 29 | − 3.483 | 4.352 | 0.573 | − 2.672 |
| | 31 | − 2.50 | 0.536 | − 4.073 | 3.258 |
| | 33 | − 1.476 | − 3.565 | 1.476 | 3.565 |

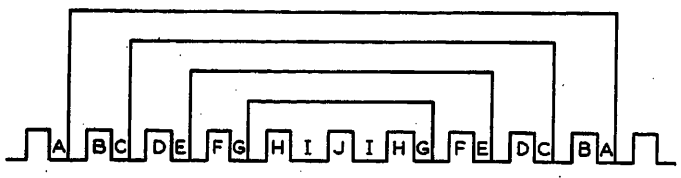



**Figure 6. Winding distribution; 9 slots per pole wound over 3, 5, 7, and 9 teeth**

Since in production it is desirable to wind the smaller coils with less turns the winding of motors for sinusoidal wave form is further desirable. It appears at present that this method can also be applied to windings where the poles overlap provided a half coil is used for the outer coil. The angle for this coil would always be 90 degrees and the sine of 90 degrees is one. A calculation with a full coil would be an impossible winding since there would be no slot room for the adjacent pole except in light starting windings. Furthermore, it would not give a very good wave form. By using half the value a practical winding is secured

## Table XIV

18 Slots Per Pole

| | Pitch | 17/18 0.9445 | 13/18 0.7223 | 11/18 0.6111 | 7/18 0.3889 | 5/18 0.2778 | 1/18 0.0555 |
|---|---|---|---|---|---|---|---|
| $m$ = | 1 | 126.82 | 115.39 | 104.29 | 73.02 | 53.81 | 11.096 |
| | 3 | 40.99 | 10.98 | − 10.98 | −40.99 | −40.99 | −10.984 |
| | 5 | 23.08 | − 14.61 | − 25.37 | 2.22 | 20.86 | 10.76 |
| | 7 | 14.90 | − 18.12 | − 7.69 | 16.49 | − 1.585 | −10.43 |
| | 9 | 10.00 | − 10.00 | 10.00 | −10.00 | −10.00 | 10.00 |
| | 11 | 6.638 | 1.009 | 10.49 | − 4.892 | 11.53 | − 9.48 |
| | 13 | 4.14 | 8.023 | − 0.854 | 9.756 | − 5.617 | 8.876 |
| | 15 | 2.197 | 8.198 | − 8.198 | − 2.197 | − 2.197 | 8.198 |
| | 17 | 0.653 | 3.166 | − 4.295 | − 6.136 | 6.788 | 7.46 |
| | 19 | − 0.584 | − 2.83 | 3.843 | 5.49 | − 6.074 | − 6.675 |
| | 21 | − 1.569 | − 5.856 | 5.856 | 1.569 | 1.569 | 5.856 |
| | 23 | − 2.34 | − 4.534 | 0.482 | − 5.514 | 3.175 | − 5.017 |
| | 25 | − 2.92 | − 0.444 | − 4.616 | 2.153 | − 5.073 | 4.172 |
| | 27 | − 3.333 | 3.333 | − 3.333 | 3.333 | 3.333 | − 3.333 |
| | 29 | − 3.596 | 4.373 | 1.855 | − 3.979 | 0.383 | 2.518 |
| | 31 | − 3.723 | 2.356 | 4.092 | − 0.358 | − 3.365 | − 1.736 |
| | 33 | − 3.727 | − 0.998 | 0.998 | 3.727 | 3.727 | 0.998 |

and one with more nearly a sinusoidal wave form. In a motor using 9 slots per pole we would then calculate the percentage of the total turns per pole for each slot as follows when using a winding over 3, 5, 7, and 9 teeth.

sine 3/9 × 90 degrees = sine 30 degrees = 0.500/3 teeth.
sine 5/9 × 90 degrees = sine 50 degrees = 0.766/5 teeth.
sine 7/9 × 90 degrees = sine 70 degrees = 0.940/7 teeth.
1/2 sine 9/9 × 90 degrees = 1/2 sine 90 degree = 0.500

100 per cent = 2.706

Percentage of turns over 3 teeth = 0.50/2.706 = 18.5 per cent
Percentage of turns over 5 teeth = 0.766/2.706 = 28.3 per cent
Percentage of turns over 7 teeth = 0.940/2.706 = 34.7 per cent
Percentage of turns over 9 teeth = 0.50/2.706 = 18.5 per cent

100.0 per cent

The few minutes spent to determine how a winding should be distributed are well spent. Instead of depending on a lucky guess mathematics is used.

## Table XIII

15 Slots Per Pole

| | Pitch | 14/15 0.933 | 13/15 0.8667 | 11/15 0.733 | 8/15 0.5333 | 7/15 0.4667 | 4/15 0.2667 | 2/15 0.1333 | 1/15 0.0667 |
|---|---|---|---|---|---|---|---|---|---|
| $m$ = | 1 | 126.61 | 124.53 | 116.31 | 94.62 | 85.2 | 51.79 | 26.47 | 13.31 |
| | 3 | 40.37 | 34.34 | 15.12 | −24.95 | −34.34 | −40.37 | −24.95 | −13.12 |
| | 5 | 22.06 | 12.73 | − 12.73 | −22.06 | −12.73 | 22.06 | 22.06 | 12.73 |
| | 7 | 13.52 | 1.902 | − 17.79 | 7.40 | 16.62 | − 3.78 | −18.09 | −12.17 |
| | 9 | 8.316 | − 4.373 | − 11.45 | 13.46 | 4.373 | − 8.316 | 13.46 | 11.45 |
| | 11 | 4.708 | − 7.746 | − 1.21 | − 2.406 | −11.32 | 11.51 | − 8.602 | −10.574 |
| | 13 | 2.036 | − 8.947 | 6.554 | − 9.74 | − 1.024 | − 7.278 | 3.984 | 9.58 |
| | 15 | 0.00 | − 8.488 | 8.488 | 0.00 | 8.488 | 0.00 | 0.00 | − 8.488 |
| | 17 | − 1.557 | − 6.842 | 5.012 | 7.448 | − 0.783 | 5.566 | − 3.047 | 7.326 |
| | 19 | − 2.726 | − 4.485 | − 0.701 | 1.393 | − 6.555 | − 6.664 | 4.98 | − 6.122 |
| | 21 | − 3.564 | − 1.874 | − 4.905 | − 5.766 | 1.874 | 3.564 | − 5.766 | 4.905 |
| | 23 | − 4.114 | 0.5787 | − 5.414 | − 2.252 | 5.057 | 1.151 | 5.505 | − 3.704 |
| | 25 | − 4.411 | 2.546 | − 2.546 | 4.411 | − 2.546 | − 4.411 | − 4.411 | 2.546 |
| | 27 | − 4.485 | 3.816 | 1.457 | 2.772 | − 3.816 | 4.485 | 2.722 | − 1.457 |
| | 29 | − 4.365 | 4.294 | 4.010 | − 3.263 | 2.938 | − 1.786 | − 0.913 | 0.459 |
| | 31 | − 4.085 | 4.018 | 3.753 | − 3.053 | 2.749 | − 1.671 | − 0.854 | 0.429 |
| | 33 | − 3.670 | 3.122 | 1.193 | 2.268 | − 3.122 | 3.67 | 2.268 | − 1.193 |

## Table XV. Strength of Harmonics for Various Distributions

| h | 9 Slots Per Pole | | | | | | |
|---|---|---|---|---|---|---|---|
| | 1–1–1–1 over 4–6–6–10 | 1–1–1–1 over 2–4–6–8 | 1–1–1–1 over 3–5–7–9 | 1–2–2–1 over 3–5–7–9 | 2–2–2–1 over 3–5–7–9 | 1–2–2–3 over 2–4–6–8 | 1–1–1 over 4–6–8 |
| 1 | 100 | 100 | 100 | 100 | 100 | 100 | 100 |
| 3 | 8.29 | −10.2 | 0 | 0 | −6.15 | 0.00 | 0.00 |
| 5 | 0.436 | 2.96 | 0.933 | −2.96 | −0.833 | 1.6 | −6.1 |
| 7 | 3.3 | −0.915 | 4.04 | 0.92 | 5.01 | 1.43 | 1.96 |
| 9 | 0.0 | 0 | 0 | 0.0 | −2.05 | 0 | 0 |
| 11 | −2.1 | 0.58 | 2.33 | 0.6 | 1.37 | −0.906 | 1.68 |
| 13 | −0.397 | −1.14 | 0.927 | −1.14 | −0.322 | −0.615 | 1.74 |
| 15 | −1.66 | 2.03 | 0 | 0.0 | −1.23 | 0.0 | 0 |
| 17 | −5.88 | −5.88 | 5.87 | 5.88 | 5.87 | −5.95 | −5.93 |
| 19 | −5.25 | −5.26 | 5.26 | 5.27 | 5.25 | −5.33 | −5.25 |
| 21 | −1.18 | 1.45 | 0 | 0.0 | −0.89 | 0.0 | 0 |
| 23 | −0.0968 | −0.642 | 0.526 | −0.633 | −0.182 | −0.346 | 0.985 |
| 25 | −0.924 | 0.255 | 0.113 | 0.257 | −0.603 | −0.4 | −0.74 |
| 27 | 0 | 0 | 0 | 0.0 | −0.685 | 0 | 0 |
| 29 | 1.02 | −0.221 | 0.972 | 0.0616 | 0.374 | 0.6 | 0.635 |
| 31 | 0.716 | 0.477 | 0.389 | 0.478 | 0.135 | −0.257 | −0.73 |
| 33 | 0.745 | 0.925 | 0 | 0.0 | 0.56 | 0.843 | 0 |

| h | 1–2–3 over 4–6–8 | 1–1–1 over 5–7–9 | 2–2–1 over 5–7–9 | A* | B** | C† | D†† |
|---|---|---|---|---|---|---|---|
| 1 | 100 | 100 | 100 | 100 | 100 | 100 | 100 |
| 3 | 10.8 | 12.2 | 7.55 | −0.08 | 4.6 | 20.6 | 1.43 |
| 5 | −0.548 | −0.835 | −5.66 | 0.00 | 0.92 | −6.1 | −1.3 |
| 7 | 0.75 | 2.15 | −0.578 | −0.04 | 1.44 | 4.2 | 1.16 |
| 9 | 0.00 | 4.1 | 2.52 | 0.00 | 0.00 | −4.0 | −0.953 |
| 11 | −0.477 | 1.37 | −0.38 | −0.02 | 0.92 | −2.8 | −0.279 |
| 13 | −0.212 | −0.322 | −2.14 | 0.008 | 1.24 | −2.3 | −0.524 |
| 15 | −2.17 | 2.46 | 1.51 | 0.01 | 0.92 | 4.1 | 0.286 |
| 17 | −5.88 | 5.88 | −5.88 | −5.88 | −5.88 | 6.5 | 6.49 |
| 19 | −5.27 | 5.3 | −5.25 | −5.27 | −5.25 | 5.3 | 5.8 |
| 21 | −1.55 | 1.76 | −1.08 | −0.09 | −0.64 | 2.9 | 0.203 |
| 23 | 0.119 | −0.153 | −1.21 | −0.09 | 0.73 | −1.3 | −0.29 |
| 25 | −0.21 | 0.6 | 0.169 | 0.01 | −0.427 | −0.25 | 0.331 |
| 27 | 0.00 | 0.137 | 0.84 | 0.00 | 0.00 | −0.00 | −0.27 |
| 29 | 0.18 | 0.52 | −0.685 | 0.08 | 0.41 | 0.2 | 0.386 |
| 31 | −0.089 | −0.095 | −0.88 | 0.00 | −0.52 | −0.2 | −0.209 |
| 33 | 0.985 | 0.112 | 0.688 | 0.01 | −0.42 | 0.8 | 0.132 |

* *A* is 0.122 over 2, 0.226 over 4, 0.306 over 6, and 0.346 over 8 teeth
** *B* is 0.258 over 4, 0.348 over 6, and 0.394 over 8 teeth
† *C* is 0.167 over 5, 0.333 over 7, and 0.500 over 9 teeth. (This is the same as 1–2–3 over 5–7–9)
†† *D* is 0.185 over 3, 0.283 over 5, 0.347 over 7, and 0.185 over 9 teeth

Table XV showing the relative strengths of the different harmonics of the above winding distribution shows how small the harmonics are. This table also shows a number of other possible distributions, some with harmonics as high as 10 to 20 per cent of the fundamental. That this is an undesirable condition from both a torque and noise standpoint need hardly be mentioned, but it should bring forcibly to the designer's attention the desirability of distributing the winding for sinusoidal wave form.

My suggestion to the designer is to calculate the percentage of total turns in each slot for the various distributions he most frequently uses. He will then refer to this sheet when calculating each new winding. I am including the most common distributions in table XVI. For the man who wants to figure the strength of the harmonic fields, I suggest that he also make a set of tables for the strength of the various harmonics for the individual coils of the pole.

The strengths of the various harmonics for each individual coil of the pole are figured and are added algebraically to get the strength of the various harmonics for the complete pole. Careful attention must be paid to the signs.

I am including some of my tables with this article to help the designer. He will very probably note that there are 2 harmonics which regardless of the method of winding distribution he cannot overcome. The number of these harmonics is twice the number of stator slots per pole plus or minus one. If, for example, 9 slots per pole are used the seventeenth and nineteenth harmonics cannot be eliminated regardless of how the motor is wound. They can, however, be skewed out. This will be discussed under the subject of skew.

It should also be mentioned that it is at times necessary for the designer to secure special results as for example in the design of a 2-speed motor. He usually develops what is known among engineers as a freak circuit. When this is the case it is sometimes so complicated and impossible to calculate the various harmonics present that he usually goes back to the method of cut and try. Needless to say, some of the motors using these circuits are very noisy.

## Skew

We have already discussed the selection of the proper number of rotor bars and the winding distribution to secure nearly sinusoidal wave form. We noted in the

section on wave form that there were 2 harmonics always present regardless of how we wound the stator.

We know that if we want to get a current flow in a wound armature we must put one side of each coil under a north pole and the other side under a south pole. If we should place both sides of the coil under like poles no current would flow. One theory of skew is based exactly on this idea. Referring again to our case of 9 slots per pole we have the seventeenth and nineteenth harmonics present regardless of the method of winding. We shall assume that there are no other bad harmonics because proper winding distribution was used. Since the fundamental has 4 poles the seventeenth and nineteenth harmonics have 68 and 76 poles, respectively, or 34 and 38 pairs of poles. It is now our object to place one end of the rotor bar under one north harmonic pole and the other end under another north harmonic pole. This will prevent any current flowing in the rotor caused by the harmonic pole.

The rotor should be skewed 1/34 of the entire rotor to eliminate the seventeenth harmonic and 1/38 of the entire rotor to eliminate the nineteenth harmonic. If we were using a 44-bar rotor the skew to eliminate the seventeenth harmonic would be 1/34 times 44 equals 1.29 bar skew. To eliminate the nineteenth harmonic we would need 1/38 times 44 equals 1.16 bar skew. If the rotor were held as nearly commercially as possible to these limits there should be little trouble caused by the seventeenth and nineteenth harmonics. Now that we have pointed out the best skew from a harmonic viewpoint let us point out the

**Table XVI. Winding Distribution for Sinusoidal Wave Form**

| Tooth Span | Per Cent Turns Per Slot | | | | | Tooth Span | Per Cent Turns Per Slot | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **18 Slots Per Pole** | | | | | | | | | | | |
| 4 | 6.3 | | | | | 3 | 4.6 | | | | |
| 6 | 9.0 | 9.6 | | | | 5 | 7.5 | 7.8 | | | |
| 8 | 11.6 | 12.4 | 13.7 | | | 7 | 10.2 | 10.6 | 11.5 | | |
| 10 | 13.8 | 14.7 | 16.4 | 18.9 | | 9 | 12.5 | 13.2 | 14.2 | 16.1 | |
| 12 | 15.7 | 16.7 | 18.4 | 21.3 | 26.8 | 11 | 14.5 | 15.2 | 16.5 | 18.6 | 22.2 |
| 14 | 17.0 | 18.1 | 20.0 | 23.2 | 28.6 | 13 | 16.0 | 16.8 | 18.2 | 20.6 | 24.6 |
| 16 | 17.8 | 18.9 | 20.9 | 24.3 | 29.9 | 15 | 17.1 | 17.9 | 19.5 | 22.0 | 26.2 |
| 18 | 9.0 | 9.6 | 10.6 | 12.3 | 15.2 | 17 | 17.6 | 18.5 | 20.1 | 22.7 | 27.0 |
| KW | 0.808 | 0.835 | 0.873 | 0.909 | 0.944 | | 0.794 | 0.820 | 0.854 | 0.892 | 0.927 |
| **16 Slots Per Pole** | | | | | | | | | | | |
| 4 | 7.9 | | | | | 3 | 5.8 | | | | |
| 6 | 11.3 | 12.4 | | | | 5 | 9.4 | 10.0 | | | |
| 8 | 14.4 | 15.7 | 17.9 | | | 7 | 12.7 | 13.4 | 14.9 | | |
| 10 | 17.2 | 18.5 | 21.1 | 25.7 | | 9 | 15.4 | 16.4 | 18.2 | 21.4 | |
| 12 | 18.9 | 20.5 | 23.4 | 28.5 | 38.4 | 11 | 17.6 | 18.7 | 20.8 | 24.5 | 31.1 |
| 14 | 20.0 | 21.8 | 24.9 | 30.3 | 40.8 | 13 | 19.2 | 20.4 | 22.6 | 26.5 | 33.8 |
| 16 | 10.3 | 11.1 | 12.7 | 15.5 | 20.8 | 15 | 19.9 | 21.1 | 23.5 | 27.6 | 35.1 |
| KW | 0.812 | 0.848 | 0.889 | 0.928 | 0.963 | | 0.797 | 0.829 | 0.868 | 0.910 | 0.946 |
| **12 Slots Per Pole** | | | | | | | | | | | |
| 2 | 6.8 | | | | | 3 | 10.3 | | | | |
| 4 | 13.2 | 14.1 | | | | 5 | 16.5 | 18.3 | | | |
| 6 | 18.6 | 20.0 | 23.3 | | | 7 | 21.4 | 24.0 | 29.3 | | |
| 8 | 22.8 | 24.5 | 28.5 | 37.2 | | 9 | 25.0 | 27.8 | 34.1 | 48.2 | |
| 10 | 25.4 | 27.3 | 31.8 | 41.4 | 65.9 | 11 | 26.8 | 29.9 | 36.6 | 51.8 | |
| 12 | 13.2 | 14.1 | 16.4 | 21.4 | 34.1 | | | | | | |
| KW | 0.789 | 0.829 | 0.883 | 0.936 | 0.977 | | 0.809 | 0.854 | 0.910 | 0.959 | |
| **9 Slots Per Pole** | | | | | | | | | | | |
| 2 | 12.1 | | | | | 3 | 18.5 | | | | |
| 4 | 22.7 | 25.7 | | | | 5 | 28.3 | 34.7 | | | |
| 6 | 30.6 | 34.8 | 47.8 | | | 7 | 34.7 | 42.6 | 65.3 | | |
| 8 | 34.6 | 39.5 | 52.2 | | | 9 | 18.5 | 22.7 | 34.7 | | |
| KW | 0.793 | 0.855 | 0.929 | | | | 0.821 | 0.893 | 0.961 | | |
| **8 Slots Per Pole** | | | | | | | | | | | |
| 2 | 15.3 | | | | | | | | | | |
| 4 | 28.0 | 33.1 | | | | 3 | 27.6 | | | | |
| 6 | 36.8 | 43.4 | 64.8 | | | 5 | 33.2 | 45.8 | | | |
| 8 | 19.9 | 23.5 | 35.2 | | | 7 | 39.2 | 54.2 | | | |
| KW | 0.795 | 0.870 | 0.950 | | | | 0.815 | 0.913 | | | |
| **6 Slots Per Pole** | | | | | | | | | | | |
| 2 | 26.8 | | | | | 3 | 42.3 | | | | |
| 4 | 46.4 | 63.4 | | | | 5 | 57.7 | | | | |
| 6 | 26.8 | 36.6 | | | | | | | | | |
| KW | 0.804 | 0.914 | | | | | 0.856 | | | | |
| **4 Slots Per Pole** | | | | | | | | | | | |
| 2 | 60.8 | | | | | | | | | | |
| 4 | 39.2 | | | | | | | | | | |
| KW | 0.822 | | | | | | | | | | |

worst. This condition exists when one end of the rotor bar lies under a north harmonic pole and the other end under a south harmonic pole. Since the seventeenth harmonic has 68 poles and the nineteenth has 76 poles the worst condition would be 1/68 times 44 equals 0.645 bar skew and 1/76 times 44 equals 0.58 bar skew.

Another condition that would not be good but which is better than the one just described is the existence of a 3-harmonic pole skew. This skew would be 3/68 times 44 equals 1.94 bars for the seventeenth harmonic and 3/76 times 44 equals 1.73 bars for the nineteenth harmonic. With this condition one end of the rotor bar would be under a north pole and the other end under a south pole. However, since the point one-third of the distance from the one would be under a pole of the same polarity as the beginning of the bar there would be a tendency to prevent a current flow in 2/3 of the bar.

Another factor to keep in mind when figuring skew is the effect of skew on the various modes of vibration of the frame as discussed by S. J. Wikina. There are 4 modes of vibration. The energy input per pole to the first, second, and fourth modes of vibration is zero with a skew of 1, 2, or any integral number of slot pitches. The maximum energy input with over one bar skew is never greater than 20 per cent of that with no skew. To eliminate the third mode of vibration it is necessary to have a skew of 1.43 bars or to have the number of rotor bars divisible by the number of poles. The energy is maximum at 2/3 bar skew. This is the most critical of the 3 modes rising rapidly on either side of the zero energy point. If, therefore, it is possible to eliminate the third mode of vibration by having the number of rotor bars divisible by the number of poles this third mode will be completely eliminated and the first and second will be lessened. Then by skewing the rotor one bar or more the first, second, and fourth modes will either be eliminated or made quite small. While I have never personally designed a quiet motor with this last method in mind, the engineer studying this paper will note that some of the designs discussed fulfill at least to some extent the requirements by meeting other requirements set forth in the earlier part of this work. The 44-bar rotor when used on a 4-pole motor is divisible by the number of poles. The same applies to the 20- and 34-bar rotors of the 2-pole motor. Since I never use less than one bar skew except on very short armatures other difficulties have been avoided.

In summarizing, there are some general statements that it is well to bear in mind.

1. Be sure the motor is built carefully in production.
2. The winding should be distributed so that all but 2 harmonics are eliminated.
3. The rotor should be skewed to eliminate these 2 harmonics and not less than one bar.
4. The number of rotor bars should be carefully selected so there will be no harmonics with a 2-pole difference. It may be advantageous to use a rotor with the number of bars divisible by the number of poles where necessary.
5. There should be no magnetic parts extremely light that will vibrate excessively. This especially refers to teeth and tooth tips.

Tables IV to XVI were calculated in 1917. They give the center ordinate value of the sinusoidal magnetomotive forces produced by a current of the instantaneous value of one ampere in a coil of 100 turns for the fundamental and all harmonics to the 33rd inclusive. The formula used for this calculation is:

$$h_m = \frac{4In_0}{m\pi} \times \sin\frac{m\pi}{2} \sin\frac{m\lambda\pi}{2}$$

in which

$h_m$ is the center ordinate value of the $m$th harmonic
$I$ is the value of the current at the given instant
$n_0$ is the number of turns per coil
$m$ is the order of the harmonic
$\lambda$ is the pitch expressed as a decimal fraction

The tabulated values are for a single coil. For distributed windings the resultant for the whole winding may be found as follows: For concentric windings, take from the tables the values for each of the coils separately, then add the respective values, with due regard to sign. The result will be the resultant of the whole winding. For diamond windings, multiply the tabular values for the center ordinate, by the expression

$$\frac{\sin\frac{m\pi}{2p'}}{\sin\frac{mp'}{2M_{sp}}}$$

in which $p'$ is the number of phase belts per pole and $M_{sp}$ is the number of slots per pole. The values of this factor are very easily calculated. This gives magnetomotive force per phase belt.

For single phase or 2-phase windings, concentric or diamond, the magnetomotive force per phase belt is also the magnetomotive force for the entire stator winding. For three-phase windings, the magnetomotive force for the entire winding is found by multiplying the magnetomotive force per phase belt by the factor $(p'/2)$ except for the harmonics whose number is divisible by 3, for which the factor zero is to be used; the latter harmonics are therefore not present in 3-phase windings.

This method was first published in *Electrical World*, August 26, 1909.

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# A Formula for the Reactance of the Interleaved Component of Transformers

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THE REACTANCE of a power transformer is materially changed when connection is made to taps of different voltages. This can be computed for concentric, core-type transformers by dividing the winding into a concentric component and an interleaved component according to the method of H. O. Stephens.[1]

The concentric component is an assumed transformer winding in which the secondary ampere-turns are equal and opposite to the primary ampere-turns for each centimeter along the axis. The cylinder of winding of the actual transformer which has no part tapped out, is taken as one of the windings of the concentric component. The other winding of the concentric component matches the first exactly in ampere-turns per centimeter along the axis, magnetizing current being left out of consideration.

The interleaved component of winding is what is needed to be added to the concentric component to make the total equal to the actual transformer for the particular connection considered. Nothing needs to be added to the cylinder which has no part tapped out and so the interleaved component is a single cylinder. Its positive and negative ampere-turns are equal and opposite. See figure 1 and the descriptions in reference 1.

It is evident, from the simple rules just given by which the interleaved component is defined, that the number of ampere-turns of the parts of the interleaved component of winding, and their location, can be easily determined without any special formulas. Examples are clearly illustrated in reference 1. See also example I of this paper.

The leakage reactance $X$ of a transformer when expressed in ohms is referred to either the primary side or the secondary. This is the same as finding the leakage reactance in ohms of a one-to-one ratio transformer. If $I$ is the current of the side taken, the stored energy of the leakage magnetic field is $I^2X$ and is equal to the summation of $H^2/8\pi$ for every cubic centimeter of the leakage magnetic field. Magnetizing current is taken equal to zero, or in other words the iron is assumed to have zero reluctance so far as the computation of leakage reactance is concerned.

If the primary and secondary of the one-to-one ratio transformer are connected in series and the current $I$ is sent through them in the proper directions, the magnetic field will be the same as the leakage magnetic field, because it is produced by the same currents. $H^2/8\pi$ will be the same and the stored energy $I^2X$ will be the same. But $X$ is now $2\pi fL$ where $L$ is the self-inductance of the complete circuit. This provides a method for computing $X$, which is used in the appendix.

Since the ampere-turns of the concentric and interleaved components are together equal to the ampere-turns of the actual transformer, the summation of $H^2/8\pi$ when both are carrying current gives $I^2X$ for the transformer. The magnetic field of the concentric component is chiefly axial where the density is greatest and the most energy is stored, and the densest parts of the field of the interleaved component are radial. See figures 2 and 3, reference 1.

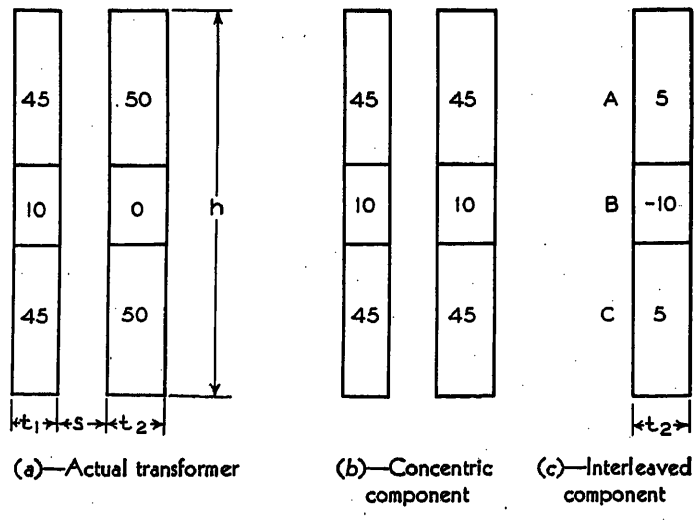



**Figure 1. Cross section of core-type transformer winding**

The fields of the 2 components are chiefly at right angles.

In any cubic centimeter, the stored energy of 2 fields $H_1$ and $H_2$ which are at right angles is $(H_1^2 + H_2^2)/8\pi$. As a consequence, the reactances of the concentric and interleaved components may be computed separately and added together to give, very nearly, the reactance of the tapped-out transformer. See the discussion by A. Boyajian, ELECTRICAL ENGINEERING (AIEE TRANSACTIONS), 1934, page 1318. This has been shown to be a close approximation, by comparing the result with the transformer reactance computed by methods not involving the division into concentric and interleaved components. Tests on practical transformers also have shown the accuracy of the method. See the discussion by A. N. Garin, ELECTRICAL ENGINEERING (AIEE TRANSACTIONS), 1934, page 1319.

The study of interleaved components has shown that the reactance can be reduced and the eddy-current losses

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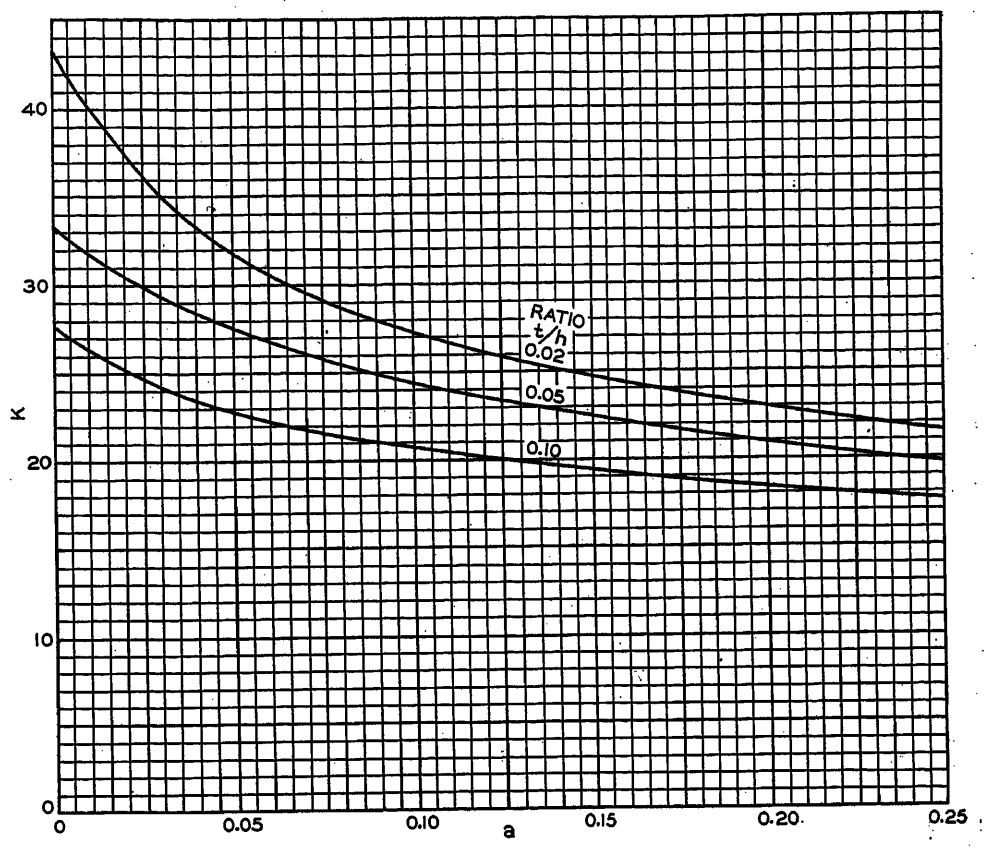
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1. For all numbered references, see list at end of paper.

**Figure 2. Curves for reactance of interleaved component**

$a$ = ratio of height of middle rectangle to $h$

$X_t = KfmT^2 10^{-9}$ ohms per leg




in the copper minimized, by thinning out the turns in one winding opposite the tapped-out section of the other winding. See reference 1. This reduces the radial flux or "cross flux." The definition of interleaved component which has been given applies quite well to the case of thinned out transformer windings and so no special arrangements are necessary in the computation. All that is needed is to find the ampere-turns of the interleaved component and then the reactance of the 2 components of winding.

The paragraghs up to this point are a review of the material developed by H. O. Stephens in his paper.[1]

The leakage reactance of one leg of a concentric, core-type transformer without tapped-out sections is given very closely by the following well-known formula:[2]

$$X_c = \frac{8\pi^2 N^2 f m_1 10^{-9}}{h}\left(s + \frac{t_1}{3} + \frac{t_2}{3}\right) \text{ ohms} \qquad (1)$$

For the meaning of the letters see figure 1. Also, $N$ is the number of turns of one cylinder of one winding, $m_1$ is the length of mean turn for the transformer, dimensions being in centimeters, and $f$ is the frequency.

For the interleaved component of one leg of a core-type transformer which has one central tapped-out section, as shown in figure 1, find $T$, the number of turns in the tapped-out section in the interleaved component. See the third paragraph of this paper. Then, as derived in the appendix,

$$X_t = \frac{4.605\pi f m T^2 10^{-9}}{a(1-a)^2}\,[(1+a)^2 \log_{10} S_{AB} - (1-a)^2 \log_{10} S_A - 2a \log_{10} S_B - 2a \log_{10} S_{ABC}] \text{ ohms} \qquad (2)$$

The rectangles $A$, $B$, and $C$ are shown in figure 1*c*.

$m$ = mean turn in centimeters of the interleaved component.

$T$ = number of turns in $B$ of the interleaved component.

$a$ = ratio of the axial length of rectangle $B$ to the length of the complete rectangle $ABC$.

$S_{AB}$ = length + width, of the rectangle $AB$, and similarly for the other rectangles.

In figure 2, curves are given by which most of the computation of formula 2 may be avoided.

Formula 2 was derived in connection with thesis work at Massachusetts Institute of Technology.

*Example I.* The transformer shown in figure 1 has a tapped-out portion equal to 20 per cent of the secondary turns. Opposite this part, the primary winding has only 10 per cent of its turns, the winding being thinned out by spacing the individual coils farther apart. If $N$ is the number of turns in one cylinder of the secondary winding when not tapped, then $T$ for formula 2 is 0.1 $N$ when operating on the 80-per-cent tap. When the transformer is operating on the 100-per-cent tap, the numerical value of $T$ is also 0.1 $N$. The figures in figure 1 are percentages.

If the primary winding were not thinned out, then for operation on the 80-per-cent tap the value of $T$ would be 0.2 $N$, and the increase in reactance would be 4 times as great, since it varies as $T^2$.

*Example II.* This utilizes the sample design of a 1,000-kva 575-to-13,800-volt 60-cycle transformer given on page 395 of "Design of Electrical Apparatus," by J. H. Kuhlmann.

The low-voltage winding is considered the primary. It is not thinned out. One-fifth of the turns of the high-voltage winding are tapped out, thus giving 11,000 volts.

The high-voltage windings are taken to be connected in star in this problem.

Mean turn, low voltage, 39.4 inches and high voltage, 53.9 inches.
Thickness of windings, low voltage 1.03 inches, high voltage 1.45 inches.
Insulation space between high and low windings, 1.063 inches.
Length of coils, 23.5 inches.
Number of turns per phase in the untapped high-voltage winding = 512.

The lengths of rectangles $A$, $B$, and $C$, figure 1$c$, are 9.4, 4.7, and 9.4 inches and their width is 1.45 inches. The reactance $X_c$ of the concentric component is computed by 1. It is the same in this case as the reactance of the transformer when it is operated on the 100-per-cent tap.

$$X_c = 8\pi^2 \times 512^2 \times 60 \times 46.65 \times 2.54 \times 10^{-9} \times \frac{1}{23.5}\left(1.063 + \frac{1.03}{3} + \frac{1.45}{3}\right)$$

= 11.83 ohms, referred to the high-voltage side

$$\text{Per cent } X_c = \frac{11.83 \times 41.8 \times 1.732 \times 100}{13800} = 6.21 \text{ per cent}$$

The reactance $X_t$ of the interleaved component is given by 2, the value of $T$ being 102.

$$\log_{10} S_{AB} = \log_{10}(9.4 + 4.7 + 1.45) = \log_{10} 15.55 = 1.19173$$

Inch dimensions are permissible for $S_{AB}$ etc. as described in the appendix.

$$\log_{10} S_A = \log_{10}(9.4 + 1.45) = 1.0354$$
$$\log_{10} S_B = \log_{10}(4.7 + 1.45) = 0.7889$$
$$\log_{10} S_{ABC} = \log_{10} 24.95 = 1.3971$$
$$a = 0.2$$

$$X_t = 4.605\pi \times 60 \times 53.9 \times 2.54 \times 102^2 \times 10^{-9} \times \frac{1}{0.2 \times 0.64} \times [1.44 \times 1.19173 - 0.64 \times 1.0354 - 0.4 \times 0.7889 - 0.4 \times 1.3971] = 1.74 \text{ ohms}$$

This result can be obtained from figure 2, using $a = 0.2$, $t/h = 0.062$ and $K = 20.4$.

$$\text{Per cent } X_t = \frac{1.74 \times 41.8 \times 1.732 \times 100}{13800} = 0.91 \text{ per cent.}$$

Reactance of the tapped transformer = 6.21 + 0.91 = 7.12 per cent

Thus, the reactance is increased about one-seventh by tapping out the section.

The rated input to the tapped transformer is taken to be 1,000 kva at 575 volts, the same as for the untapped transformer, neglecting magnetizing current.

The way in which $N$ and $T$ are used, and the way in which reactance ohms are converted to percentages, should be noted, as the definitions for these items perhaps may be taken most easily from the example.

In order to make an approximate check of the calculations, a $^1/_4$-size model of the transformer coils was made. The reactance of the coils was measured without any iron core. In order to have the reactance larger than the resistance, 530-cycle current was used. The reactance then was corrected for 60-cycle current and for size. The result was 6.3 per cent for the tapped transformer, to compare with 7.12 per cent computed.

A $^1/_4$-size model of the interleaved component of the windings also was made and tested. Its reactance was 1.0 per cent, to compare with 0.91 per cent computed.

This test should be considered as a preliminary, approximate check. The question of the accuracy and usefulness of formula 2 presented in this paper should be settled by its application to the cases of practical power transformers, whose reactance has been accurately tested in the usual way.

## Appendix

### Derivation of Formula 2

The interleaved component has the same number of positive as negative ampere-turns. Assuming that the windings of the 3 rectangles $A$, $B$, and $C$, figure 1$c$, are connected in series,

$$L_t = 2L_A + L_B - 4M_{AB} + 2M_{AC} \tag{3}$$

since $A$ and $C$ are the same size and their current is opposite in direction to that of $B$.

Let $L_{AB}^{(B)}$ = self-induction of $A$ and $B$ connected in series but with current direction and winding density in turns per square centimeter in both the same as in $B$. Let $k$ = ratio of winding density of $B$ to that of $A$.

$$L_{AB}^{(B)} = L_A^{(B)} + L_B + 2M_{AB}^{(B)} \tag{4}$$

since the entire inductive voltage drop in $AB$ is made up of drop in $A$ caused by its own current plus drop in $B$ caused by its own current plus drop in $A$ caused by current in $B$ plus drop in $B$ caused by current in $A$.

$$2M_{AB}^{(B)} = 2kM_{AB} = L_{AB}^{(B)} - k^2L_A - L_B$$

$$2M_{AB} = \frac{1}{k} L_{AB}^{(B)} - kL_A - \frac{1}{k} L_B \tag{5}$$

$$L_{ABC}^{(B)} = 2L_A^{(B)} + L_B + 4M_{AB}^{(B)} + 2M_{AC}^{(B)} = 2L_{AB}^{(B)} - L_B + 2M_{AC}^{(B)}$$

from 4.

$$2M_{AC} = \frac{2}{k^2} M_{AC}^{(B)} = \frac{1}{k^2} L_{ABC}^{(B)} - \frac{2}{k^2} L_{AB}^{(B)} + \frac{1}{k^2} L_B \tag{6}$$

From 3,

$$L_t = 2L_A + L_B - \frac{2}{k} L_{AB}^{(B)} + 2kL_A + \frac{2}{k} L_B + \frac{1}{k^2} L_{ABC}^{(B)} - \frac{2}{k^2} L_{AB}^{(B)} + \frac{1}{k^2} L_B$$

$$L_t = 2(1 + k)L_A + \left(1 + \frac{2}{k} + \frac{1}{k^2}\right) L_B + \frac{1}{k^2} L_{ABC}^{(B)} - \frac{2}{k}\left(1 + \frac{1}{k}\right) L_{ABC}^{(B)} \tag{7}$$

Turns in $B = T$
Turns in $A = T/2$
Turns in $AB^{(B)} = T + kT/2$
Turns in $ABC^{(B)} = T + kT$

$$L_A = 2m \frac{T^2}{4} \log_n \frac{u}{G_A} \text{ abhenries}$$

$$L_B = 2mT^2 \log_n \frac{u}{G_B} \text{ abhenries}$$

$$L_{AB}^{(B)} = mT^2 \frac{(2+k)^2}{2} \log_n \frac{u}{G_{AB}} \text{ abhenries}$$

$$L_{ABC}^{(B)} = 2mT^2 (1+k)^2 \log_n \frac{u}{G_{ABC}} \text{ abhenries}$$

where logn denotes natural logarithm, where $u$ is a certain large distance to which flux is counted and which cancels out later, and where $G_A$ is the self geometric mean distance of the rectangle $A$, and similarly for the other rectangles. This type of computation, which applies quite well for transformer reactance, deals with the reactance per centimeter of the circuit made up of the primary and secondary windings, and it is assumed that the effect of their curvature is negligible.

From 7,

$$L_t = mT^2(1+k) \log_n \frac{u}{G_A} + 2mT^2 \left(1+\frac{1}{k}\right)^2 \log_n \frac{u}{G_B} +$$

$$2mT^2 \left(1+\frac{1}{k}\right)^2 \log_n \frac{u}{G_{ABC}} - mT^2 \left(\frac{2+k}{k}\right)^2 (1+k) \log_n \frac{u}{G_{AB}} \quad (8)$$

From the definition of $a$ following equation 2 and from the fact that the total turns in $A$, $B$, and $C$ of the interleaved component are zero,

$$ka - (1-a) = 0$$

$$k = \frac{1-a}{a}$$

$$1 + k = \frac{1}{a}$$

$$1 + \frac{1}{k} = \frac{1}{1-a}$$

$$\left(\frac{2+k}{k}\right)^2 (1+k) = \frac{(1+a)^2}{a^2} \frac{a^2}{(1-a)^2} \frac{1}{a} = \frac{(1+a)^2}{a(1-a)^2}$$

A very close approximation[3] to the self geometric mean distance of a rectangular area is 0.2235 times (sum of sides). If this is used in 8, the following is obtained:

$$L_t = \frac{2.303mT^2}{a(1-a)^2} [(1+a)^2 \log_{10} S_{AB} - (1-a)^2 \log_{10} S_A - 2a \log_{10} S_B - 2a \log_{10} S_{ABC}] \quad (9)$$

From this, 2 is directly obtained.

The coefficient of logn $u$ in 8 is

$$1 + 2a + a^2 - (1 - 2a + a^2) - 4a$$

which is equal to zero, and so $u$ cancels out. In the same way, 0.2235 cancels out and does not appear in the final formula. Also, if $S_{AB}$, etc., are given in inches, their multipliers 2.54 cancel out, but this does not apply to the dimension $m$, which must always be changed to centimeters.

## References


1. Transformer Reactance and Losses With Non-Uniform Windings, H. O. Stephens. AIEE Transactions, volume 53, 1934, page 346.

2. Electrical Machine Design, A. Gray and P. M. Lincoln. Page 447, equation 65, and other textbooks.

3. Formulas and Tables for Mutual and Self-Induction, E. B. Rosa and F. W. Grover. Sci. Paper 169 of the Bureau of Standards, equation (128), page 167.


# "Inside a Metal"

CAREFUL RESEARCH into the nature of the metallic state has yet to discover, with any certainty, its essential quality, says L. R. van Wert, lecturer on metallurgy, Harvard University, Cambridge, Mass., in an article of the above title published in the October 1937 issue of *Mining and Metallurgy*, pages 453–8.

The basic fact underlying nearly all metallic behavior is that a metal is crystalline in its nature; any mass of metal that has been formed in the ordinary way is made up of many small crystals tightly bound together. It is true that a few properties, such as valence and ferromagnetism, are atomic in origin, so one must actually go within the atom for their ultimate source, but excepting these, metallic properties come about through varieties in interatomic organization.

All matter is atomic in nature, and the metals are no exception. However, with respect to the way the atoms are arranged matter is of 2 kinds: isotropic, of which liquids and gasses are examples; and crystalline, of which metals are examples. The crystalline state of matter is characterized, first, by a lower total energy than the isotropic form, and secondly, by the atoms being essentially at rest, and in regularly and definitely spaced positions. This regularity in atomic spacing confers on the crystal a definite internal architecture in which a certain pattern, often quite simple, is indefinitely repeated. This unit pattern is called the space lattice; the first word indicates that one is dealing with 3 dimensions, and the second suggests a rigid framework on which the atoms hang. The bonds are electrostatic in nature and electronic in origin.

It is not easy to create a simple physical picture of metal linkage [or bonding in metal], but in briefest outlines the picture is somewhat as follows: Because there are not sufficient valency electrons for the atoms to form groups among themselves by either the ionic or covalent manners of bonding, it becomes necessary for the electrons to act for several atoms. Like covalent bonding, metal linkage is one of electron sharing, but differs from it in that the sharing is really quite free and unrestricted. One may then "regard a metal not as an assembly of metal atoms, but rather as an array of positive metal ions held together by the attraction of intervening valence electrons." (Hume-Rothery, "The Structure of Metal and Alloys," page 17.) Or to put it differently, the crystal structure of metals may be looked upon as made up essentially of 2 interpenetrating lattices, one of positive metal ions, and the other exclusively of electrons.

These shared electrons, which are not the exclusive property of a particular atom, are responsible for many properties of the metal crystal other than its coherence and rigidity. Among these are such characteristic properties as electrical conductivity, thermionic emission, photoelectric phenomena, and a dozen or so thermo-magneto-electrical effects.

# New Types of D-C Transformers

By C. C. HERSKIND
ASSOCIATE AIEE

This paper presents 2 new types of d-c transformers using grid-controlled mercury-arc rectifiers. These transformers perform the same function on a d-c system as does the usual transformer on an a-c system. One type of d-c transformer which is discussed has a constant-current output characteristic, while the other has a constant-potential output. The theory of operation and operating characteristics are described and oscillograms taken on a small unit are shown.

## Introduction

FROM TIME to time various methods have been proposed for the purpose of transforming voltage on d-c systems without using a motor-generator set. Most of these schemes have employed some type of commutating device for interrupting the direct current; the interrupted current then being transformed by means of a transformer of the conventional type and finally again changed back into direct current by the commutating device. None of these schemes has proved practical, chiefly because of commutating difficulties with the interrupting device.

The use of thyratron tubes for the construction of a d-c transformer was proposed several years ago.[1] However, due in part to the limitations of the circuit then proposed, no applications have been made up to the present time.

This paper describes 2 new types of d-c transformers using grid-controlled mercury-arc rectifiers for commutating the direct current. The development of these d-c transformers is based upon a new circuit which was invented by Mr. C. A. Sabbah. This circuit operates upon an entirely new principle and possesses unique operating characteristics. It provides the commutating voltage, required for transferring current from winding to winding, which is essential to successful operation when using grid-controlled mercury-arc rectifiers. In addition, the circuit may also be used to change constant potential to constant current, as in the case of the constant-current d-c transformer.

The operation of the d-c transformer does not merely involve the conduction of current in succession through the several transformer windings. In order to accomplish this action, 2 requirements must be met, which influence directly the character of the circuit employed. These requirements are: First, magnetizing current must be supplied for exciting the core of the main transformer, and second, commutating voltage must be supplied for overcoming the counter electromotive forces which oppose the transfer of current from winding to winding. When grid-controlled mercury-arc rectifiers for commutating the current are used, further requirements must also be met; namely, sufficient commutating voltage must be supplied to provide a positive voltage on the anode, prior to conduction in order to obtain reliable pick-up, and to provide a negative voltage at the end of the conduction period for a sufficiently long time, in order to permit deionization of the anode; also the circuit action must be such that no attempt will be made to pass current through the circuit in the reverse direction during the anode conduction period.

Two types of d-c transformers, namely, the constant-current d-c transformer and the constant-potential d-c transformer, and their circuits and manner of operation, will be described. Oscillograms are included showing the wave forms obtained in actual operation.

## The Constant-Current D-C Transformer

The operation of the constant-current d-c transformer will be described first, inasmuch as it serves best to illustrate the principles of operation whereby the commutating voltage is obtained from the combination of 3-phase transformer and 3 capacitors.

The schematic connection diagram of the constant-current d-c transformer is shown on figure 1. The transformer consists of:

1. A 3-phase transformer having 2 coils per phase.
2. Three capacitors, one connected across each phase of the transformer.
3. Six mercury-arc rectifier tubes for commutating the current.
4. Two d-c reactors, one in the input and the other in the output circuit, for maintaining a smooth current wave.

In addition a source of a-c power is required for exciting the grids of the tubes. (A pilot motor-generator set driven from the d-c supply may be used.)

## Theory of Operation

The principle of operation may be best described by reference to the connection diagram figure 1, and the wave forms shown on figure 2. Referring to figure 2, let it be assumed that the grids of the primary and secondary anodes are excited from the pilot generator at a constant frequency, so that each secondary anode will fire before the primary anode on the corresponding leg of the transformer, by a time interval equal to $\alpha$ degrees. Then the primary and secondary anode current waves will be as shown by curves $a$ and $b$, since it is assumed that there is sufficient reactance in series with the 2 d-c circuits so that the d-c currents are constant.

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1. For numbered reference, see end of paper.

The capacitor current wave is fully determined if the primary and secondary anode current waves are known, as the capacitor must supply the current required to maintain the magnetomotive force in each transformer leg constant (neglecting magnetizing current). That this is the case will be evident if it is remembered that in a transformer, the primary and secondary ampere turns, neglecting magnetizing current, must be equal and opposite and that any current in a primary coil, which is not opposed by an equal and opposite current in the secondary coil, meets magnetizing reactance and generates a high voltage. Of course, there is no unidirectional component of current in the usual transformer, but this will not alter the validity of this requirement. The above principle is highly important, as the whole theory of operation of the constant-current d-c transformer is based upon the fact that the transformer magnetomotive force (neglecting magnetizing current) is maintained constant.

The average magnetomotive force in each transformer leg, during the whole cycle, is equal to the average of the magnetomotive forces due to the primary and secondary anode currents, each averaged over the cycle. In order to maintain this constant value of magnetomotive force on the transformer leg, the capacitor current must have the wave form shown by curve *c* on figure 2. The capacitor voltage wave is shown on curve *d*. The voltage is readily determined from the capacitor current as the current is constant during each interval.

The input and output voltages, curves *e* and *f*, are found by taking the capacitor voltages during the interval that the anode is conducting. The voltage will be supplied by any one phase only during the time that its anode is conducting. When the anode is not conducting, the voltage will be supplied from the other phases. The ripple in the d-c voltage wave is absorbed by the reactors in series with the 2 d-c lines. A clearer conception of the physical processes involved may be obtained if it is noted that during the interval $t_1$ to $t_2$, capacitor 1 is discharging into the output circuit. Its voltage falls as the secondary anode continues firing, until the secondary anode on the second phase is permitted to fire (by grid control), and the current transfers from anode 1′ to anode 2′, as capacitor 2 has a higher voltage than capacitor 1, and in the proper direction to force commutation. At $t_2$, the capacitor 1 is practically discharged, but now the primary anode on phase 1 is firing, and it is again being charged from the input circuit. At the end of the charging period, anode 2 is permitted to fire, and the input current is transferred from anode 1 to anode 2, as capacitor 2 has a lower counter electromotive force voltage than 1. During the period when neither primary nor secondary anode on phase 1 are firing, capacitor 1 discharges into the transformer winding, in order to maintain the required leg magnetomotive force,

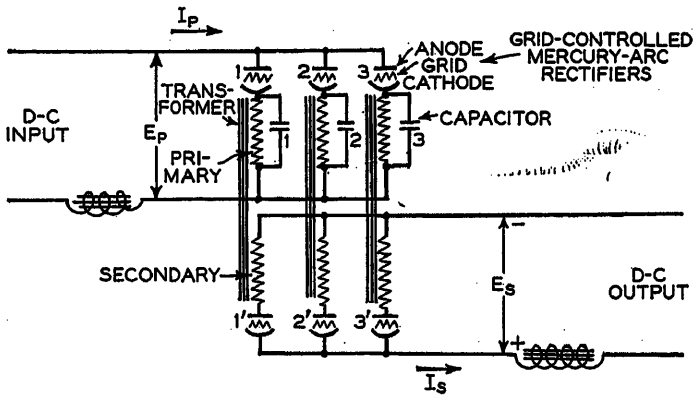



**Figure 1. Connection diagram of constant-current d-c transformer**

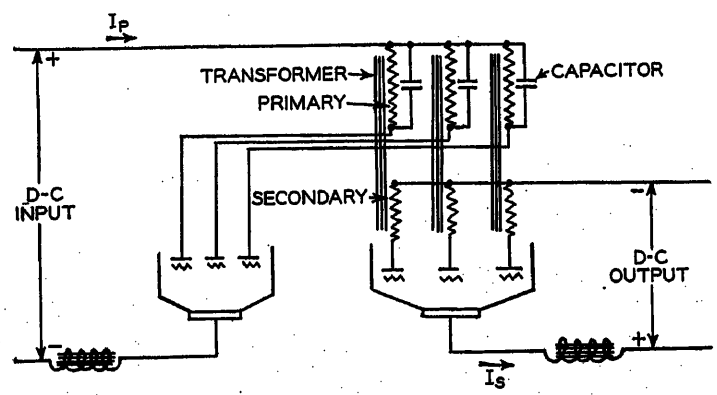



**Figure 1a. D-c transformer using 2 3-anode metal-tank grid-controlled mercury-arc rectifiers**

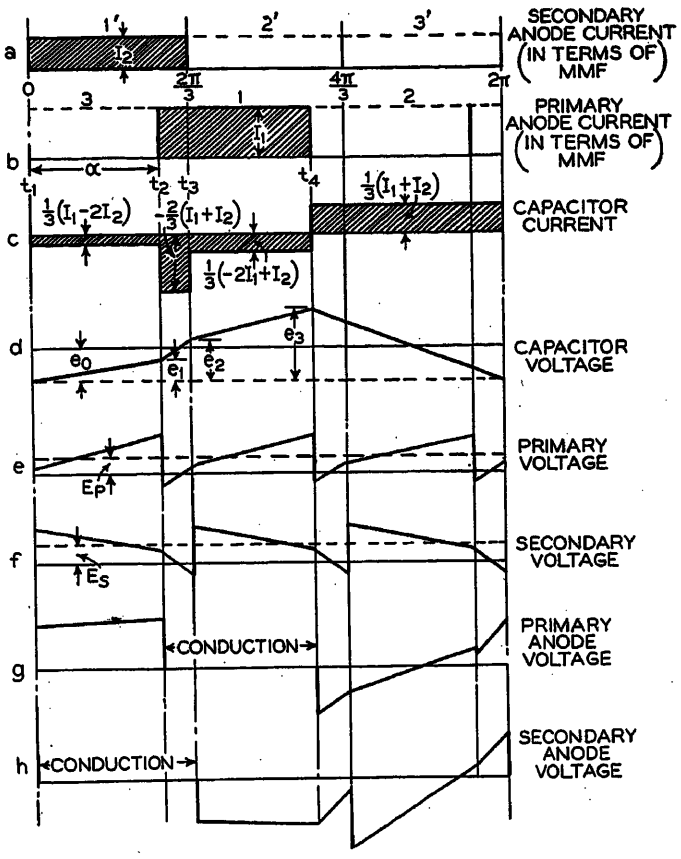



**Figure 2. Constant-current d-c transformer wave forms. Case I—$\alpha >$ 0 degrees and $<$ 120 degrees**

and reverses its polarity, so that it has the correct polarity to supply power to the output circuit, when it is again permitted to fire.

The anode voltages during the period when the anode is not conducting (that is, the anode-to-cathode voltages) may also be found from the capacitor voltages. They are shown by curves *g* and *h*. From curve *g* it will be noted that the primary anode operates essentially as an inverter, the anode having a negative voltage for a short time during the first part of the idle period, and then a positive voltage during the rest of the period. Also, from curve *h*, the secondary anode will be seen to operate essentially as a rectifier, having a negative voltage during most of the idle period and becoming positive shortly before conduction. In other words, the constant current d-c transformer is a unique combination of inverter and rectifier, which supplies its own commutating requirements.

## Voltage Relations

The voltage and current relations between the input and output sides of the constant-current d-c transformer may be readily derived if the capacitor current and voltage waves are determined by assuming various values of primary and secondary current. Referring to figures 1 and 2, let

$I_p$ = primary d-c current input
$I_s$ = secondary d-c current output
$n$ = ratio pri-sec turns on transformer
$f$ = frequency of grid excitation (supplied by pilot generator)
$\alpha$ = angle of retard of primary anodes with respect to secondary anodes (degrees)

$$k = \frac{\alpha}{120^\circ}$$

The average d-c component of the magnetomotive force on each leg of the transformer due to the anode currents is $^1/_3(I_1 + I_2)$, where $I_1$ is the magnetomotive force due to primary anode current $I_p$ flowing in primary winding, that is, $I_1 = I_p$ times the number of primary turns, and $I_2$ is the magnetomotive force due to secondary anode current $I_s$ flowing in secondary winding, that is, $I_2 = I_s$ times the number of secondary turns $= (I_s/n)$ times the number of primary turns. For simplicity the magnetomotive force may be expressed in terms of primary current, that is, $I_1 = I_p$ and $I_2 = I_s/n$.

In order to maintain the magnetomotive force on the transformer leg constant, the capacitor currents during the successive intervals will have the values indicated on curve *c* of figure 2.

Inasmuch as the capacitor current is constant during each interval due to the smoothing reactors in the input and output circuits, (if transformer magnetizing current is neglected) the capacitor voltage wave is of trapezoidal form during any interval and the change in capacitor voltage during any interval is

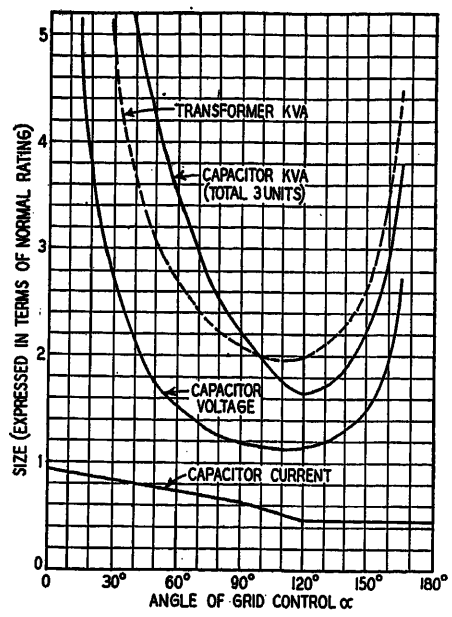



**Figure 4. Size of capacitors and transformer**

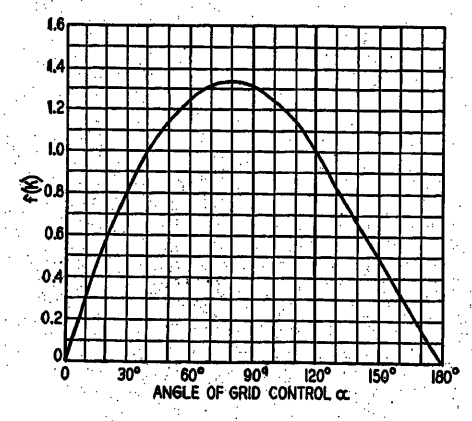



**Figure 3. Value of functions $(4K - 3K^2)$ and $(3 - 2K)$**

$$e = \int \frac{idt}{c} = \frac{it}{cf}$$

where

$t$ = duration of the interval expressed as a fraction of one cycle
$c$ = capacity of one capacitor
$i$ = capacitor current
$f$ = frequency of grid excitation

CASE I

If it is assumed that the conducting periods of the primary and secondary anodes connected to the same leg overlap, that is, if $\alpha$ is greater than zero and less than 120 degrees, the capacitor voltages indicated on figure 2 curve *d* will be:

$$e_1 = \frac{1}{9cf}[-I_1k + 2I_2k] \quad (1)$$

$$e_2 = \frac{1}{9cf}[2I_1 + 2I_2 - 3I_1k] \quad (2)$$

$$e_3 = \frac{1}{9cf}[2I_1 + 2I_2 - I_1k - I_2k] \quad (3)$$

Since the capacitor current wave must be such that $\int edt$ over the cycle is zero, it follows that

$$e_0 = \frac{1}{9cf}[I_1 + I_2 - I_1k] \quad (4)$$

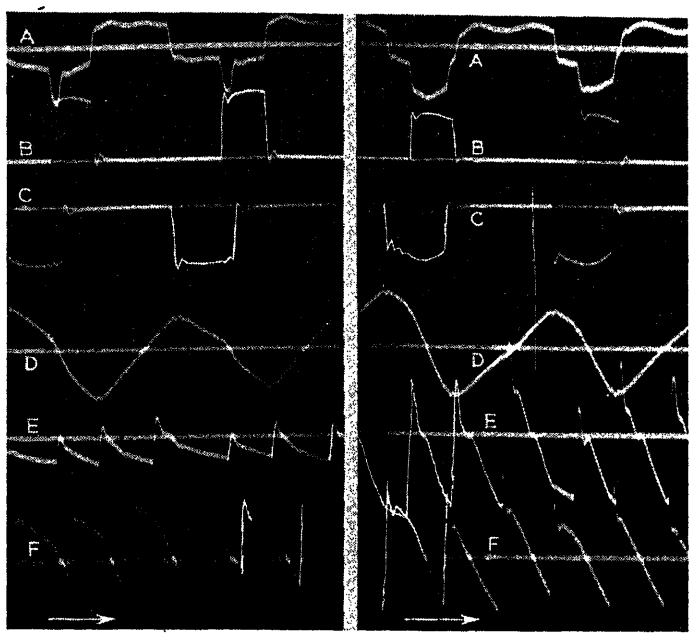



**Figure 5. Oscillograms showing constant-current d-c transformer current and voltage wave forms**

Curve *A*—Capacitor current
Curve *B*—Primary anode current
Curve *C*—Secondary anode current
Curve *D*—Capacitor voltage
Curve *E*—D-c input voltage
Curve *F*—D-c output voltage

The average value of both the input and output voltages may readily be calculated from these capacitor voltages. The average input voltage is then

$$E_p = \frac{1}{18\ cf}\,[4k - 3k^2]\,I_2 = \frac{1}{18cf}\,[4k - 3k^2]\,\frac{I_s}{n} \qquad (5)$$

and the average output voltage is

$$E_s = \frac{1}{18\ cf}\,[4k - 3k^2]\,I_1 = \frac{1}{18\ cf}\,[4k - 3k^2]\,\frac{I_p}{n} \qquad (6)$$

CASE II

Similar expressions may be derived for the case where the conducting periods of the primary and secondary anodes do not overlap, that is, $\alpha$ is greater than 120 degrees and less than 180 degrees. The equations for the average input and output voltages when the anodes do not overlap, are, respectively,

$$E_p = \frac{1}{18\ cf}\,[3 - 2K]\,\frac{I_s}{n} \qquad (7)$$

and

$$E_s = \frac{1}{18\ cf}\,[3 - 2K]\,\frac{I_p}{n} \qquad (8)$$

These equations establish the voltage relations required for constant-potential-to-constant-current transformation. From the above expressions it will be noted that the relation between the voltage input and the current output may be changed in four ways, namely; first, by changing the grid phase angle between primary and secondary anodes; second, by changing the frequency; third, by changing the capacity; and fourth, by changing the transformer turn ratio between primary and secondary coils.

The constant-current d-c transformer may be operated with any angle of grid retard of the primary anodes with respect to the secondary anodes between the values zero and 180 degrees. The relation between the primary voltage and secondary current, as the angle of grid retard varies, is expressed by the functions $(4k - 3k^2)$ and $(3 - 2k)$, which are shown graphically on figure 3; with angles of grid retard at or near zero and 180 degrees, the secondary current becomes very large and is close to infinity for all values of impressed voltage. The characteristics of the transformer-capacitor combination under these conditions will be described in connection with the constant potential d-c transformer.

The effective values of the voltage and current appearing on the capacitors and transformer may be calculated from the relations indicated on figure 2, and the voltage equations (1), (2), (3), and (4). The calculated sizes of the capacitors and transformer for various angles of grid retard are shown on figure 4.

In the d-c transformer circuit, shown on figure 1, there exists a d-c component of magnetomotive force on each leg of the transformer core. This is apparent when it is

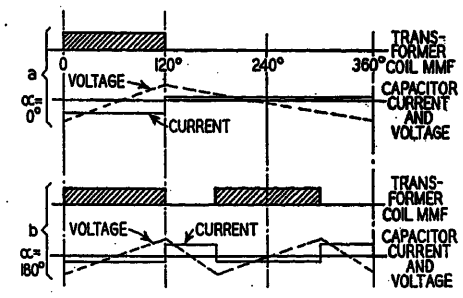



**Figure 6. Commutation transformer wave forms**

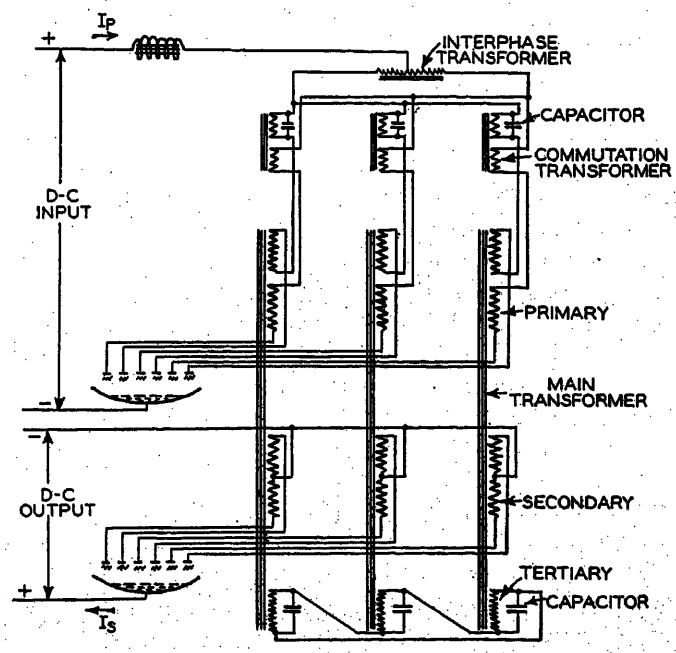



**Figure 7. Connection diagram of constant-potential d-c transformer**

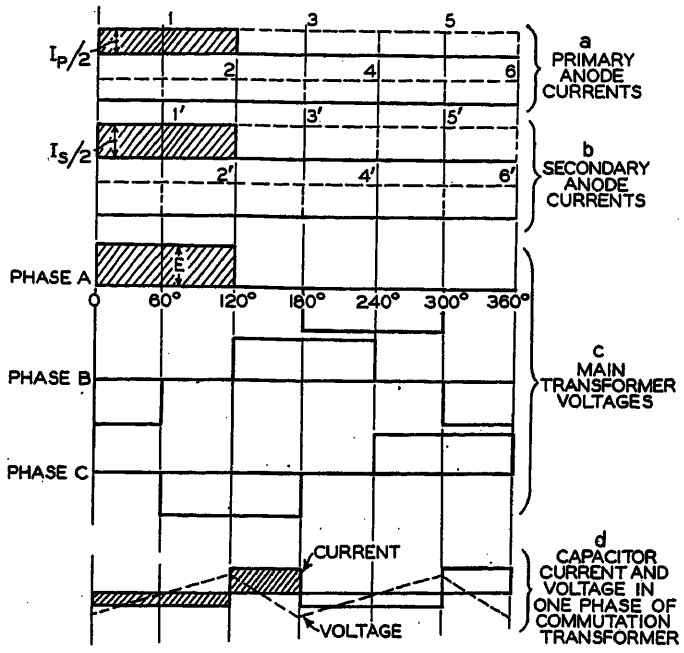



**Figure 8. Constant-potential d-c transformer wave forms**

noted that all currents entering the unit from the input side and leaving on the output side flow through the transformer coils in the same direction. This d-c component may be eliminated without altering the action of the transformer, by suitably zig-zagging the transformer coils.

## Test Results

A constant-current d-c transformer of approximately 40-kw capacity has been tested in the factory. The tests were made with the d-c transformer connected to a constant-voltage source and the output current was used to drive a d-c motor. The output current was controlled by varying the frequency applied to the grids (speed control on pilot motor-generator set). The high output current required to start the motor was obtained by operating the transformer at a high grid frequency. As the motor came up to speed, the grid frequency was reduced. The motor was held at any desired speed by varying the frequency of the grid control. On another test, the d-c transformer connections were reversed and it was forced to pump power back into the supply, that is, to regenerate.

The constant-current relationship has been proved by these tests. Figures 5*a* and 5*b* are oscillograms of voltages and currents in various parts of the circuit. The close agreement between the theoretical wave form, shown on figure 2, and the actual wave form, as determined by test, should be noted.

## The Constant-Potential D-C Transformer

For many applications, the constant-current characteristic is not suitable, and a d-c transformer having a constant-potential characteristic is required. A constant-potential d-c transformer may be constructed by making use of the transformer and capacitor combination, which has already been described in connection with the constant-current d-c transformer. In the case of the constant-potential transformer the transformer and capacitor combination is used to provide a commutating voltage and it will be referred to hereafter as the commutation transformer.

The commutation transformer consists of the transformer and capacitor combination used in the constant-current d-c transformer, with the angle of grid control between primary and secondary winding adjusted for either zero or 180 degrees. The capacitor current and voltage relations with angle of control equal to zero or 180 degrees are shown on figure 6. It should be noted that the capacitor voltage is directly proportional to the load current, so that the commutation transformer will furnish the required voltage at all loads to overcome the reactive voltages opposing transfer from winding to winding since these reactive voltages are proportional to the load.

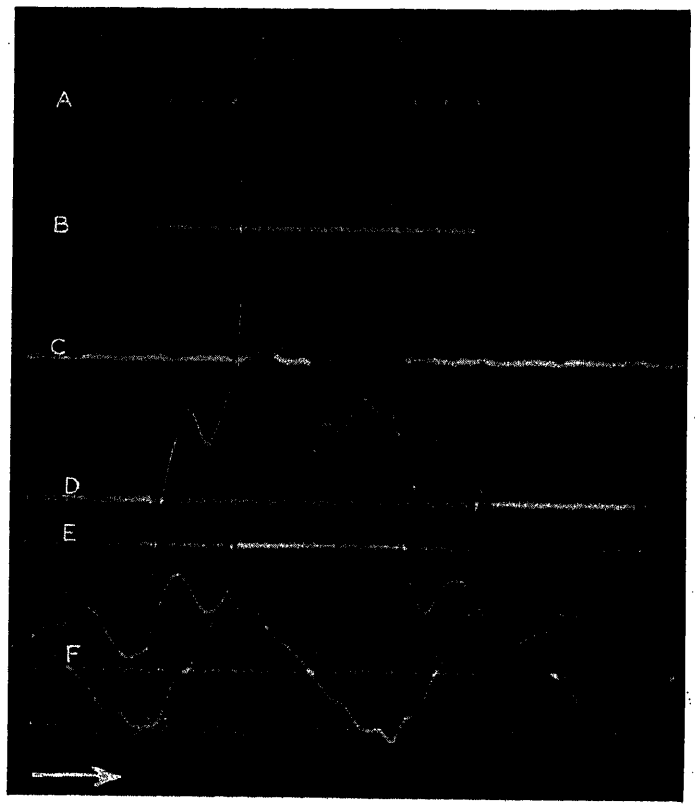



**Figure 9. Oscillogram showing constant-potential d-c transformer current and voltage wave forms**

Curve *A*—Main transformer primary-coil voltage
Curve *B*—Primary anode current
Curve *C*—Secondary anode current
Curve *D*—Primary anode-to-cathode voltage
Curve *E*—Secondary anode-to-cathode voltage
Curve *F*—Commutating-transformer coil voltage

The schematic connection diagram of the constant-potential d-c transformer is shown on figure 7. Referring to this diagram, the constant-potential d-c transformer

consists of (1) a 3-phase main transformer, having 2 primary coils, 2 secondary coils, and tertiary coil on each phase; (2) a commutation transformer having a 3-legged core with 2 coils per phase; (3) 3 capacitors, one connected across each phase of the commutation transformer; (4) an interphase transformer; (5) 3 capacitors, one connected across each tertiary coil on the main transformer; (6) 2 6-anode grid-controlled mercury-arc rectifiers, one connected to the primary windings of the main transformer and the other connected to the secondary windings of the main transformer.

The constant-potential d-c transformer consists essentially of a 6-anode inverter supplying power to the primary windings of the main transformer, and a 6-anode rectifier, receiving power from the secondary windings of the main transformer. The commutating voltage for transferring current from anode to anode on the inverter is supplied by the commutation transformer. The inverter is caused to operate as 2 3-anode circuits by means of the interphase transformer. The magnetizing current

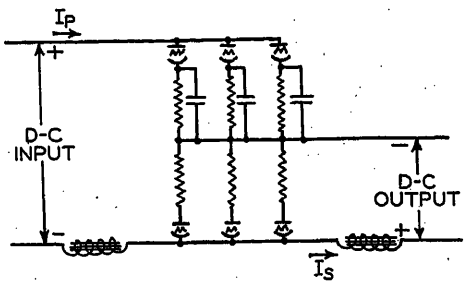



**Figure 10. Diagram showing alternative connections for constant-current d-c transformer**

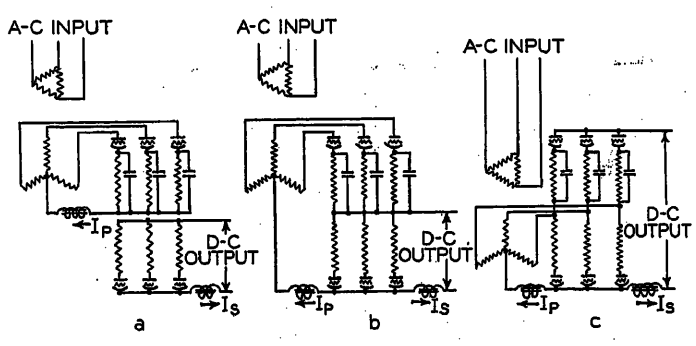



**Figure 11. Circuits for changing constant-potential alternating current to constant-current direct current (single frequency)**

for the main transformer is supplied by the capacitors connected across the tertiary windings of the main transformer.

The operation of the constant-potential d-c transformer will best be understood by referring to figure 8, which shows the wave form in the d-c transformer circuit. On figure 8 curves *a* and *b* show the primary anode current and secondary anode-current wave forms, respectively. It will be noted that each anode carries current for approximately 120 degrees. Curve *c* shows the transformer coil voltages on the different phases of the main transformer. Curve *d* shows the voltage supplied by the commutation transformer for effecting the transfer of current from anode to anode, and permitting deionization of the main anode, following the conduction period.

The voltage ratio of the constant-potential d-c transformer is determined by the winding ratio between primary and secondary coils on the main transformer. This voltage ratio is not susceptible to control by means of the grids, as in the case of the constant-current d-c transformer, and no control grids are required on the output rectifier.

## Test Results

A constant-potential d-c transformer has been set up and tested in the factory, drawing power from a 500-volt d-c shop system, and driving a 250-volt d-c motor. The constant-potential d-c transformer was found to have a shunt voltage characteristic similar to that of an ordinary rectifier.

Figure 9 shows an oscillogram of the voltage and current in various parts of the constant-potential d-c transformer circuit.

## Other Arrangements and Applications

Various arrangements of the combination of 3-phase transformer and 3 capacitors forming the constant-current d-c transformer are possible. Figure 10 shows an alternative method of connecting the input side of the constant-current d-c transformer. This connection has been shown to have the same constant-current characteristic as that of figure 1.

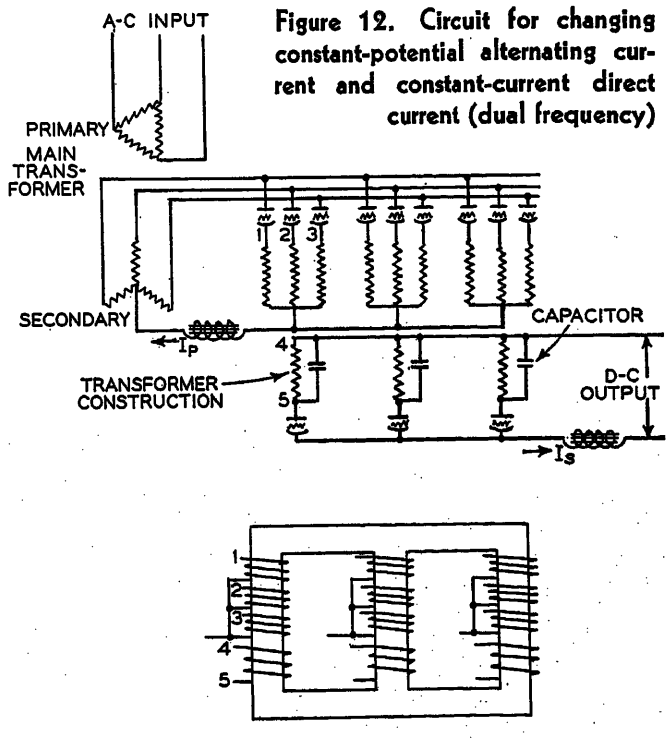



**Figure 12. Circuit for changing constant-potential alternating current and constant-current direct current (dual frequency)**

The constant-current d-c transformer circuit can also be used for changing constant-potential alternating current

to constant-current direct current, that is, as a constant-current rectifier. Figure 11 shows 3 similar circuits of this type. In these circuits, the grids are excited at the same frequency as that of the a-c system. Figure 12 shows a circuit for changing constant-potential alternating current to constant-current direct current, in which the grids may be excited at a different frequency than that of the a-c system. The circuits shown in figures 11 and 12 may also be operated as inverters, that is, either changing constant-potential direct current to constant-current alternating current or changing constant-current direct current to constant-potential alternating current.

## Conclusions

The general circuit and principles of operation which are described in this paper in connection with the constant-potential and constant-current d-c transformers, may also be applied to other rectifier circuits. Various arrangements of this general circuit utilizing a 3-phase transformer and 3 capacitors in combination with rectifier tubes, are possible. The new principles which have been described will undoubtedly prove useful in the development of apparatus for various rectifier applications, particularly those involving inverter operation.

## Reference

1. THE DIRECT CURRENT TRANSFORMER UTILIZING THYRATRON TUBES, D. C. Prince. *General Electric Review*, July 1928, page 346.

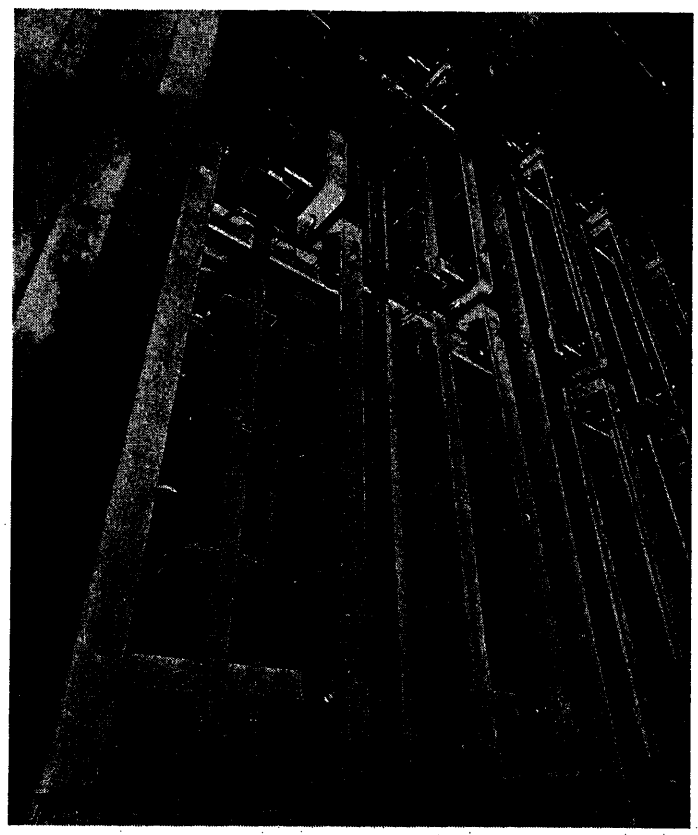
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# Workers in New Chicago Building to Breathe Electrically Cleaned Air

THAT MANY PEOPLE are interested in air conditioning and its allied processes was evidenced by the wide discussion of a paper on "A New Electrostatic Precipitator" by G. W. Penney (A'26) at the 1937 winter convention (ELECTRICAL ENGINEERING, volume 56, January 1937, pages 159–63). That the principle of electrostatic cleansing of air has a large-scale practical use now has been demonstrated by the use of this method in cleaning the entire air supply of the first 4 floors and lower arcade of the new Field Building in Chicago, Ill. Located in Chicago's downtown loop area, where annually the dirt deposited from the atmosphere is said to average 1,000 tons per square mile, the precipitators in this building supply more than 16 million cubic feet of cleaned air per hour.

Dust particles so small that they pass through any ordinary mechanical filter are readily removed by means of electrostatic precipitation. By this process impurities are taken from the air not by sifting them out mechanically, but by charging the particles electrically and withdrawing them as they pass through an electrostatic field. The air is first ionized by passing it through a maze of grounded cylinders and fine wires; the wires, charged to a negative potential of 12,000 volts, are only 0.005 inch in diameter and of course cannot be seen in the photograph of the intake side of one of the Field Building precipitators shown on this page. After the solid particles have been charged, the treated air next is drawn through a series of cells consisting of alternately spaced high-potential and grounded plates, the charged particles of impurities adhere to the plates, and the air so freed of solid matter passes on through ducts that lead to the areas being served by the equipment. Each cell of the Chicago system contains 111 plates 8 by 9 inches in size, and nearly half a mile of the fine tungsten ionizing wire was used in the construction of the 369 cells. The high-potential precipitator plates are charged to a positive potential of 5,000 volts.

Particles having diameters smaller than 0.0025 inch pass readily through 200-mesh screens of mechanical filters. These particles ordinarily are invisible, except in



rays of bright light, but are extremely coarse in comparison with the atmospheric dust particles that fill the air of a busy city. The average solid particle in cigarette smoke has a diameter of only 0.0000039 inch. Enlarged 250,000 times, the larger particles that pass through a 200-mesh screen would be 50 feet in diameter; an average atmospheric dust particle would appear as big as a baseball; but at the same magnification the average cigarette-smoke particle would be a little more than an inch in diameter, or slightly smaller than a golf ball.

# Load Loci for Transformers in Parallel

By ANATOLI C. SELETZKY
MEMBER AIEE

## Abstract

The method of circular loci is applied to the problem of 2 transformers operating in parallel. It is shown that with comparatively little computation the variation of current in either transformer or the ratio of the 2 currents may be obtained as a function of the load impedance or the ratio of transformation. A numerical problem is given to illustrate a typical application.

## Introduction

THE OPERATION of 2 transformers in parallel under ideal conditions assumes equal percentage resistances and reactances and equality of high-tension and low-tension voltages, neglecting excitation currents. Frequently it is necessary to connect in parallel transformers which do not conform to the ideal requirements. It is then necessary to change the ratio of transformation of one of the transformers to prevent overloading. The problem of parallel operation of transformers has been treated by many investigators, references to several being given at the end of this paper.[1–5]

When confronted simultaneously with several variables, involved in parallel operation, such as load impedance, load power factor, tap position and internal impedance, the author has found the method of circular loci to be convenient and time saving for determining the variation of transformer currents as a function of any of the variables present. This method is the only alternative to the laborious and time-consuming point-by-point solution of expressions with complex coefficients.

This paper develops the application of circular loci to the determination of currents and current ratios for the general case of 2 transformers connected in parallel. It is shown how, with comparatively little computation, a circular locus may be plotted which gives directly the magnitude and phase angle of the desired unknown as the variable passes through its complete range, from minus infinity or zero to plus infinity.

A paper recommended for publication by the AIEE committee on power transmission and distribution. Manuscript submitted July 12, 1937; released for publication September 21, 1937.

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1. For all numbered references, see list at end of paper.

## General Equations for Parallel Operation

In figure 1 are shown 2 transformers, numbered 1 and 2, respectively, connected in parallel and supplying a load $Z_L$. The equivalent circuits of the transformers are assumed to be reduced to the low-tension side. The exciting admittances are considered to be negligible and the elements of the circuits are assumed to be linear. The load impedance, $Z_L$, may have any phase angle and its magnitude may vary from short circuit to open circuit. The following symbols will be used throughout the paper:

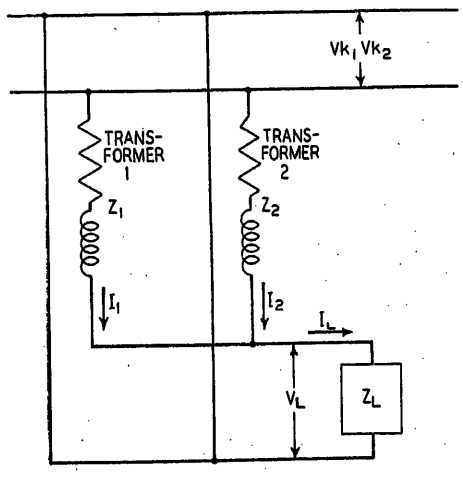



**Figure 1**

$I_1$ = current in low-tension winding of transformer 1
$I_2$ = current in low-tension winding of transformer 2
$I_L$ = load current in low-tension side
$Z_1$ = equivalent impedance of transformer 1 referred to low-tension side
$Z_2$ = equivalent impedance of transformer 2 referred to low-tension side
$V$ = terminal voltage on high-tension side
$V_L$ = terminal voltage on low-tension side
$k_1$ = ratio of transformation of transformer 1
$k_2$ = ratio of transformation of transformer 2

$$\text{ratio of transformation} = \frac{\text{induced voltage in low-tension winding}}{\text{induced voltage in high-tension winding}}$$

The problem to be considered is the behavior of the individual transformer currents, $I_1$ and $I_2$, as $Z_L$ varies and the transformer ratios, $k_1$ and $k_2$, remain constant; also the variation of transformer currents when $Z_L$ is fixed and one of the ratios, $k_1$ or $k_2$, varies.

Writing the voltage drops in the 2 circuits

$$V_L = Vk_1 - I_1Z_1 = Vk_2 - I_2Z_2$$

and eliminating the load voltage and current by the relationships:

$$I_L = \frac{V_L}{Z_L} \text{ and } I_L = I_1 + I_2$$

the equations may be solved for $I_1$ and $I_2$ giving

$$I_1 = V\frac{k_1Z_2 + (k_1 - k_2)Z_L}{Z_1Z_2 + (Z_1 + Z_2)Z_L} \quad (1)$$

$$I_2 = V\frac{k_2Z_1 - (k_1 - k_2)Z_L}{Z_1Z_2 + (Z_1 + Z_2)Z_L} \quad (2)$$

Both expressions for current are linear in numerator and denominator with respect to all the circuit constants $Z_1$, $Z_2$, $Z_L$, $k_1$, and $k_2$.

The canonical form of a circle, written as a linear fractional transformation is

$$S = \frac{\alpha + \beta\rho}{\gamma + \delta\rho} \tag{3}$$

Here $S$ is a vector whose extremity follows a circle as the scalar variable $\rho$ varies from minus to plus infinity and $\alpha$, $\beta$,$\gamma$,$\delta$ are complex constants.[6]

It is evident that the transformer currents follow circular loci when any one of the circuit constants be considered as the variable, because in each case both numerator and denominator can be written in the form of a constant term plus a constant times the variable scalar, giving thereby the equation of a circle.

That the transformer currents follow circular loci could also have been realized immediately from the theorem of circularity for a general network which states: "that in a network containing any number of linear and bilateral self- and mutual-impedance elements connected in any manner, with constant sinusoidal electromotive forces of like frequency connected in any arm, all currents and all voltages follow circular loci when any one impedance is varied along a straight line in the complex plane."[7] Thus, if any one of the circuit impedances be considered to vary at constant power-factor both transformer currents will follow circular loci.

## Loci of $I_1$ and $I_2$ With Variable $Z_L$

With the load impedance $Z_L$ assumed to be the variable the equation for $I_1$ is written as

$$I_1 = V\frac{k_1Z_2 + (k_1 - k_2)1\angle\theta_L \mid Z_L \mid}{Z_1Z_2 + (Z_1 + Z_2)1\angle\theta_L \mid Z_L \mid} \tag{4}$$

Here the variable $Z_L$ has been put in the form

$$Z_L = \mid Z_L \mid e^{j\theta_L} = 1\angle\theta_L \mid Z_L \mid \tag{5}$$

where $\theta_L$ is the phase angle of $Z_L$ and $|Z_L|$is the magnitude of $Z_L$. In this way the scalar variable $\rho$ of the canonical form becomes $|Z_L|$and the phase angle of $Z_L$ becomes part of the complex constant $\delta$.

The constants of the canonical form for $I_1$ are then:

$$\left.\begin{aligned} \alpha &= Vk_1Z_2 & \gamma &= Z_1Z_2 \\ \beta &= V(k_1 - k_2)1\angle\theta_L & \delta &= (Z_1 + Z_2)1\angle\theta_L \\ \rho &= \mid Z_L \mid \end{aligned}\right\} \tag{6}$$

The invariant points, that is the values of $I_1$ for $|Z_L| = 0$ and $|Z_L| = \infty$ are

$$\left.\begin{aligned} I_{1(0)} &= V\frac{k_1}{Z_1} \quad \text{(short circuit)} \\ I_{1(\infty)} &= V\frac{k_1 - k_2}{Z_1 + Z_2} \quad \text{(open circuit)} \end{aligned}\right\} \tag{7}$$

In the same manner the current in transformer 2 is written as

$$I_2 = V\frac{k_2Z_1 - (k_1 - k_2)1\angle\theta_L \mid Z_L \mid}{Z_1Z_2 + (Z_1 + Z_2)1\angle\theta_L \mid Z_L \mid} \tag{8}$$

The constants in this case are:

$$\left.\begin{aligned} \alpha &= Vk_2Z_1 & \gamma &= Z_1Z_2 \\ \beta &= -V(k_1 - k_2)1\angle\theta_L & \delta &= (Z_1 + Z_2)1\angle\theta_L \\ \rho &= \mid Z_L \mid \end{aligned}\right\} \tag{9}$$

The invariant points are:

$$\left.\begin{aligned} I_{2(0)} &= V\frac{k_2}{Z_2} \quad \text{(short circuit)} \\ I_{2(\infty)} &= -V\frac{k_1 - k_2}{Z_1 + Z_2} \quad \text{(open circuit)} \end{aligned}\right\} \tag{10}$$

The internal impedances $Z_1$ and $Z_2$ used in the equations should correspond to the particular transformer ratios $k_1$ and $k_2$ associated with them. In certain problems it is desired to study load sharing when either ratio $k_1$ or $k_2$ is changed. For a theoretically correct solution of such a problem it would be necessary to know the variation of internal impedance corresponding to each tap on the transformer. If such data are available, the proper values of $Z_1$ and $Z_2$ appropriate to the particular tap positions being used should be employed in the equations.

If the problem involves small changes in ratio from the one pertaining to the value of internal impedance used in the equations, it is frequently permissable, for the degree of accuracy desired in the results, to consider the internal impedance a constant as the ratio is changed slightly.

With this assumption the construction of a family of circles, considering the transformation ratio $k_1$ or $k_2$ as the parameter, is greatly simplified. The ratios $k_1$ and $k_2$ occur only in the numerators of the expressions for transformer currents. If, for the moment, the load impedance $Z_L$ and one of the ratios, as $k_1$ be assumed fixed, and the ratio $k_2$ be assumed as the variable, the currents $I_1$ and $I_2$ will follow straight lines. For example, the current $I_1$ in equation 1 may be expressed as

$$I_1 = \frac{Vk_1(Z_2 + Z_L)}{Z_1Z_2 + (Z_1 + Z_2)Z_L} - k_2\frac{VZ_L}{Z_1Z_2 + (Z_1 + Z_2)Z_L} \tag{11}$$

which is of the form $\alpha + k_2\beta$.

This is a straight line with a linear scale in $k_2$, passing through the point $\alpha$ with an angle equal to the argument of $\beta$.

Similarly the current $I_2$ in equation 2 may be regarded under the same conditions as

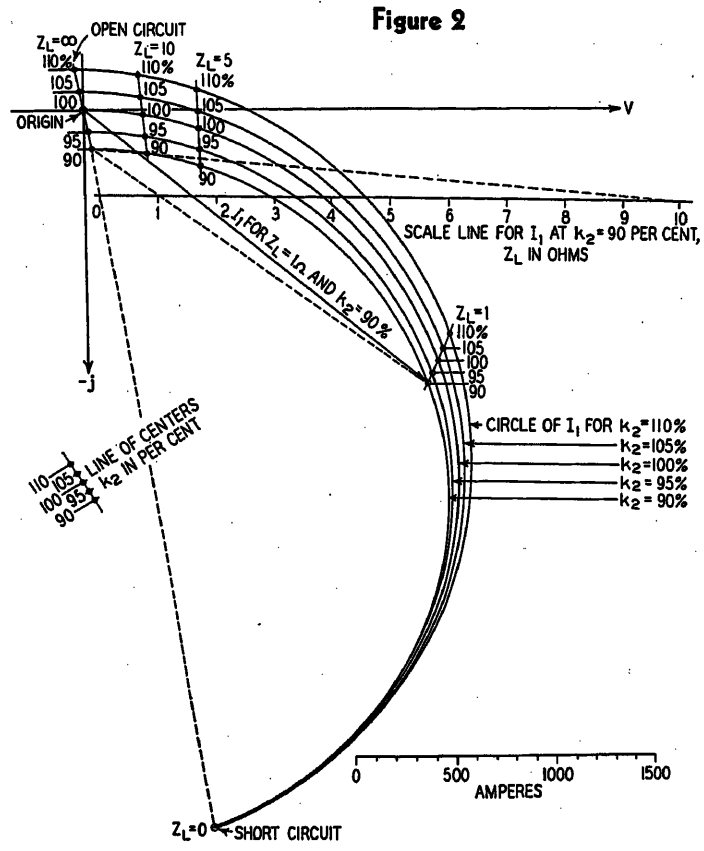
$$I_2 = \frac{-Vk_1Z_L}{Z_1Z_2 + (Z_1 + Z_2)Z_L} + k_2\frac{V(Z_1 + Z_L)}{Z_1Z_2 + (Z_1 + Z_2)Z_L} \tag{12}$$

This is another straight line. In the same manner the 2 equations for currents may be regrouped with respect to $k_1$ as the variable. These straight-line relationships facilitate the plotting of a family of circles with either transformer ratio as the parameter and the load impedance as the variable. For instance, 2 circles are drawn with the load impedance as the variable for 2 different values of $k_2$. Points on these circles for equal values of $Z_L$ are then connected by straight lines. The interval of $k_2$ between such pairs of corresponding points may then be used as a scale of $k_2$ to spot points on circles for other values of $k_2$.

The vector to the center of a circle is[6]

$$C = \frac{\alpha\bar{\delta} - \beta\bar{\gamma}}{\gamma\bar{\delta} - \delta\bar{\gamma}} \tag{13}$$

**Figure 2**




in which the vinculum (−) indicates the conjungate of the vector to which it is attached.

Substituting the constants given in equations 6 the center vector $C_1$ to the center of the circle for $I_1$ is

$$C_1 = j\frac{V}{Q}\left[k_1 Z_2(\overline{Z_1 + Z_2})1\angle -\theta_L - (k_1 - k_2)1\angle\theta_L(\overline{Z_1 Z_2})\right] \quad (14)$$

where

$$\left.\begin{aligned} Q &= 2(R'X'' - R''X') \\ Z_1 Z_2 &= R' + jX' \\ (Z_1 + Z_2)1\angle\theta_L &= R'' + jX'' \end{aligned}\right\} \quad (15)$$

Similarly the center vector $C_2$ to the center of the circular locus of $I_2$ becomes

$$C_2 = j\frac{V}{Q}\left[k_2 Z_1(\overline{Z_1 + Z_2})1\angle -\theta_L + (k_1 - k_2)1\angle\theta_L(\overline{Z_1 Z_2})\right] \quad (16)$$

It should be noted that both center vectors $C_1$ and $C_2$ are linear functions of $k_1$ and $k_2$. Thus if the families of circles for $I_1$ and $I_2$ are drawn with $Z_L$ as the variable and either $k_1$ or $k_2$ as the parameter, the centers of the circles for both families will lie on straight lines whose equations are $C_1$ and $C_2$, respectively. Furthermore the distances between the centers of the circles will be proportional to the increments of the parameter $k_1$ or $k_2$.

The radius of a circle is given by the expression[6]

$$R = \left|\frac{\alpha\delta - \beta\gamma}{\bar{\delta}\gamma - \gamma\bar{\delta}}\right| \quad (17)$$

Substituting the transformer constants into the above equation, the radius $R_1$ for the locus of $I_1$ is

$$R_1 = \left|\frac{VZ_2}{Q}\left[Z_1(k_1 - k_2) - k_1(Z_1 + Z_2)\right]\right| \quad (18)$$

Similarly the radius $R_2$ for the locus of $I_2$ is

$$R_2 = \left|\frac{VZ_1}{Q}\left[Z_2(k_1 - k_2) + k_2(Z_1 + Z_2)\right]\right| \quad (19)$$

The expressions for the 2 radii $R_1$ and $R_2$ are likewise linear with respect to $k_1$ and $k_2$. Thus if the radii of 2 circles for different values of transformer ratio are known, the difference between these 2 radii may be used as a linear scale for obtaining radii for other values of transformer ratio.

Hence, to obtain a plot of a family of circles of transformer current with variable load impedance and one of the transformer ratios as the parameter, it is necessary to employ the analytical expression for only 2 of the circles; the linear relationships between corresponding points on different circles and between the centers of the circles suffice to locate other circles and points thereon, for any desired values of $k_1$ or $k_2$.

A circular locus may be determined by calculating 3 points on its periphery from the analytical expression or by computing the center vector and the radius. The 3-point method generally involves less computation because 2 of the points used for location are the invariant points which reduce the expression from the quotient of the sums of 2 complex terms to a quotient of 2 complex terms only. For the third point any convenient value of $Z_L$ may be chosen. In this manner the entire analytical expression need be used only once, namely, for the calculation of the third point.

The third point is also used in conjunction with the invariant points for the determination of the linear scale line. This scale line is any line drawn perpendicular to the line joining the center of the circle and the point on the circle corresponding to $I_{1(\infty)}$, the open-circuit point. The intersections of the scale line, drawn in this manner, with lines joining points on the circle at which $Z_L$ is known and the open-circuit point, determine a linear scale of $Z_L$ on the scale line. Any chord then drawn through the open-circuit point and intersecting the scale line, connects corresponding points of $Z_L$ on the scale line and on the circle.

If, for example, it is desired to plot a family of circles of $I_1$ with the ratio of the transformer 2, $k_2$, as the parameter, the 3-point method is employed to locate 2 circles for 2 different values of $k_2$. The center vectors and the radii of these circles may be computed to check the results. Scale lines are then drawn for both circles and as many points of $I_1$ as desired are spotted on the 2 circles. Corresponding points of $I_1$ (for equal values of $Z_L$) are then joined with straight lines. The intervals on the connecting lines are then linearly subdivided to form a convenient scale of $k_2$. These scales are then projected at both ends of the connecting lines, thereby giving points on other circles for the same values of $Z_L$. A straight line through the centers of the 2 circles is similarly subdivided and extended with a scale of $k_2$ thus locating the center points of circles for other values of $k_2$.

With $k_2$ as the parameter of the $I_1$ circles, the short-circuit point $L\,I_{1(0)} = Vk_1/Z_1$ is common to all the circles and the open-circuit point follows the straight line,

$$I_{1(\infty)} = V\frac{k_1 - k_2}{Z_1 + Z_2}$$

**Table I. Equations and Constants for Division of Currents Between 2 Transformers Operating in Parallel**

| Conditions | Variation of $I_1$ and $I_2$ with $Z_L$; $k_1$ and $k_2$ Constant | |
|---|---|---|
| Equation | $I_1 = V\dfrac{k_1Z_2 + (k_1 - k_2)1\angle\theta_L \mid Z_L \mid}{Z_1Z_2 + (Z_1 + Z_2)1\angle\theta_L \mid Z_L \mid}$ | $I_2 = V\dfrac{k_2Z_1 - (k_1 - k_2)1\angle\theta_L \mid Z_L \mid}{Z_1Z_2 + (Z_1 + Z_2)1\angle\theta_L \mid Z_L \mid}$ |
| Locus | Circle | Circle |
| Circle constants and invariant points | $\alpha = Vk_1Z_2$<br>$\beta = V(k_1 - k_2)1\angle\theta_L$<br>$\gamma = Z_1Z_2$<br>$\delta = (Z_1 + Z_2)1\angle\theta_L$<br>$\rho = \mid Z_L \mid$<br>$I_{1(0)} = \dfrac{Vk_1}{Z_1}$<br>$I_{1(\infty)} = V\dfrac{k_1 - k_2}{Z_1 + Z_2}$ | $\alpha = Vk_2Z_1$<br>$\beta = -V(k_1 - k_2)1\angle\theta_L$<br>$\gamma = Z_1Z_2$<br>$\delta = (Z_1 + Z_2)1\angle\theta_L$<br>$\rho = \mid Z_L \mid$<br>$I_{2(0)} = V\dfrac{k_2}{Z_2}$<br>$I_{2(\infty)} = -V\dfrac{k_1 - k_2}{Z_1 + Z_2}$ |
| Denominator constants for center and radius | Let $Z_1Z_2 = R' + jX'$; Let $(Z_1 + Z_2)1\angle\theta_L = R'' + jX''$; Let $Q = 2(X''R' - X'R'')$ | |
| Radius | $\left\lvert\dfrac{VZ_2}{Q}[Z_1(k_1 - k_2) - k_1(Z_1 + Z_2)]\right\rvert$ | $\left\lvert\dfrac{VZ_1}{Q}[Z_2(k_1 - k_2) + k_2(Z_1 + Z_2)]\right\rvert$ |
| Center vector | $\dfrac{jV}{Q}[k_1Z_2(\overline{Z_1 + Z_2})1\angle -\theta_L - (k_1 - k_2)1\angle\theta_L(\overline{Z_1Z_2})]$ | $\dfrac{jV}{Q}[k_2Z_1(\overline{Z_1 + Z_2})1\angle -\theta_L + (k_1 - k_2)1\angle\theta_L(\overline{Z_1Z_2})]$ |
| Definitions | $Z_1$ = equ. ohmic imp. of Trans. 1, referred to L. T. side<br>$Z_2$ = equ. ohmic imp. of Trans. 2, referred to L. T. side<br>$Z_L$ = load imp. in ohms, in L. T. side<br>$\theta_L$ = phase angle of $Z_L$<br>$\lvert Z_L \rvert$ = magnitude of $Z_L$<br>$I_1$ = current in L. T. wdg. of Trans. 1<br>$I_2$ = current in L. T. wdg. of Trans. 2<br>$k_1$ = ratio of transformation of Trans. 1<br>$k_2$ = ratio of transformation of Trans. 2<br>Ratio of transformation = Ind. voltage in L. T. wdg. / Ind. voltage in H. T. wdg.<br>$I_L$ = load current = $I_1 + I_2$<br>$V$ = terminal voltage on H. T. side | Equation of a circle $S = \dfrac{\alpha + \beta\rho}{\gamma + \delta\rho}$<br>vinculum ($^-$) represents conjugate |

A family of $I_2$ circles with either transformer ratio as the parameter is constructed similarly. It should be observed that if $k_2$ be taken as the parameter, $k_2$ occurring in both invariant points of $I_2$ (see equation 10), the short-circuit point follows the line $I_{2(0)} = Vk_2/Z_2$ and the open-circuit point follows the line

$$I_{2(\infty)} = -V\frac{k_1 - k_2}{Z_1 + Z_2}$$

Although any values of $k_1$ or $k_2$ may be used to obtain a family of $I_1$ and $I_2$ circles, it should be remembered that the circles used for final results should not pertain to values of $k_1$ or $k_2$ far enough away from the values of these ratios which apply to the internal impedances used in the parametric expressions of the circles, to vitiate the approximation that the internal impedances remain constant. Otherwise it is not possible to draw a family of curves as described above and a separate expression must be set up for each circle with values of $Z_1$ and $Z_2$ corresponding to the particular values of $k_1$ and $k_2$ desired.

If the expressions for $I_1$ and $I_2$, equations 1 and 2, be divided one by the other, a convenient relationship for the ratio of load currents $I_1/I_2$ results. This is

$$\frac{I_1}{I_2} = \frac{k_1Z_2 + (k_1 - k_2)Z_L}{k_2Z_1 - (k_1 - k_2)Z_L} \tag{20}$$

This equation is linear in both numerator and denominator with respect to all variables and therefore follows a circular locus with $Z_L$, $k_1$, or $k_2$ considered as the variable. The construction of the circular loci of $I_1/I_2$ may be carried out in the same manner as indicated for the individual loci of $I_1$ and $I_2$.

For convenience in reference the various equations and constants necessary for the cases treated above have been grouped together in chart form and tabulated in table I.

With the analysis that has just been presented, the engineer has at his disposal a complete set of equations which permits ready plotting of the currents or current ratios for parallel transformer operation, as a function of any of the variables encountered in practice.

## Numerical Example

To illustrate the application of this method to a typical problem, the circular loci of $I_1$ and $I_2$ will be determined for the following 2 transformers:

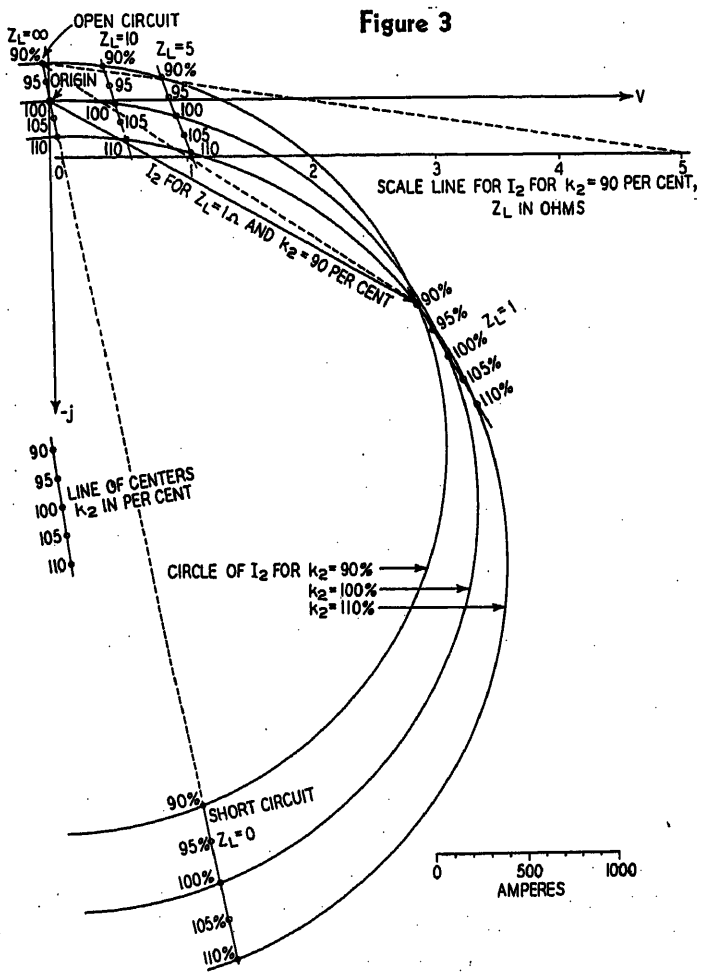
| | Transformer 1 | Transformer 2 |
|---|---|---|
| High-tension terminal voltage | 33,000 volts | 33,000 volts |
| Low-tension terminal voltage at open circuit | 6,600 volts | 6,600 volts |
| Rating | 3,000 kva | 1,500 kva<br>3,000 kva |
| Rated low-side current | 455 amperes | 227.5 amperes |
| Percentage leakage reactance | 12 per cent | 5 per cent |
| Percentage resistance | 2 per cent | 1 per cent |
| Percentage impedance | 12.2 per cent | 5.1 per cent |
| Equivalent impedance reduced to low side | $0.2915 + j1.745$ ohms<br>$1.77\angle 80.5°$ ohms | $0.289 + j1.45$ ohms<br>$1.48\angle 78.7°$ ohms |
| Transformer ratio $k$ | 0.2 | 0.2 |

The load will be taken at unity power factor. Then $Z_L = 1\angle 0° \, |Z_L|$

$Z_1 Z_2 = -2.44 + j0.926 = 2.61 \angle 159.2°$
$Z_1 + Z_2 = 0.5805 + j3.195 = 3.24 \angle 79.7°$

The loci of the individual transformer currents will be obtained for the ratios $k_1 = k_2 = 0.2$ as given above. The ratio of 0.2 will be considered as 100 per cent. To indicate how readily a family of circles can be plotted with the assumption that the change in internal impedance may be neglected for small changes in ratio, the ratio $k_1$ will be kept constant and the ratio $k_2$ will be treated as a parameter for the family. The high-tension terminal voltage $V$ will be taken as the reference vector throughout.

Figure 3




## Locus of $I_1$

Inserting the constants into equation 4 the current $I_1$ in transformer 1 becomes

$$I_1 = 33{,}000 \frac{0.2(0.289 + j1.45) + (0.2 - k_2) \, | \, Z_L \, |}{(-2.44 + j0.926) + (0.5805 + j3.195) \, | \, Z_L |} \qquad (21)$$

Two circles will be determined, for $k_2 = 0.18$ and 0.20, that is for ratios of 90 and 100 per cent, respectively, for transformer 2. The circles will be plotted by obtaining the invariant points and one other point on each, which in this case will be taken at $Z_L = 1$ ohm. The 2 sets of points for the circles are as shown in table II.

The 2 circles as determined by these points are drawn in figure 2. Straight lines are drawn connecting points of equal load impedance on the 2 circles. The intervals on these lines are used as scales for locating corresponding points on circles for $k_2$ = 95, 105, and 110 per cent. A straight line is drawn through the center points and the interval on this line is employed as a scale for obtaining the centers of the other circles. A scale line is drawn for the

Table II

| | $I_1$ Amperes | |
|---|---|---|
| $Z_L$ | $k_2$ = 90 Per Cent | $k_2$ = 100 Per Cent |
| 0 | $3{,}730 \angle -80.5°$ | $3{,}730 \angle -80.5°$ |
| 1 | $2{,}195 \angle -39.4°$ | $2{,}160 \angle -35.6°$ |
| ∞ | $203.5 \angle -79.7°$ | 0 |

90-per-cent circle. The value of $I_1$, in magnitude and phase, for any value of $Z_L$, is obtained by placing a straight edge on the infinity point and the desired value of $Z_L$ on the scale line. The intersection of the straight edge with the circle is then the extremity of the vector $I_1$ for the particular value of $Z_L$. A similar scale line may be drawn for another circle and points of $I_1$ for various values of $Z_L$ spotted on it. Straight lines connecting corresponding points on these circles suffice to locate corresponding points of $I_1$ on the other circles. Such lines are shown for $Z_L$ = 5 and 10 ohms. A scale line was drawn for the 110-per-cent circle for this purpose, but it is omitted in the figure for the sake of clarity.

To verify the construction the center vectors and the radii of the 2 circles may be calculated. From equations 15 the constant $Q$ is

$$Q = 2[-3.195 \times 2.44 - 0.926 \times 0.5805] = -16.7 \qquad (22)$$

The center vectors are then computed from equation 14 which gives

$$C_1 = j \frac{33{,}000}{-16.7} \Big[ 0.2(0.289 + j1.45)(0.5805 - j3.195) - (0.2 - k_2)(-2.44 - j0.926) \Big] \qquad (23)$$

when $k_2 = 0.18$ (90 per cent), $C_1 = 1{,}990 \angle -89.9°$
when $k_2 = 0.20$ (100 per cent), $C_1 = 1{,}890 \angle -91.0°$

From equation 18 the expression for the radius becomes

$$R_1 = \left| \frac{33{,}000 \times 1.48}{16.7} \Big[ (0.2915 + j1.745)(0.2 - k_2) - 0.2(0.5805 + j3.195) \Big] \right| \qquad (24)$$

when $k_2 = 0.18$ (90 per cent), $R_1 = 1{,}795$
when $k_2 = 0.20$ (100 per cent), $R_1 = 1{,}890$

## Locus of $I_2$

Under the same conditions, using equation 8 the current $I_2$ in transformer 2 becomes

$$I_2 = 33{,}000 \frac{k_2(0.2915 + j1.745) - (0.2 - k_2) \, | \, Z_L \, |}{(-2.44 + j0.926) + (0.5805 + j3.195) \, | \, Z_L |} \qquad (25)$$

The same 3 points on the 2 circles for different ratios $k_2$ are as shown in table III.

These circles are plotted in figure 3. Connecting lines are drawn through equal values of $Z_L$ to obtain corresponding points on circles for other values of $k_2$. A scale line is shown for the 90-per-cent circle. Points are indicated

**Table III**

| | $I_2$ (Amperes) | |
|---|---|---|
| $Z_L$ | $k_2$ = 90 Per Cent | $k_2$ = 100 Per Cent |
| 0 | 4,025 ∠ −78.7° | 4,470 ∠ −78.7° |
| 1 | 2,310 ∠ −30.2° | 2,590 ∠ −33.8° |
| ∞ | 203.5 ∠ 100.3° | 0 |

on the circles of $I_2$ for $k_2$ = 95, 105, and 110 per cent, but only the 110-per-cent circle is drawn in.

The center vectors in this case from equation 16 are:

$$C_2 = j\,\frac{33{,}000}{-16.7}\Big[k_2(0.2915 + j1.745)(0.5805 - j3.195) + (0.2 - k_2)(-2.44 - j3.195)\Big] \quad (26)$$

when $k_2$ = 0.18 (90 per cent), $C_2$ = 1,960 ∠ −90.2°
when $k_2$ = 0.20 (100 per cent), $C_2$ = 2,270 ∠ −89.2°

The radii are obtained from equation 19 which gives

$$R_2 = \left|\frac{33{,}000 \times 1.77}{-16.7}\Big[(0.289 + j1.45)(0.2 - k_2) + k_2(0.5805 + j3.195)\Big]\right| \quad (27)$$

when $k_2$ = 0.18 (90 per cent), $R_2$ = 2,150
when $k_2$ = 0.20 (100 per cent), $R_2$ = 2,270

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# Mechanical Engineering in the Electrical Industry

PROBABLY no other industry in the world offers the variety and scope for mechanical engineering that the electrical business does, according to the article "The Young Mechanical Engineer in the Electrical Industry," by A. R. Stevenson, Jr. (A'20) and E. E. Parker, which was published in *Mechanical Engineering* for October 1937, pages 725–31.

Electrical engineering is so interwoven with mechanical engineering that the electrical engineer must be familiar with mechanical matters, and, vice versa, the mechanical engineer should know considerable about electrical matters. Even in nonelectrical industries, the design of machinery includes application of electric motors and control. Because electrical engineering is recognized as a separate branch, the fact is sometimes overlooked that the design and manufacture of electrical apparatus involve to a large degree work designated as mechanical engineering. For example, after an electrical engineer has decided on the size and type of punchings and windings to give the proper magnetic-flux distribution and the insulation and electrostatic shields to give the proper distribution of electric potential, someone must do the mechanical engineering involved in designing the supporting structure, determining the heat transfer, the fluid flow of the cooling media, the lubrication, and similar factors. Furthermore, factory processes for construction of the apparatus are also purely mechanical.

Electrical apparatus is seldom used alone. It is either driven by mechanical apparatus or it drives or controls some other machinery. The electrical manufacturer, therefore, must have application engineering departments to study and sales departments to keep in touch with the mechanical industries, so that he can make proper recommendations with regard to the application of electric equipment in those industries.

The variety of mechanical engineering engaged in by an electrical company extends from the design and manufacture of kitchen mixers, clothes washers, dishwashers, and other household appliances to the design and construction of locomotives and large steam turbines. Switchgear and industrial-control apparatus, although nominally classed as electrical apparatus, depend for their success largely upon the mechanical design of the parts. For instance, in the mechanism for a 287-kv circuit breaker for Boulder Dam service, compressed springs release a force of 24,000 pounds in 0.01 second when the circuit breaker is tripped, and the mechanism develops approximately 300 horsepower for 0.06 second during interruption of a circuit. These springs are compressed by a motor and are released by an electrical impulse; otherwise, the circuit-breaker mechanism is completely a mechanical-engineering job.

Most electrical manufacturers also produce a variety of related equipment which is purely mechanical in nature, having been forced to do this to develop the electrical industry to its fullest capabilities. For instance, steam-driven electric generators were limited to about 5,000 horsepower in size because of the lack of a suitable prime mover to drive them until the electrical industry developed steam turbines that could be made in larger sizes. It is the electrical industry that has pioneered the development of the steam turbine from a few hundred to many thousand horsepower. Development work on the mercury-steam binary cycle has been carried on entirely by an electrical manufacturer in co-operation with several electrical utilities. This project includes development not only of turbines to operate with mercury vapor but also mercury boilers and condensers.

# Unsymmetrical Short Circuits on Water-Wheel Generators Under Capacitive Loading

By C. F. WAGNER
MEMBER AIEE

WATER-WHEEL GENERATORS without damper windings under capacitive load may have abnormally high voltages developed across their terminals at times of unsymmetrical short circuits. These voltages are due to 2 causes. First, the difference in permeance of the magnetic circuit in the direct and quadrature axes produces, under unsymmetrical short circuits, distorted voltages which have high peak values even if there is no capacitance connected to the machine. Second, the capacitance of the line and the reactance of the machine resonate or partially resonate and produce still greater distortion of the voltages on the sound phase. The phenomenon associated with single-phase short circuits with no connected capacitive load, has been analyzed by Doherty and Nickle.[1] The present paper is concerned with the effect of the capacitive load and an analysis of the factors involved in this phenomenon. Consideration is given to the system conditions under which these harmful voltages may arise and the remedial measures which may be applied for their elimination.

The practical value of this investigation arises from the damage that might occur to system insulation or the destruction of lightning arresters that might ensue if such voltages are permitted to exist. As a matter of interest, the problem was first drawn quite forcibly to our attention by the destruction of an arrester in the field, the circumstances having been such as to present incontrovertible proof that the failure was due to the presence of excessively high sustained voltages; conditions which arresters are not expected to withstand. Relay tests were being made on an unloaded transmission line connected through a transformer to a synchronous generator without damper windings. Upon the application of a line-to-line short circuit the arrester failed. In a repeat test the arresters were removed and the line-to-ground voltages were measured and found to be of such magnitude as to account for the arrester failure. It is quite probable that other arrester failures, previously attributed to lightning or other causes, can also be explained on this basis.

The body of the paper is concerned with an oscillographic study of the factors involved in the general problem and the appendix with an analytical study of the terminal voltages which appear for a terminal-to-terminal short circuit on a generator under capacitive load.

## Nature of Phenomenon

In order to form a preliminary idea of the nature of the phenomenon, a terminal-to-terminal short circuit and a capacitive load were simultaneously applied to a 100-kva 2,300-volt generator without damper windings operating at half rated voltage. Oscillograms were taken of the voltage from the shorted phases to the sound phase. As shown in the appendix from theoretical considerations, resonating points are encountered as the capacitive load is progressively decreased from a large value. If the reactance to neutral of the capacitance load at fundamental frequency is denoted by $x_c$ and the reactances of the generator to neutral in the direct and quadrature axes are denoted by $x_d'$ and $x_q$, respectively, then resonating points are reached when the quantity $x_c/\sqrt{x_d'x_q}$ is equal to $n^2$, where $n$ may be any odd integer. Oscillograms are shown in figure 1 for a wide variation of $x_c/\sqrt{x_d'x_q}$. Beginning with (*a*) it will be observed that the voltage consists of a fundamental component with a pronounced third harmonic. As $x_c/\sqrt{x_d'x_q}$ increases the fundamental decreases and the third harmonic increases, until a maximum deflection, as compared with the no-load value before the short circuit, is reached in oscillogram (*e*). This oscillogram has a value of $x_c/\sqrt{x_d'x_q}$ of 8.65 which does not correspond exactly to the theoretical value of 9. However, the computed value was based upon values of $x_d'$ and $x_q$ for normal frequency and rated current. Actually $x_d'$ and $x_q$ may not be regarded as constant. In figure 2 $x_d'$ and $x_q$ are plotted as functions of frequency for constant current and in figure 3, as a function of current for rated frequency. The root-mean-square value of the short-circuit current of figure 1*e* varies with time but is of the order of 1.2 to 1.4 per unit.* If it is assumed that the current is 1.25 per unit and that the reactances at this current vary in the same proportion as for the smaller currents in figure 2 then the corrected value of $x_c/\sqrt{x_d'x_q}$ is 9.1. This constitutes a very close check upon the theory.

As $x_c/\sqrt{x_d'x_q}$ is further increased the third harmonic becomes smaller and the fifth harmonic larger. This is progressively illustrated until oscillograms (*j*) and (*k*) are reached. Resonance occurs between these 2 oscillograms at a value somewhat smaller than the theoretical value of 25. Continuing still further, the seventh harmonic reaches a maximum in oscillogram (*o*). The voltage resulting for a terminal-to-terminal short circuit with no connected capacity is shown in (*q*). Theoretically, of course, if the resistance is negligible the voltage for the different resonating points should be infinitely large. Actu-

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1. For all numbered references, see list at end of paper.

* In this paper the per-unit system is used in designating the machine constants.

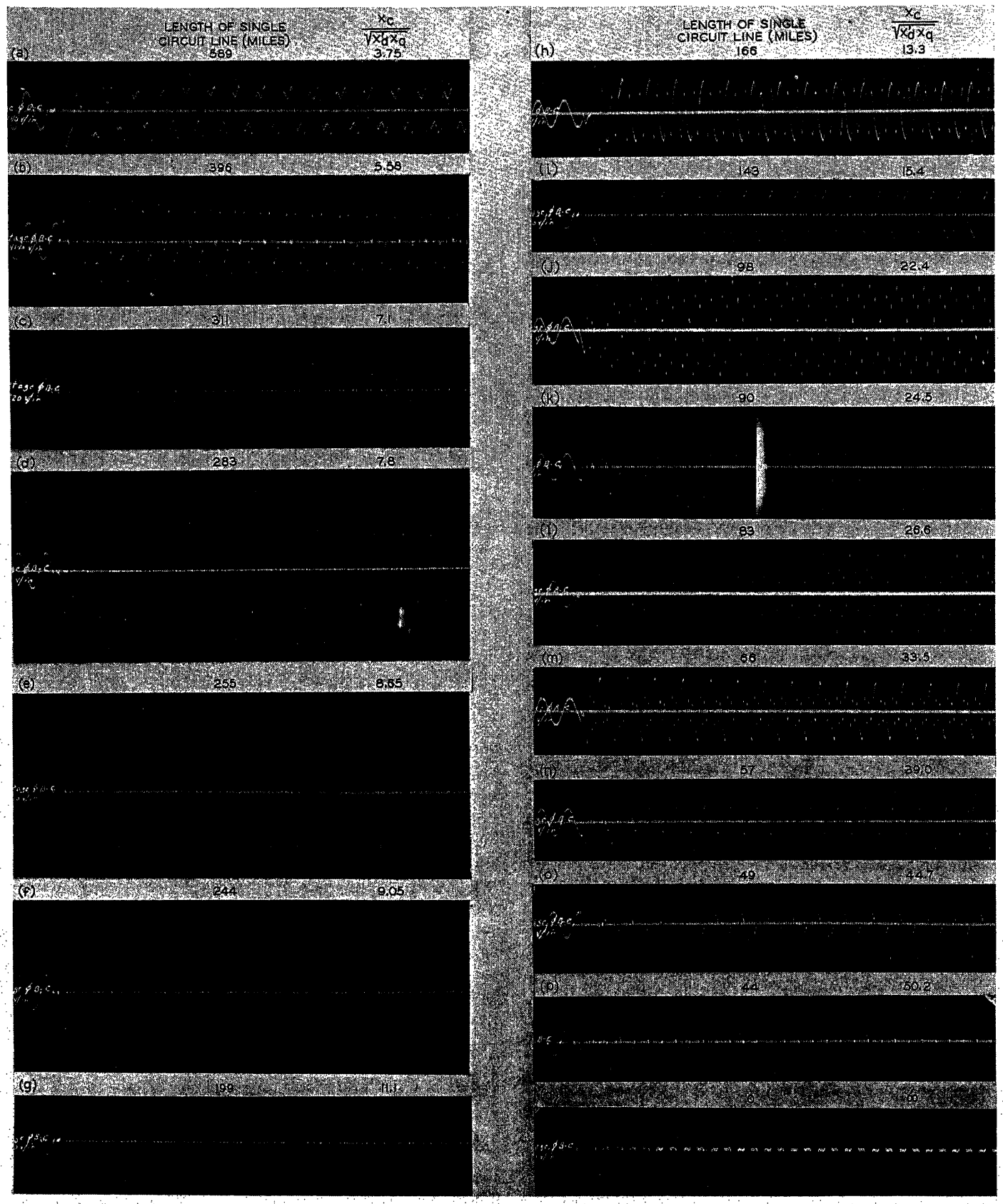



**Figure 1. Effect upon the terminal voltage of varying the shunt capacitive reactance when a terminal-to-terminal short circuit is applied to a machine without damper windings**

ally the resistance limits the magnitude to which the voltage rises, its effect increasing as the frequency increases. The truth of this statement is borne out by the curves of resistance for the 2 axes plotted in figure 2. These values were obtained by applying single-phase potential of variable frequency across 2 terminals of the machines with the rotor stationary as is done in the conventional method for determining $x_d''$ and $x_q''$. The resistance components of the impedances in the 2 axes are indicated as $r_{ad}''$ and $r_{aq}''$. It will be observed that for the seventh harmonic $r_{aq}''$ is 0.68 and $r_{ad}''$ is 0.17, values sufficiently high to significantly limit the voltages for resonance at this frequency. The curves of figure 2 were taken at the small currents indicated because of limitations

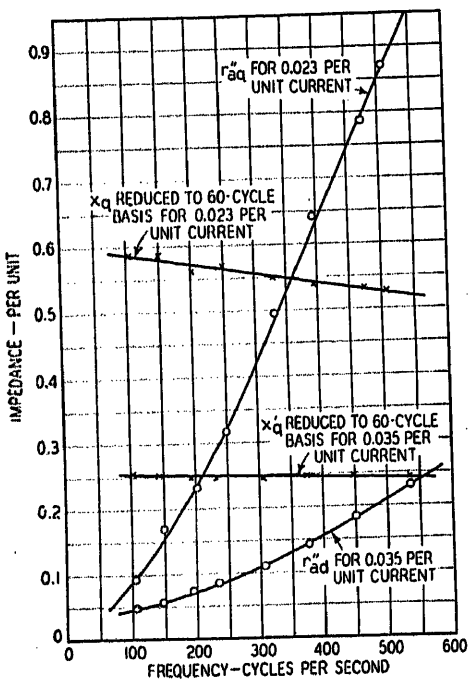



**Figure 2. Variation of $x_d'$, $x_q$, $r_{ad}''$, and $r_{aq}''$ with frequency**

100-kva 2,300-volt machine without damper winding

in the power of the source. The general effect of resistances will be discussed further in the appendix.

It will be observed that under certain conditions an initial transient of quite high value is present. This usually occurs at even harmonic resonant values of $x_c/\sqrt{x_d' x_q}$ as evidenced by oscillograms (*a*), (*b*), and (*h*). The point of greatest significance in connection with these oscillograms is that the maximum voltages occur for resonant conditions near the third and fifth harmonics.

In order to orient one's self with regard to the length of line involved in these considerations, the figure in miles which appears above each oscillogram represents approximately the length of single circuit 66-kv or 220-kv transmission line which, with a generator having the characteristics of the one used in the test, is required to satisfy the given value of $x_c/\sqrt{x_d' x_q}$. These figures were arrived at by assuming a generator capacity of 25,000 kva, 75,000 kva, and 200,000 kva for a 66 kv, 132 kv, and 220 kv, respectively. For smaller machines the length will decrease in proportion.

## Effect of Parallel Machines Having Damper Windings

In practice water-wheel generators are usually paralleled with machines having damper windings or their equivalent, that is, the generator may feed power over a line into a system which includes turbogenerators or, again, synchronous condensers may be connected to the system at the receiving end of the line. Under what conditions then may these harmful voltages appear and to what extent do parallel machines hold these voltages down? If upon the inception of a fault upon a single-circuit transmission line to which a generator without damper windings is connected, the breaker at the end remote from the generator opens first, then the condition prevails under which it is known these abnormal voltages can exist, namely, an essentially capacitive load connected to a machine without damper windings. This condition will persist until the breaker at the supply end is opened. During the interval while both breakers are closed, the machines with damper windings reduce the maximum voltages. If the line involved is a 2-circuit line, then opening the breaker at the receiving end of one line does not open the tie between the 2 ends of the system and the dangerous condition of having an open line tied to a generator cannot exist unless the second breaker at the receiving end is opened.

The extent to which connected machines with damper windings are effective is illustrated in figure 4. The schematic diagram shows the arrangement of the test equipment which represents a transmission system in miniature. Machine 1 is a generator *without* damper windings and machine 2 is a generator with *end-connected copper* damper windings. The intervening transmission line is representative of a 100-mile single-circuit line. Oscillogram (*b*) shows the phase-to-ground voltage for a phase-to-phase short circuit on the left-hand side of the line and oscillogram (*a*) the same voltage for the condition in which machine 2 is not connected to the line. The calibration of the oscillograph elements was not the same in these 2 cases, but by comparing the deflections with the no-load voltages before the short circuit it may be seen that the presence of the machine with copper dampers reduces the peak voltages to 68 per cent. In taking oscillogram (*a*) the series reactance ($j0.47$) was not in the circuit but its omission will not change the conclusions. The significant factor is that the harmonics are suppressed to a very great extent. Oscillograms (*c*) and (*d*) were taken under con-

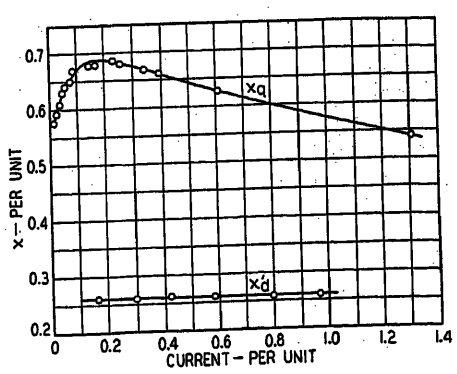


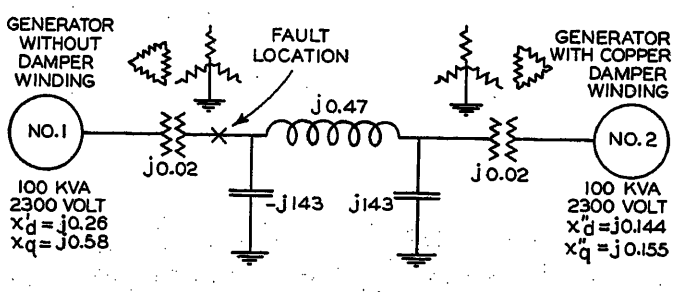

**Figure 3. Variation of $x_d'$ and $x_q$ as a function of current**

100-kva 2,300-volt machine without damper windings

ditions identical to (*a*) and (*b*), respectively, except that the fault was a line-to-neutral short circuit. For shorter transmission lines or any case in which there is less reactance between the machines, the damper windings will be still more effective in limiting the excessive voltages.

## Effect of Load

The question naturally arises as to the effect of connected load in suppressing the harmonics associated with these voltages. If load is taken from the generator end of a transmission line will a short circuit on an open-ended transmission line connected to the bus result in smaller voltages than if the load were absent? Oscillographic



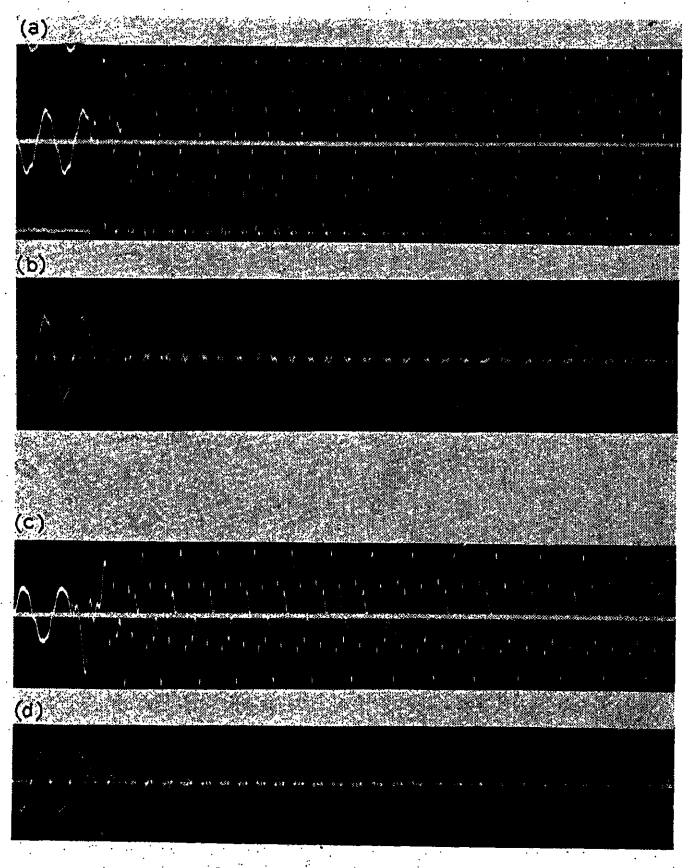




**Figure 4. Effect of paralleling machine having a copper damper winding with a machine having no damper winding**

Oscillograms show voltage of phase having maximum voltage
(*a*) Phase-to-phase short circuit, machine 2 not connected
(*b*) Phase-to-phase short circuit, machine 2 connected
(*c*) Phase-to-neutral short circuit, machine 2 not connected
(*d*) Phase-to-neutral short circuit, machine 2 connected

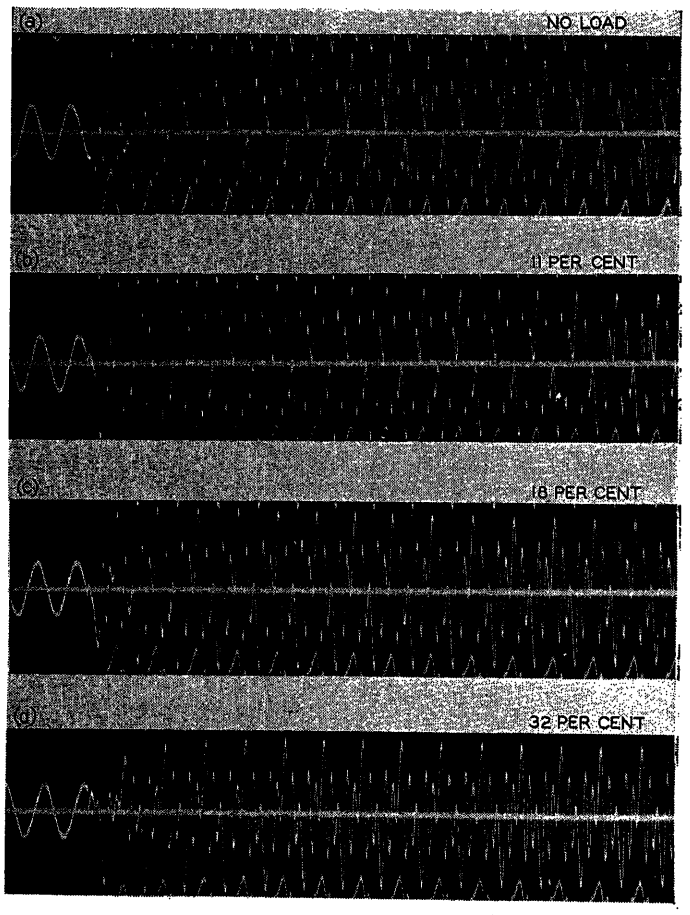



**Figure 5. Effect of pure reactance load**

tests were made on a 100-kva generator loaded with capacitors through a delta-star transformer. The capacitance was equal to 8.85 per unit and approximates the lengths of single-circuit line given in the last column of table I. It must be borne in mind that a capacitor is not strictly analogous in characteristics to a transmission line, especially at the higher frequencies, but it is sufficiently representative for the purpose in hand. Loads of different character were then applied to the line side of the transformer.

### Pure Reactance

Figure 5 shows the results of tests made with essentially pure reactance loads. To preclude the need for obtaining 3-phase reactors the load in the form of a single reactor was applied simultaneously with a phase-to-phase short circuit on the line. The capacitors were connected at the same time. The line-to-ground voltage of the unshorted phase on the load side of the transformer is shown by the oscillograms for reactor values equivalent to steady-state loads of 0, 11, 18, and 32 per cent of rated values. The reactor loading over the entire range has little if any effect upon the magnitude of these voltages or in suppressing harmonics unless very near a resonance point in which case the reactor would dissonate or detune the circuit. Thus the reactive load merely changes the resonating points. Of course, as the load reactance is still further decreased the voltage will decrease, approaching zero as the load reactance approaches zero.

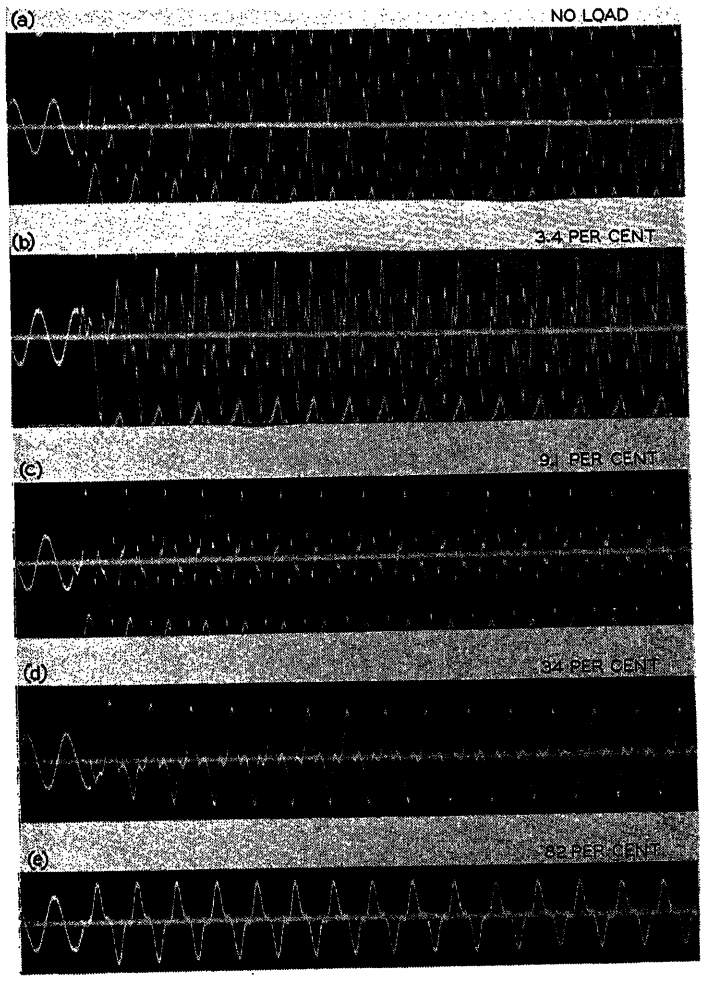



Figure 6. Effect of pure resistance load

PURE RESISTANCE

Pure resistance load, on the other hand, becomes quite effective in reducing the voltage of the sound phase as may be evidenced by the oscillograms of figure 6. A load of 34 per cent reduced the sound phase voltage to about 65 per cent of the voltage for the no-load condition.

INDUCTION MOTOR

An induction-motor load of equal kilovolt-amperes is still more effective in reducing the peak voltages than is a pure resistance load. The upper 3 curves of figure 7 show the effect upon the sound phase-to-neutral voltage on the load side of the transformer as a phase-to-phase short circuit, the capacitor load, and an induction-motor load of 0, 12.2, and 49 per cent, respectively, are simultaneously applied to the 100-kva generator. A 25-horsepower induction motor was used for this purpose, the generator being operated at half voltage and the induction motor at such voltages, by means of transformers, as to produce an impedance equivalent to the loads indicated. The induction motors were unloaded. By comparing the oscillogram voltages with the values before the short circuit, it will be seen that induction motors are quite effective in reducing these abnormal voltages. This is due to the lower impedance for the harmonics than that possessed by a proportionate pure reactance load.

The lower 3 oscillograms give verifying results for phase-to-neutral short circuits.

## Damper Windings

It is shown in the appendix that for a terminal-to-terminal short circuit on an unloaded machine *without* damper windings the voltage from the sound phase to the shorted phases can be resolved into odd and even harmonics. The even harmonics, including the zero'th, decay quite rapidly (within a few cycles if several per cent resistance, representative of that in a transmission line, is inserted in the armature circuit) and the odd harmonics more slowly. The crest value of the sum of the odd harmonics just after short circuit is equal to $(3/2)/(x_q/x_d')$ times the crest of the normal line-to-neutral voltage. For a machine *with* damper windings this multiplying factor is $(3/2)(x''/x_d'')$. Thus the crest voltages, neglecting the rapidly decaying even harmonics, increase proportionately

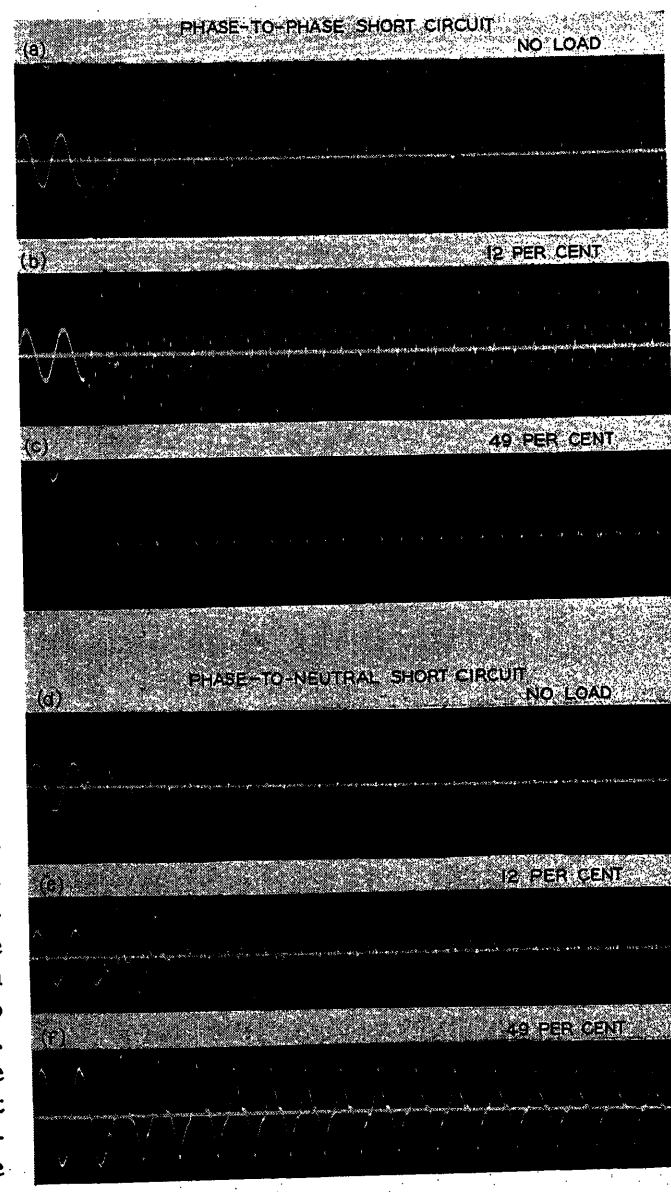



Figure 7. Effect of induction-motor load

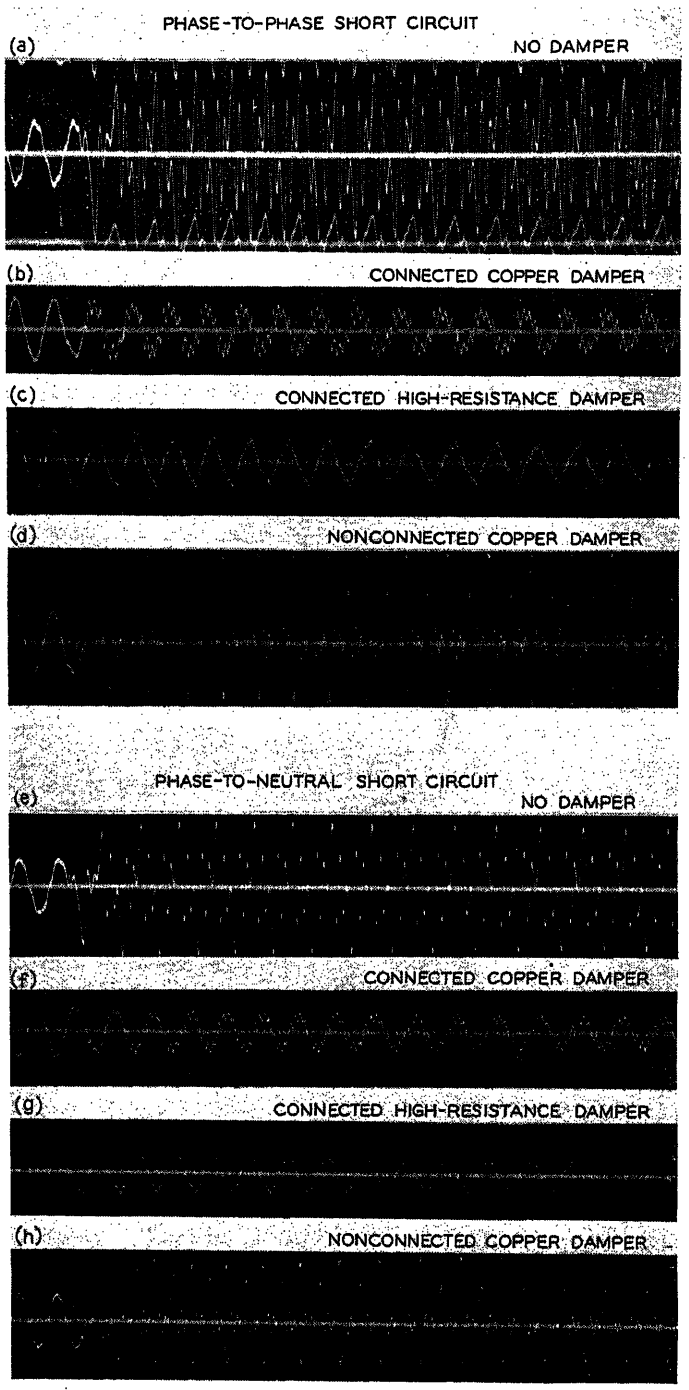



**Figure 8. Effect of damper windings**

:o the ratio $x_q/x_d'$ for machines without damper windings and to the ratio $x_q''/x_d''$ for machines with damper windings. One would expect also that the abnormal voltages encountered under capacitive loading might also vary with $x_q/x_d'$ or $x_q''/x_d''$.

Tests were made on 3 100-kva synchronous generators that were identical except as to damper windings. One of the machines had no damper windings, one a copper damper, and the other an Everdur* or high-resistance damper. In addition, the tests were repeated with the machine with copper dampers after the end straps had been insulated between poles thus constituting in effect a nonconnected damper winding. The constants of the machines are given in table II. Each of the machines was in turn connected through a delta-wye bank of 3 $37\frac{1}{2}$-kva transformers to a capacitive load consisting of capacitors connected from the phase wires to the neutral point of the transformer secondary. The capacitors were of such magnitude to simulate the line lengths represented in table I.

The specific tests consisted of phase-to-phase and phase-to-neutral short circuits, the results of which are shown by the oscillograph study of figure 8. It will be observed that for both kinds of short circuits, the voltages are reduced considerably by the presence of connected dampers, whether they be of the low-resistance (copper) type or the high-resistance (Everdur) type. To this extent the surmise is borne out that the ratio $x_q''/x_d''$ constitutes a rough measure of the distortion one might expect. In oscillograms (*a*) and (*e*), the combination of machine reactance and line capacitance is such as to be near the resonance point for the fifth harmonic but with the decrease in machine reactance occasioned by the copper damper (the line capacitance remaining the same) the resonance point has been moved closer to the seventh as shown in oscillograms (*b*) and (*f*). For the machine with Everdur dampers [oscillograms (*c*) and (*g*)], the reactance is such as to also approach the resonating point for the seventh harmonic, but it will be observed that the amplitude of the harmonic is much smaller than that for the copper damper winding. This is because the higher values of $r_{ad}''$ and $r_{aq}''$ for Everdur (see table II) tend to prevent to a greater extent the building up of the large currents and voltages associated with resonant conditions.

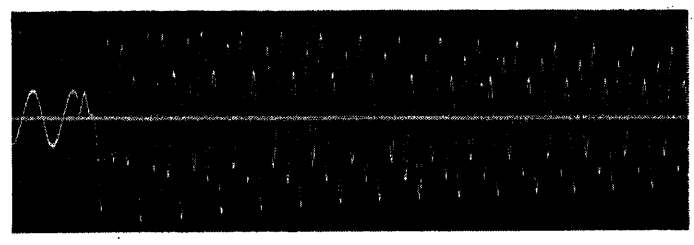


**Figure 9. Terminal-to-terminal voltage across sound phase for simultaneous application of terminal-to-terminal short circuit and capacitor load for a machine with nonconnected copper damper windings**

Circuit near third harmonic resonance

While in this case, nonconnected dampers are not anywhere near as effective as connected dampers in reducing the peak voltages, they are somewhat more effective than no dampers. Additional terminal-to-terminal short circuits were made on machines with nonconnected damper windings under capacitive load covering a wide range of capacitance. The case for near resonance of the third harmonic is shown in figure 9. By comparison with figure 1*e* it may be seen that the voltages from the sound phase to the short-circuited phases are somewhat less. This is

* The conductivity of Everdur is approximately 6 per cent.

probably due to larger values of $r_{ad}''$ and $r_{aq}''$ for the machine with nonconnected dampers. Table II shows a variation of these constants in this general direction and at 180 cycles the difference is probably greater. In any case figures 8*d* and 8*h* show that dangerously high voltages can be attained with this kind of damper unless precautions are taken to insure that the ratio $x_q''/x_d''$ is made more nearly equal to unity.

Additional data[4] relative to the effect of damper windings upon the constants of machines are given in table III.

## Conclusions

It has been shown that dangerously high voltages can be attained under unbalanced short circuits when synchronous generators without damper windings are connected to capacitive loads such as represented by an unloaded transmission line. These voltages may consist of very high initial transients of a few cycles duration followed by

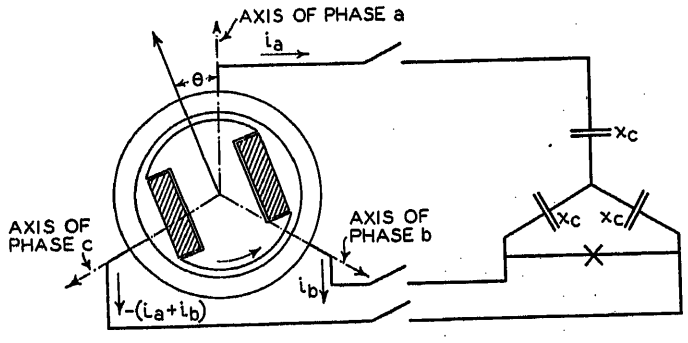



Figure 10

distorted waves having a slower decay. For a given machine resonating points are encountered as the length of unloaded connected line is varied. The voltages are maximum at these resonating points. The length of line required for resonance is also dependent upon the type of fault considered. A particular line represents a particular electrostatic capacity but since the fault may occur at any point, the reactance is variable. This fact increases the difficulties of attempting to operate at a point of dissonance. In general if conditions are such that resonance is obtained for a short circuit at the generator end of the line, the voltages that can be expected will be larger than if conditions are such as to produce resonance for short circuits at the far end of the line. This follows because the resistance of the line tends to prevent the building up of the currents and voltages at resonance. These abnormal voltages are larger in proportion to normal values on the line side of transformers than on the machine side.

If other synchronous machines having damper windings or their equivalent are kept in parallel or if sufficient resistance or induction-motor load is maintained connected to the machines, the excess voltages may be reduced a very considerable degree.

It has been shown that these phenomena are very closely associated with the ratio $x_q/x_d'$ in the case of machines without damper windings and $x_q''/x_d''$ in the case of machines with damper windings, the magnitude of the abnormal voltages increasing as this ratio increases from unity. Connected damper windings, either high or low resistance, because their presence results in a machine for which this ratio is very nearly equal to unity, are very effective in preventing these abnormally high voltages. Damper windings which result in a higher value of this ratio, such as may be the case for windings not connected between poles, are not so effective in preventing these voltages.

Tests have shown (figure 1*e*) that the crest value of the voltage from the sound phase to the shorted phases may attain a value 5.5 times the normal crest line-to-line value. Without making an attempt to obtain resonant conditions, the line-to-neutral voltages for a line-to-line short circuit (figure 8*a* and 8*d*) gave a measured value of 2.9 times normal crest value for both a machine with connected and one with nonconnected copper damper windings.

## Appendix

In approaching the analytical investigation of this problem the simplest case will be chosen which still incorporates the essential

**Table I. Lengths of Single-Circuit Transmission Lines Having Capacitance Impedance of 8.85 Per Unit**

| Line Voltage (Kilovolts) | Conductor | Spacing (Feet) | Rating of Generator (Kilovolt-amperes) | Length of Line (Miles) |
|---|---|---|---|---|
| 22 | 00 A.C.S.R. | 4 | 10,000 | 372 |
| 66 | 000 Copper | 6 | 25,000 | 110 |
| 132 | 0000 Copper | 13 | 75,000 | 92 |
| 220 | 605,000 circular mil A.C.S.R. | 21 | 200,000 | 87 |

**Table II. Constants of a Synchronous Generator as Affected by Type of Damper Winding**

100 Kva, 2,300 Volts, 25.2 Amperes

| Type | $x_d'$ | $x_q$ | $\sqrt{x_d'x_q}$ | $\frac{x_q}{x_d'}$ | $r_{ad}''$ | $r_{aq}''$ |
|---|---|---|---|---|---|---|
| No damper | 0.260 | 0.577 | 0.388 | 2.22 | 0.028 | 0.105 |
| | $x_d''$ | $x_q''$ | $\sqrt{x_d''x_q''}$ | $\frac{x_q''}{x_d''}$ | | |
| Connected copper | 0.157 | 0.146 | 0.151 | 0.93 | 0.036 | 0.047 |
| Connected Everdur | 0.171 | 0.157 | 0.164 | 0.92 | 0.063 | 0.111 |
| Nonconnected copper | 0.154 | 0.390 | 0.245 | 2.53 | 0.037 | 0.113 |

**Table III. Constants of a Synchronous Condenser as Affected by Type of Damper Winding**

5,000 Kva, 4,000 Volts, 721 Amperes

| Type | $r_2$ | | $x_2=\frac{1}{2}(x_d''+x_q'')$ | |
|---|---|---|---|---|
| | Test | Calculated | Test | Calculated |
| No damper | 0.045 | 0.040 | 0.75 | 0.69 |
| Connected copper | 0.026 | 0.029 | 0.195 | 0.215 |
| Connected brass | 0.045 | 0.044 | 0.195 | 0.215 |
| Connected Everdur | 0.12 | 0.125 | 0.20 | 0.215 |

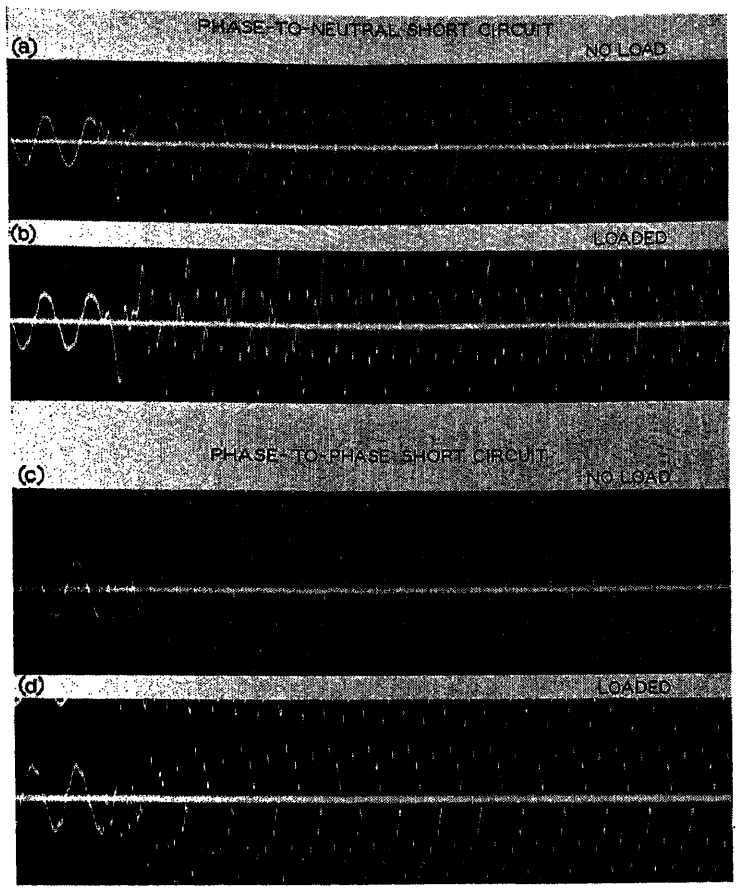



**Figure 11. Effect of loading machine with capacitive load before short circuit**

factors of the problem. To this end consideration will be given to the voltage between the short-circuited and the sound terminals of a synchronous machine without damper windings as a terminal-to-terminal short circuit and a 3-phase capacitive load are applied simultaneously. The schematic diagram of the circuit is shown in figure 10. The notation and assumptions will be the same as that used by Park[2,3] in his papers relating to the theory of synchronous machines. Thus the machine will be "idealized" to the extent that each armature winding will be assumed to produce a sinusoidal wave of magnetomotive force. Saturation, hysteresis, and eddy currents will be neglected.

The "per unit" system will be employed in which the units are defined as follows:

| | |
|---|---|
| Armature current | $\sqrt{2}$ rated value |
| Armature voltage | $\sqrt{2}$ rated terminal-to-neutral value |
| Armature flux | value which will generate rated voltage at no load |
| Field current | value which will produce unit armature flux at no load |
| Reactance | ratio of normal phase-to-neutral voltage to normal phase current |
| Angle | electrical radian |
| Time | time for rotor moving at rated speed to move through one electrical radian |

Let

$i_a, i_b, i_c$ = terminal currents
$e_a, e_b, e_c$ = terminal-to-neutral voltages
$\psi_a, \psi_b, \psi_c$ = terminal-to-neutral linkages
$I_d$ = field current
$\theta$ = angular displacement of rotor from axis of phase $a$

From figure 10, it is evident that

$$I_c = -(i_a + i_b) \tag{1}$$

so that equation 3 of reference 3 becomes

$$i_d = \frac{2}{3}\left\{\left[\cos\theta - \cos\left(\theta + \frac{2\pi}{3}\right)\right] i_a + \left[\cos\left(\theta - \frac{2\pi}{3}\right) - \cos\left(\theta + \frac{2\pi}{3}\right)\right] i_b\right\} \tag{2}$$

The flux linkages with the field winding, $\Psi$, are given by

$$\Psi = I_d - (x_d - x_d')i_d \tag{3}$$

Therefore, corresponding to any sudden change in armature currents,

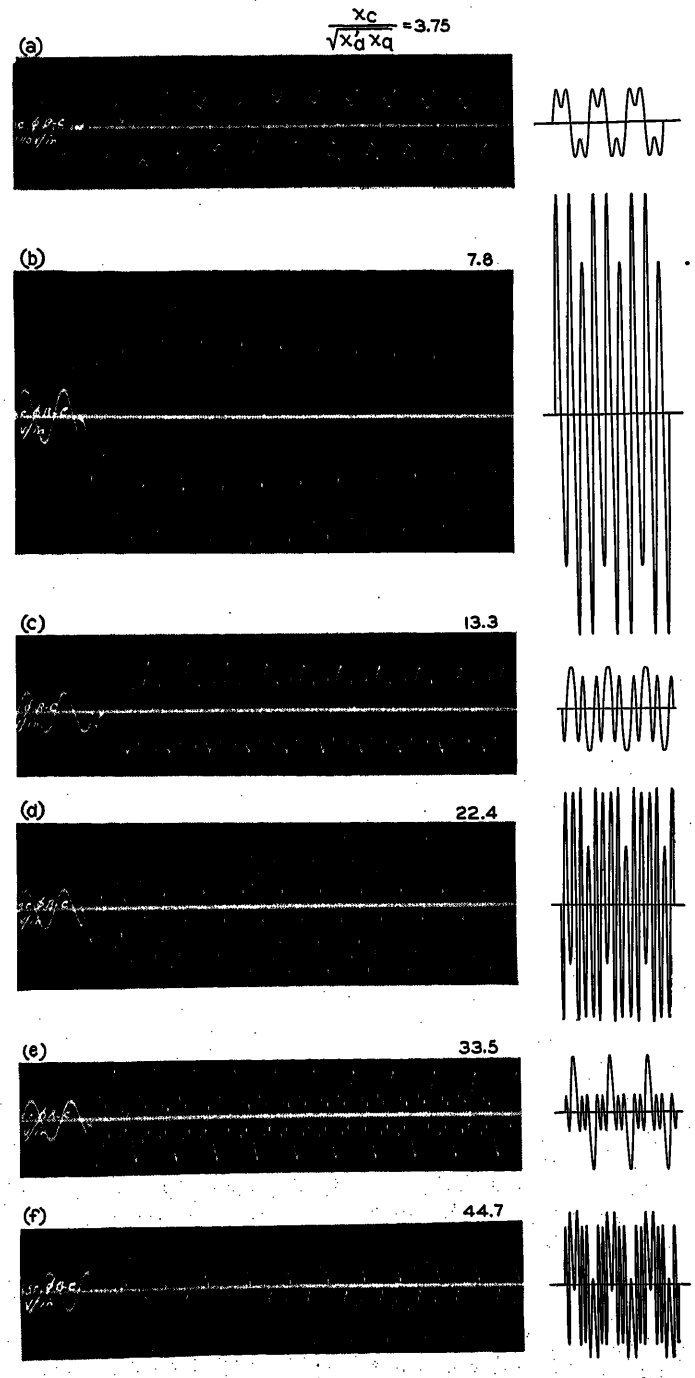



**Figure 12. Comparison between test and calculated values of voltage**

there follows from this equation (since $\Psi$ cannot change instantly) that

$$0 = \Delta I_d - (x_d - x_d')i_d \tag{4}$$

where $\Delta I_d$ is the current induced in the field winding. Therefore, upon substituting 2 in 4

$$\Delta I_d = \frac{2(x_d - x_d')}{3}\left\{\left[\cos\theta - \cos\left(\theta + \frac{2\pi}{3}\right)\right]i_a + \left[\cos\left(\theta - \frac{2\pi}{3}\right) - \cos\left(\theta + \frac{2\pi}{3}\right)\right]\right\} \tag{5}$$

Equations 1 to 3 of Park's paper give the flux linkages $\psi_a$, $\psi_b$, and $\psi_c$ for any values of $i_a$, $i_b$, $i_c$, and $I_d$. If the value of $i_c$ from 1 and $\Delta I_d$ from 5 are substituted in these equations, the values of flux linkages for the suddenly appearing armature currents are obtained. These are:

$$\psi_a = -\frac{x_d' - x_q}{3}\left\{\left[\cos 2\theta - \cos\left(2\theta + \frac{2\pi}{3}\right)\right]i_a + \left[\cos\left(2\theta - \frac{2\pi}{3}\right) - \cos\left(2\theta + \frac{2\pi}{3}\right)\right]i_b\right\} - \frac{x_d' + x_q}{2}i_a \tag{6}$$

$$\psi_b = -\frac{x_d' - x_q}{3}\left\{\left[\cos\left(2\theta - \frac{2\pi}{3}\right) - \cos 2\theta\right]i_a + \left[\cos\left(2\theta + \frac{2\pi}{3}\right) - \cos 2\theta\right]i_b\right\} - \frac{x_d' + x_q}{2}i_b \tag{7}$$

$$\psi_c = -\frac{x_d' - x_q}{3}\left\{\left[\cos\left(2\theta + \frac{2\pi}{3}\right) - \cos\left(2\theta - \frac{2\pi}{3}\right)\right]i_a + \left[\cos 2\theta - \cos\left(2\theta - \frac{2\pi}{3}\right)\right]i_b\right\} + \frac{x_d' + x_q}{2}(i_a + i_b) \tag{8}$$

In addition to the flux linkages due to the suddenly appearing armature currents there also exist flux linkages due to the normal value of field current. These values are

$$\psi_a = I_d \cos\theta \tag{9}$$

$$\psi_b = I_d \cos\left(\theta - \frac{2\pi}{3}\right) \tag{10}$$

$$\psi_c = I_d \cos\left(\theta + \frac{2\pi}{3}\right) \tag{11}$$

The total flux linkages between $b$ and $c$ for the sudden change in armature current (including the normal field current) are

$$\psi_b - \psi_c = \sqrt{3}\,I_d \sin\theta - (x_d' - x_q) \times \left[i_a \cos\left(2\theta - \frac{2\pi}{3}\right) - i_b \cos 2\theta\right] - \frac{x_d' + x_q}{2}(i_a + 2i_b) \tag{12}$$

and for the flux linkages across $a$ and $b$

$$\psi_a - \psi_b = \sqrt{3}\,I_d \sin\left(\theta + \frac{2\pi}{3}\right) - (x_d' - x_q) \times \left[i_a \cos 2\theta - i_b \cos\left(2\theta + \frac{2\pi}{3}\right)\right] - \frac{x_d' + x_q}{2}(i_a - i_b) \tag{13}$$

The voltage across the terminals $b$ and $c$ is equal to

$$\frac{d}{dt}(\psi_b - \psi_c) = 0$$

or

$$\psi_b - \psi_c = \text{constant} \tag{14}$$

The significance of this equation is that the flux linkages immediately before and immediately after short circuit are equal, an application of Doherty's theorem of "constant flux linkages." Stated otherwise, the constant is determined from the value just before short circuit. If

$$\theta = t + \alpha \tag{15}$$

in which $t$ is measured from the instant of short circuit, then

$$\sqrt{3}\,I_d \sin\alpha = \sqrt{3}\,I_d \sin\theta - (x_d' - x_q)\left[i_a \cos\left(2\theta - \frac{2\pi}{3}\right) - i_b \cos 2\theta\right] - \frac{x_d' + x_q}{2}(i_a + 2\,i_b) \tag{16}$$

or

$$i_b = \frac{\sqrt{3}\,I_d\,[\sin\alpha - \sin\theta] + \left[(x_d' - x_q)\cos\left(2\theta - \frac{2\pi}{3}\right) + \frac{x_d' + x_q}{2}\right]i_a}{(x_d' - x_q)\cos 2\theta - (x_d' + x_q)} \tag{17}$$

The voltage across terminals $a$ and $b$ is equal to the voltage across the capacitors and also the time differential of the flux linkages across $a$ and $b$ so that

$$e_a - e_b = \frac{d}{dt}(\psi_a - \psi_b) = \frac{3}{2}x_c\int_0^t i_a dt$$

Upon substituting 13 and 17 into this equation,

$$\frac{d}{dt}\left\{\sqrt{3}\,I_d \sin\left(\theta + \frac{2\pi}{3}\right) - \left[(x_d' - x_q)\cos 2\theta + \frac{x_d' + x_q}{2}\right]i_a + \frac{(x_d' - x_q)\cos\left(2\theta + \frac{2\pi}{3}\right) + \frac{x_d' + x_q}{2}}{(x_d' - x_q)\cos 2\theta - (x_d' + x_q)}\sqrt{3}\,I_d\,[\sin\alpha - \sin\theta] + \frac{(x_d' - x_q)\cos\left(2\theta + \frac{2\pi}{3}\right) + \frac{x_d' + x_q}{2}}{(x_d' - x_q)\cos 2\theta - (x_d' + x_q)} \times \left[(x_d' - x_q)\cos\left(2\theta - \frac{2\pi}{3}\right) + \frac{x_d' + x_q}{2}\right]i_a\right\} = \frac{3}{2}x_c\int_0^t i_a dt$$

or rearranging

$$\sqrt{3}\,I_d \frac{d}{dt} \times \left\{\frac{\cos\left(2\theta + \frac{2\pi}{3}\right) - \frac{x_q + x_d'}{2(x_q - x_d')}}{\cos 2\theta - \frac{x_q + x_d'}{2(x_q - x_d')}}\,[\sin\alpha - \sin\theta] + \sin\left(\theta + \frac{2\pi}{3}\right)\right\} = + (x_q - x_d')\frac{d}{dt}\left[\left\{-\left[\cos 2\theta - \frac{x_q + x_d'}{2(x_q - x_d')}\right] + \frac{\cos\left(2\theta + \frac{2\pi}{3}\right) - \frac{x_q + x_d'}{2(x_q - x_d')}}{\cos 2\theta + \frac{x_q + x_d'}{x_q - x_d'}} \times \left[\cos\left(2\theta - \frac{2\pi}{3}\right) - \frac{x_q + x_d'}{2(x_q - x_d')}\right]\right\}i_a\right] + \frac{3}{2}x_c\int_0^t i_a dt \tag{18}$$

By further manipulation, whose proof space will not permit, it may be shown that this equation can be written in the following form

$$\frac{3}{2}I_a\frac{d}{dt}f(t) = \frac{3}{2}\sqrt{x_q x_d'}\,\frac{d}{dt}[F(t)\,i_a] + \frac{3}{2}x_c\int_0^t i_a dt \tag{19}$$

in which

$$f(t) = K' [\epsilon^{j\theta} + b\epsilon^{j3\theta} + b^2\epsilon^{j5\theta} + \dots + \epsilon^{-j\theta} + b\epsilon^{-j3\theta} + b^2\epsilon^{-j5\theta} + \dots] - \sin\alpha \left[\frac{1}{\sqrt{3}} + jb\epsilon^{j2\theta} + jb^2\epsilon^{j4\theta} + jb^3\epsilon^{j6\theta} + \dots - jb\epsilon^{-j2\theta} - jb^2\epsilon^{-j4\theta} - jb^3\epsilon^{-j6\theta} + \dots\right] \quad (20)$$

$$F(t) = [1 + b\epsilon^{j2\theta} + b^2\epsilon^{j4\theta} + b^3\epsilon^{j6\theta} + \dots + b\epsilon^{-j2\theta} + b^2\epsilon^{-j4\theta} + b^3\epsilon^{-j6\theta} + \dots] \quad (21)$$

and

$$b = -\frac{\sqrt{x_q} - \sqrt{x_d'}}{\sqrt{x_q} + \sqrt{x_d'}} \quad (22)$$

$$K' = \frac{\sqrt{x_q}}{\sqrt{x_q} + \sqrt{x_d'}} \quad (23)$$

The solution sought, namely, the voltage from terminal $a$ to $b$, is equal to last term of equation 19. The terms in 19 were arranged in that particular order because it suggests an equivalent problem to which it may be reduced, namely a constant capacitor $(3/2)x_c$ and a variable reactor having a mean value $(3/2)\sqrt{x_d'x_q}$ connected in series. The reactor varies harmonically in accordance with equation 21. The problem then consists of determining the voltage drop across this constant capacitor as the voltage given by

$$\frac{3}{2} I_a \frac{d}{dt} f(t)$$

is suddenly applied across the combination. This equivalent circuit suggests that resonance points exist for values of $x_c/\sqrt{x_q x_d'}$ equal to the square of the integers. The applied voltage equals the voltage across the sound phase for a terminal-to-terminal short circuit with no connected capacitors.

The formulation of the problem which resulted in equation 19, neglected the resistances in all circuits. The effect of resistance is dependent upon the particular component of the solution affected: Thus the odd harmonics of the applied voltage decrease gradually to their sustained value along an exponential curve whose time constant, which as shown by Doherty and Nickle,[1] is

$$T_d' = \frac{1}{\sigma_f} = \frac{x_d' + \sqrt{x_d'x_q}}{x_d + \sqrt{x_d'x_q}} T_{d_0} \quad (24)$$

The even harmonics of the applied voltage decrease to zero, and their time constant as shown also by Doherty and Nickle[1] is

$$T_a = \frac{1}{\sigma_a} = \frac{\sqrt{x_d'x_q}}{r} \text{ in seconds}$$

$$= \frac{\sqrt{x_d'x_q}}{r} 2\pi f \text{ in radians} \quad (25)$$

The time constant of a circuit consisting of a reactor $x_L$, capacitor $x_c$, and resistance $r$ (all in per unit) is

$$T = \frac{x_L}{2r} \text{ in seconds}$$

$$= \frac{x_L}{r} \pi f \text{ in radians} \quad (26)$$

Thus steady-state conditions in such circuit would be attained in a time equal to approximately $3T$.

For the general solution, therefore, one would expect the voltage across the capacitor obtained by the solution of 19 to exist for possibly a cycle, since the effect of resistance might not have had time to become effective in this time. This should be followed by a rather rapid change because of the disappearance of the even harmonics of 20 in accordance with $T_a$ of 25 and also the approach to the steady state solution for the odd harmonics of 20 in accordance with 26. This change should be followed by a more gradual decay in accordance with 24. The general performance outlined above is borne out by the oscillograms shown in the body of the paper, which in general show an initial transient that persists for just a few cycles, followed by a transient that lasts about a second. If the short circuit occurs out on the transmission line, the time constants $T_a$ and $T$ of equations 25 and 26 are reduced further, so that the initial transients decay still more rapidly than for faults on the terminals of the machine. The nature of the initial transient depends upon the instant during the cycle at which short circuit occurs. If $\alpha$ of 20 is equal to zero only odd harmonic voltages are applied to the circuit. In general, the excessively high voltages occur near resonance points for odd harmonics. For these values of $x_c/\sqrt{x_d'x_q}$ the initial transient delays the appearance of the crest value of voltage for about a cycle as evidenced by figures 1*e*, *f*, *k*, and *l*. For other values of $x_c/\sqrt{x_d'x_q}$, the initial transient requently results in much higher peaks during the first cycle than occurs subsequently. Illustrations of initially high peaks are offered by figures 1*a*, *b*, *c*, and *h*. For the high frequencies associated with large values of $x_c/\sqrt{x_d'x_q}$ the effective resistance becomes so high as to damp out rapidly the transients due to the high-frequency components. The character of the voltage, therefore, approaches that of the record obtained when no capacitors are connected to the machine. Compare oscillograms, figures 1*p* and *q*.

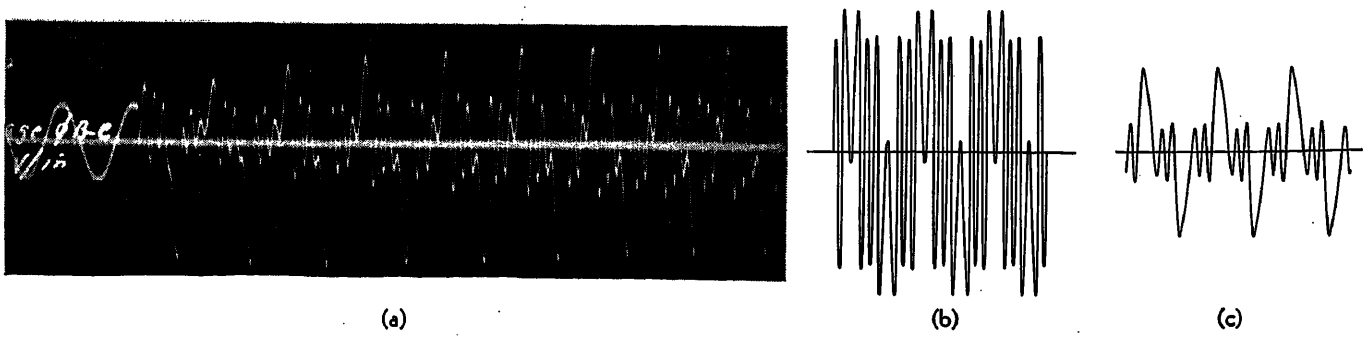
The principal virtue of a comparison of calculated and test curves of terminal voltage in a problem of this nature is the verification that no important factor has been omitted in the analysis. The rigorous solution even for the initial condition represented by equation 19 is quite involved and, after all, the initial boundary conditions set up by this case are not truly representative of the conditions met in practice. First, in practice, the machine will be under capacitive loading at the time of short circuit. However, this particular point makes little difference as evidenced by the oscillograms of figure 11 which show the effect upon the initial transients as influenced by the initial loading condition for similar short circuits. Second, of greater importance is the fact that the practical boundary condition most likely to be met is the opening of a breaker at the receiving end of a faulted line after the short circuit had been on for some time and the flux conditions within the machine had had ample time to change materially from the no-load conditions upon which the present development is premised. In view of these considerations the labor and difficulties incident to a determination of the initial transient voltages are not justified. However, the much simpler case of the quasi-steady-state solution for equation 19 in which the even harmonics of applied voltage have disappeared and the rapid transients due to the circuit constants have also disappeared, is justified. To be specific, the assumption will be made that $T_a$ of equation 25 and $T$ of equation 26 are zero and that $T_d'$ is infinitely large. The transients associated with the field winding have not had opportunity to change appreciably. This solution will now be obtained.

The solution will follow the line of successive approximations. It will be assumed that a voltage $e_n$ equal to the odd terms of the applied voltage of 19 is applied to a reactor of constant value, $(3/2)\sqrt{x_q x_d'} = x_L$, and a capacitor of impedance $(3/2)x_c$ connected in series. For this simple circuit the current $i_n'$ for each harmonic component can be obtained. Thus

$$e_n = j\frac{3}{2} K' [\epsilon^{j\theta} + 3b\epsilon^{j3\theta} + 5b^2\epsilon^{j5\theta} + \dots \text{ and } \epsilon^{-j\theta} + 3b\epsilon^{-j3\theta} + 5b^2\epsilon^{-j5\theta} + \dots] \quad (27)$$

$$x_L i_n' = \frac{1}{j}\sum_1^n Y_n E_n \epsilon^{jn\iota} = \frac{1}{j}\sum_1^n \frac{n}{\left(n^2 - \frac{3x_c}{2x_L}\right)} E_n \epsilon^{jn\iota} \quad (28)$$

where $n$ is odd integers.



(a) (b) (c)

**Figure 13. Comparison between test and calculated values of voltage**

$x_c/\sqrt{x_d' x_q} = 44.7$ (a) Test (b) Neglecting resistance (c) Including resistance

Actually the reactor, $x_L$, is not constant but varies harmonically with time. The instantaneous flux linkages, assuming that the current $i_n'$ flows, is obtained by multiplying 28 by 21 giving the quantity $x_L i_n' F(t)$. The drop, $e_L'$, across the reactor for this current is then

$$e_L' = \frac{d}{dt}\left[x_L i_n' F(t)\right] \tag{29}$$

and the drop across the condenser for the current $i_n'$ is

$$e_c' = -j\frac{3}{2}\frac{x_c}{x_L}\frac{(x_L i_n')}{n} \tag{30}$$

The sum of $e_L'$ and $e_c'$ gives the voltage necessary to force the current $i_n'$ through the capacitor and variable reactor. This sum will not equal the actual applied voltage but the excess or deficiency will be a second order quantity. Thus let

$$e - e_L' - e_c' = e' \tag{31}$$

Now let the voltage $e'$ be absorbed in the constant $x_L$ and $(3/2)x_c$ circuit and obtain a second current $i''$ through the application of 28. Assume the currents $i'$ and $i''$ flow and obtain the instantaneous flux linkages by multiplying $(x_L i' + x_L i'')$ by 21. The time differential of this quantity gives the drop, $e_L''$, across the reactor for the assumed current flow and the drop, $e_c''$, across the condenser is

$$e_c'' = \frac{3}{2}\frac{x_c}{x_L}\frac{(x_L i' + x_L i'')}{n} \tag{32}$$

As before, determine the excess or deficiency between the applied voltage $e$ and the sum of the drops $e_L''$ and $e_c''$. Thus

$$-e_L'' - e_c'' = e'' \tag{33}$$

Operate upon $e''$ as upon $e'$. By successive applications of these steps $e^n$ will become negligibly small. The desired solution is the last value of $e_c$ obtained.

This method has been applied to a number of cases, the results of which are shown in figure 12 which offers a comparison between test and calculated results. Since the calculations do not include the initial transients a rough comparison, neglecting the field transients which merely reduces the magnitude but does not affect the wave shape, may be made between the last few cycles of the oscillograms and the calculated curves. It will be observed that the results are quite close for those cases which are not near odd harmonic resonance, namely (*a*), (*c*) and (*e*). The lack of agreement of the other cases is due primarily to the assumption that resistance is neglected. Near resonance the resistance assumes great importance in limiting the current and also the voltage. Aside from affecting the magnitude of the voltage the resistance also introduces dissymmetry in the wave shape. To a lesser degree than the effect of resistance, the variation of reactance with frequency also contributes to the discrepancy between test and calculated results.

In order to verify the effect of resistance, case figure 12*e* was recalculated taking resistance into consideration by introducing a series resistance into the circuit equal to 0.05 $n$ per phase or 0.075 $n$ in the equivalent circuit. In the absence of more definite knowledge of the resistance at the higher currents and frequencies, this value of resistance cannot be regarded as more than an intelligent guess. The results of this calculation are plotted in figure 13. It will be observed that the wave shape of the calculated result including resistance, partakes of the general character of the oscillogram. The similarity is about as close as can be expected in view of the somewhat arbitrary assumption regarding the resistance. The seventh harmonic in particular is suppressed considerably as compared to the calculation in which resistance was neglected. In many of the calculations, and particularly this one, the solution converged very slowly which necessitated a large number of steps in the method of successive approximation.

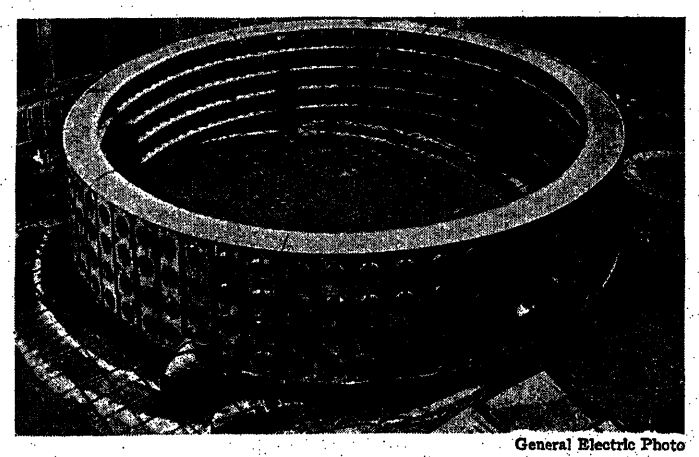
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4. Damper Windings for Water Wheel Generators, C. F. Wagner. AIEE Transactions, volume 50, March 1931, pages 140–51.

General Electric Photo

**Stator frame of a 13,000-volt 35,000-kva single-phase 25-cycle water-wheel generator, designed to operate at 100 rpm**

# Discussions

## Of AIEE Papers—as Recommended for Publication by Technical Committees

ON THIS and the following 12 pages appear discussions submitted for publication, and approved by the technical committees, on papers presented at the sessions on instruments and measurements, education, and insulation co-ordination at the 1937 AIEE summer convention, Milwaukee, Wis., June 21–25. Authors' closures, where they have been submitted, will be found at the end of the discussion on their respective papers. Other discussion of summer convention papers will be published as it is made available.

Members anywhere are encouraged to submit written discussion of any paper published in ELECTRICAL ENGINEERING, which discussion will be reviewed by the proper committee and considered for possible publication in a subsequent issue. Discussions of papers scheduled for presentation at any AIEE meeting or convention will be closed 2 weeks after presentation. Discussions should be (1) concise; (2) restricted to the subject of the paper or papers under consideration; and (3) typewritten and submitted in triplicate to AIEE headquarters, 33 West 39th Street, New York, N. Y.

## A Suggested Course on Industrial Economics and Business Methods

**Discussion and author's closure of a paper by R. E. Hellmund published in the April 1937 issue, pages 446–54, and presented for oral discussion at the education session of the summer convention, Milwaukee, Wis., June 22, 1937.**

**A. H. Lovell** (University of Michigan, Ann Arbor): I believe the author is offering a distinct contribution to engineering economy and has outlined a very successful course of advanced grade for engineers actually in contact with manufacturing. It would appear difficult, however, to accomplish such training in an undergraduate college course because of the lack of design and manufacturing experience in the students together with their diversity of professional interest. Furthermore, there is a dearth of public costs and practical problem material available to an instructor who is not an integral member of a manufacturing organization. The University of Michigan has tried to present the fundamentals of engineering economy to its electrical students for the past 15 years using the senior course in power plants and distribution as the vehicle. This work follows 6 semester-hours of classical fundamental economics taught by our economics department. I wish to emphasize that, at present, for the college undergraduate, the field of generating stations is far richer in public engineering problem material and typical costs than is that proposed by the manufacturing industry.

**M. G. Malti** (Cornell University, Ithaca, N. Y.): I have nothing but praise for Mr. Hellmund's scholarly paper and I consider the bibliography as particularly valuable to those interested in this subject. I do however want to make a few remarks which are applicable to this as well as to all papers which recommend the inclusion of certain courses in engineering curricula.

A visitor found his host engaged in constructing a cabinet. Upon enquiring whether his host had had a course in wood work, the guest was told that the would-be carpenter had had no course in wood work but was constructing the cabinet out of plans he had acquired.

Many of us know the famous *psychologist* Doctor Thurston of Chicago. But few of us know that Doctor Thurston graduated as a *mechanical engineer* from Cornell University.

Kettering has stated that he generally tries to give a graduate a job in which he has had no previous training because the man's mind is not prejudiced by what he had learned in college.

This and similar papers, dealing with particular topics which engineering colleges should or should not teach, opens the broad question of what is the purpose of an engineering education—nay all education. To my mind the purpose of education is to develop one's ability to:

*a.* Study independently of teachers.
*b.* Synthesize isolated facts.
*c.* Generalize from fundamentals.
*d.* View facts objectively.
*e.* Visualize things.
*f.* Do original work.

Notice that nothing has been said about knowledge of facts of engineering or economics or psychology or any other branch of science. The reason is that facts are quickly forgotten. *We use facts merely as vehicles to train the mind.* Very few engineers remember how to integrate sine $x$. But the training they acquired in analysis and straight thinking from their course in mathematics remains with them to the end of their days.

These remarks should not be interpreted to mean that I am opposed to training along the lines suggested in this paper. Indeed I recognize the value of economics not only to engineers but also to all professional and business men. For this very reason I am also in favor of training in "human relations." I do maintain, however, that any engineer who has been subjected to a proper and well-balanced mental training can and should be able to read and assimilate the contents of Mr. Hellmund's bibliography merely through his own efforts and without the advantage (or perhaps the disadvantage) of a college course.

I would like to add another word regarding the economic aspects of this course. The value of such a course depends largely on the caliber of the person teaching it. If it is taught by one of our academic economists it is likely to consist either of antiquated economic theories or of mere statements of economic facts with very little emphasis placed on correlation, analysis, synthesis, and other mental processes which the student can use in solving his future economic problems. This remark is based on the reaction of our engineering students to courses now offered to engineers in economics. The teacher of such a course should be an experienced mature individual who knows the facts, who knows these facts as a part of a science, and who possesses the ability to put his science across. Persons with these qualifications in "*industrial economics*" are rare and command salaries far beyond the scale of university salaries.

In view of these facts I believe that the plan, adopted by Mr. Hellmund, of teaching this course as a part of the training that a company gives to its cadet engineers, seems to be the best solution to the problem.

**R. C. Putnam** (Case School of Applied Science, Cleveland, Ohio): Mr. Hellmund's paper gives pertinent and challenging suggestions to the teachers of electrical engineering. In this regard, I believe that it will be of interest to bring before this discussion an independent, parallel development that has been a part of the electrical engineering curriculum at Case for the past 3 years.

Briefly, this is twofold: first, a course in engineering economy given to all seniors in electrical engineering, and second, an integrated group of studies on business and engineering administration subjects which may be optioned by the senior student.

Since this second part will be discussed next week at the convention of the Society for the Promotion of Engineering Education I shall not take it up here.

The course in engineering economy is similar in aims and content to the suggested course outlined by Mr. Hellmund in this paper. The treatment, however, is somewhat different. A 3-hour course for one semester, it comes in the last of the senior year, in order to give the student all the technical background and maturity of outlook possible.

It first considers the fundamentals of engineering economy, such as the various factors involved in problems of immediate economy as contrasted to the ultimate

economy where long-range considerations are necessary, break-even points of equal economy, the economics of capacity, of replacement, and of future increased demand. This includes the study of depreciation and its various methods of computation, of sinking funds, amortization, capitalized cost, and the various other methods of comparing present out of pocket expenses of maintenance, labor, etc., with the more intangible costs of capital expenditure, either present or future.

The second part of the course is devoted to consideration and solution of problems in the generation, distribution, and application of power and in the design, manufacture, and sales of electrical apparatus. Here the problems are based on case material furnished by electrical manufacturers, public utilities, etc. Some involve an understanding of public utility rates and their underlying costs.

This may sound like a lot of material to be covered in one course, but it must be kept in mind that the object is to give the student an understanding and appreciation of the economic principles which an electrical engineer should know for the proper practice of his profession. After the fundamentals have been established, a comparatively few well chosen problems should give such a background.

As previously mentioned, this course has now been given for 3 years, and the reaction of students, alumni, and those in industry who are acquainted with the work has been most gratifying.

**E. D. Ayres** (University of Wisconsin, Madison): I have been requested to discuss Mr. Hellmund's paper in the light of the studies which I have been making concerning the teaching of business and economics to engineers. Frankly, it is a great pleasure to get this opportunity, because I believe Mr. Hellmund has brought you not just another paper, but a note which I am convinced must be sounded loud and long until the engineering educator realizes its importance.

Coming out of industry into teaching 7 years ago I was convinced then that there was something fundamentally amiss with an education which divorced engineering from its normal economic atmosphere. After 5 years of building up a comprehensive course at Wisconsin comparable to Mr. Hellmund's suggested course, and after 2 years of intensive study, analysis, and report on the subject of what should be done about teaching business and economics to engineers, I find myself with a message which I believe to be exceptionally sound and carefully considered in the light of criticism and experience.

We hear on both sides of the fence—that is both in college and in industry—that the job of the engineering college is to teach fundamentals. Nevertheless the college has for one reason or another steadily refused to accept this duty with respect to the economic considerations of engineering. As any engineer in industry will agree, the time of most engineers is taken up to a great extent with economic considerations. (See Mr. Hellmund's paper, second column, line 8, page 446, ELECTRICAL ENGINEERING, April 1937.) Why then are not these considerations just as important as other fundamental studies in engineering? The answer is decidedly that they are. But our teaching system is frankly not equipped (for a discussion of the implications of this sentence see "Treatment of Cost Aspects of Engineering in School," by Edmund D. Ayres, page 477, *Journal of Engineering Education*, February 1936) to furnish the background nor "pocket-book consciousness" so essential to efficient handling of these matters. The issue is therefore one of leaving this matter with industry where it has largely been or doing something about it in college.

It is not uncommon—but it is inconsistent for the "dyed in the wool fundamentalist" in engineering to cling tenaciously to the sound idea of "teaching fundamentals" and to cast into "outer darkness" all suggestions toward improvement in the treatment of the cost aspect of engineering yet deplore in the same breath the "hired man" status of the professional engineer. Gentlemen, there is but one solution to the dilemma, and it is in training the engineer early and often for leadership upon the firm base of an understanding of the economic and social factors which govern the world in which he must move. From the viewpoint of this broader problem the college must assume a responsibility.

The special course in adminstrative engineering, industrial engineering, and the like cannot solve the problem either. They are excellent treatments for the "commercially minded" student, but they do not reach the "backbone of our profession"—the technical engineer. These courses must weaken the engineering preparation of the student to accomplish their goal and I have ample proof that they do. To reach the technical engineer we must do a better job in his particular college curriculum or rely upon a post scholastic effort for both the treatment of the economic aspects of engineering and the generation of an ability for the engineer to express himself orally and on paper.

To put strength into any move to accomplish these ends, the start must in general be made in college. Living with this problem will force you just as it has me to state that the engineering college must accept the duty of including the fundamentals of economic considerations in the college engineering curriculum. Long study of the problem will also bring you, I believe, to the conclusion that the comprehensive survey course is the only practical solution in sight for the technical engineer. I should like to commend Mr. Hellmund's suggestion to you with all the force I can command, because I believe it now to be imperative that our profession consider well and act immediately upon these matters.

But all is not said when conclusions as to the need for this work are drawn. The most obvious answer to whether such a course as Mr. Hellmund suggests should be a general requirement is yes. The answer to whether it should come early in the engineering work is also yes—but if we insist on being realistic the answers to both of these questions must be qualified in accordance with the teaching resources of the college. Mr. Hellmund has prescribed for his course 2 hours a week for a year. Such a course can be given in that time, and its success will depend directly upon the quality of teaching. Such a brief time, however, forces the teaching quality to such difficult heights that certain practical steps must be taken if such a course is to be a practical success in the engineering college atmosphere. A course such as Mr. Hellmund has described must be taught by an engineer with a background firmly rooted in industrial practice. The teacher to handle the fundamentals of such work properly must assume the role of engineer, accountant, lawyer, and to some extent economist and salesman in turn and all at the same time. The swift transition from one topic to another must be skillfully handled or else a bewilderment in the student is created which to overcome requires a high order of interest on the part of the student (whom you must remember cannot evaluate his interest yet against a particular job in industry as a bench mark). In ordinary English such a course is forever threatened with being christened a "hodge-podge" and losing the respect of the college.

After 5 years' experience in teaching such a course I am firmly convinced that such orientation courses must have a "vehicle" to carry the breadth of material which is included. In our case accounting is used as the vehicle for the first half of the course and economic selection is used as the vehicle for the second half. I discussed this matter briefly last June at the annual meeting of the Society for the Promotion of Engineering Education and in order to conserve time here I should like to refer you to that paper. ("Graduate Work in Engineering and Economics," page 103, *Journal of Engineering Education*, October 1936.) Orientation courses of necessity are like a tramp along a range of hilltops. If a student is inattentive while you are striving to make the panorama that unfolds itself from the various hillcrests mean as much as you can, he is nevertheless quite satisfied if you can place in his basket during the trip something tangible such as an understanding of the rudiments of accounting or a grasp of the principles of economic selection. This philosophy of course results in the need for at least 3 hours per week during the school year to accomplish what Mr. Hellmund proposes to accomplish in 2. The selection of accounting as a vehicle also introduces naturally an expansion of Mr. Hellmund's course further into the financial field than he has suggested. In our case we believe this to be justified in view of the thought which I wish to bring next into this discussion and because of the existence of the third course of 2 hours a week for one half a school year called "manufacturing and production methods," required of all mechanical engineers and emphasizing in considerable detail much of the production and marketing phases included in Mr. Hellmund's course. Our 3-hour a week year course cannot be permitted to duplicate this course to the point of placing a pall upon the interest of the mechanical engineers required to take both courses. There is much more which could be said about the pedagogy and content of courses such as Mr. Hellmund has outlined but time will not permit their treatment. Before closing I am anxious to stress that Mr. Hellmund's suggestion and our practice should be but the starting point of the engineer's training in business and economics.

This thought is treated in full in a recent paper of mine entitled "The Next Step in Engineering Education" (*Wisconsin Engi-*

*neer*, page 136, April 1937; *Milwaukee Engineering*, page 9, May 1937; also promised publication in an early issue of *Mechanical Engineering*).

The guidance in economic matters afforded by the comprehensive survey course is important, but unless the profession finds some way to continue and organize this guidance, the engineer is going to fail to achieve the economic competence which can only come with a well rounded view of the operation of economic factors in society as a whole. Digging on one's own power will do it—yes—but it takes a much longer time and a consuming interest to drive the process through—and if the engineer is to stand up to the lawyer, accountant, business graduate, and politician early he must be given effective help. In advance of the ultimate 5- or 6-year curriculum which some day seems to be coming for all engineers, the dire need is for a continuation process—a floating curriculum of work which can be partly or wholly taken in either the post graduate or post scholastic period or both.

**M. S. Coover** (Iowa State College, Ames): Since a measure of responsibility for shaping one curriculum in electrical engineering rests upon me, Hellmund's suggested course on industrial economics and business methods is of more than passing interest. It is an ambitious outline including essential factors of timely importance and I concur in the opinion that some way ought to be found to include a course of instruction in the program of training commonly designed for chemical, electrical, and mechanical engineering students that would be molded around the thoughts set forth in his article.

Inasmuch as it has been my privilege to have organized and taught courses on management, the proposal strikes a receptive chord. These courses, however, were offered by the school of business and were open to seniors in both the school of business and school of engineering, thus creating the sort of tie that I think has many strong points in its favor. One of the restrictions, however, was the necessity to avoid indulging too heavily into engineering terminology and engineering processes that were little or not at all familiar to seniors in the school of business. On the other hand, a course such as Hellmund proposes for engineering students only leaves the field wide open.

To put the proposed course into a reality is not without certain obstacles, principal among which is the element of time. From certain leaders in industry and in engineering education we hear the urge to stick tenaciously to fundamentals, then teach more fundamentals, and then some more fundamentals, with no venture whatever toward specialization. The reasoning being that the employer will by special training shape the man to fit his particular organization.

From other leaders in the same 2 groups comes the urge to include cultural or broadening courses. Still from others comes the declaration that the young engineer's training is incomplete without a thorough grounding in basic principles in the sciences and including industrial economics and industrial relations. Finally there are advocates who believe that the well-rounded graduate should have a reasonably good mastery of fundamentals, a pretty clear conception of economics with all that it implies, and a fair sprinkling of cultural subjects, such as foreign language, history, government, etc. All of these proposals have my hearty endorsement, provided they do not have to be jammed into a 4-year period.

Granting that provision has been made in the curriculum for a sprinkling of elective courses and that a course in industrial economics and business methods is to be made available, best results will accrue if the instructor has had some good sound commercial seasoning so that he can teach, at least in part, on the basis of plain realities and with confidence rather than have to lean entirely upon printed matter. The instructor should be accumulating constantly from the field, and preferably in person, such data on current management problems that he shape into problems for the classroom so as to make them commensurate with the time allotted to the course. One thought to bear in mind is that the capable and interested student should be able to round out the solutions to his assignments with personal satisfaction of mind without having to devote an unreasonable amount of time on them in relation to his other equally important courses.

Personally, I cannot be enthusiastic about 2-hour courses. It is plenty long from Tuesday to Thursday and longer from Thursday to Tuesday. The plan admits of too much lost motion. More effective results, I believe could be obtained from a 4-hour credit course running for one term or one semester. It would include say 3 discussion periods of one-hour duration and one 3-hour laboratory period for analytical and layout problems. Only neat free-hand sketches of layouts would be required.

As for the course content, the chronology of presenting the material and the required amount of coverage to be made each time the course is offered, I would first have implicit confidence in the instructor employed and leave the balance of the program thoroughly flexible, so that he could constantly adjust it to current data procured and to changing economic condition. Since no single textbook could possibly give adequate coverage of course content, free use of library material should be expected of the student.

**D. F. Miner** (Westinghouse Electric & Manufacturing Company, East Pittsburgh, Pa.): Since Mr. Hellmund's paper was written, an opportunity was presented for trying out a portion of the outlined course. A 2-hour one-semester course on economics of using goods was offered for graduate credit under the University of Pittsburgh-Westinghouse plan. Forty-five men, mostly recent engineering graduates, registered, of whom 25 were taking the course for credit toward a master's degree. The subjects covered were the first half of table I in Mr. Hellmund's bibliography.

Although the lecturers were selected from the staff (chiefly engineering) of the Westinghouse company rather than from the University, care was taken to provide men whose major experience had been on the subjects covered. It was felt that the intimate knowledge of the subjects and the practical viewpoint thus presented made up for any deficiency in classroom technique. The lecture method used for many sessions, was supplemented by problems, outside reading and class discussions.

As part of the course, each student was requested to submit frank criticisms of the course both as to subject matter and manner of presentation. Practically all opinions favored the idea back of the course and stated that interesting and useful phases of the subject were covered. Some students said they had previously thought economic problems were solved by executives and they did not realize that even the young engineer must make frequent decisions requiring consideration of economic factors. Many stated they had received no training of the sort before and realized what an important bearing it had on their present and future work. Some stated they thought colleges should present similar work. Others thought they could get more out of such work given by industry after they were on the job. Possibly only a limited number of industries are in a position to organize such classes and that being the case, some general parts of the subjects will, of necessity, have to be covered by college work if it is done at all.

The course was conducted without adherence to specific details of one company's operations. Many commented on this and desired more definite information. While this may be of immediate use in their daily work, it is still considered best to cover each subject in as general terms as possible. As to teaching methods there was a definite desire for more illustrative problems and more class participation through discussions, possibly led by students. The students commented that the personal enthusiasm and specific knowledge of the lecturers vitalized the course in a way not so easily possible with recourse only to textbooks. We were gratified to observe that the students were keenly aware of the importance of industrial relations problems—that a satisfactory handling of people is necessary to the economic success of work with machines and materials.

In the autumn the second semester's work on economics of producing goods will be started and some of the ideas contributed by students will be tried out.

**R. W. Sorensen** (California Institute of Technology, Pasadena): Mr. Hellmund's authoritative advice regarding the use of some of the engineering student's time during his regular 4-year baccalaureate course for the study of things not strictly technical, such as industrial economics and business methods, is indeed timely. Having advocated and used such a program in the teaching of electrical engineers for more than 25 years, I can certify the fact that men with such training on the whole are better prepared for entry into industry than are students who have taken highly specialized technical courses without obtaining the values which are present in parallel courses involving economics and other humanities.

Of course it is quite evident to all of us that the problem is not simple and there is no clear-cut answer as to just what part of the young engineer's education shall be strictly in the field of his profession and what part shall prepare him to associate without embarrassment with his fellowmen who are not particularly interested in the technique of the mechanical aids to civilization which are in such common use today.

As a group, engineering educators have recognized the demand for a larger amount of knowledge of economic subjects on the part of some of our engineers by having in some of the engineering colleges curricula designated by the names: engineering economics, management engineering, etc. In my experience, the evils of these courses, as evidenced by the skimpiness of the engineering obtained and the tendency which they have to attract students who cannot make a satisfactory showing in the strictly technical fields, indicate that they are at least dangerous in any set of college curricula, if not inadvisable when they are undergraduate courses.

In fact, I think we should fairly generally refrain from adding to our 4-year courses more and more of the technical content of our profession, which is so rapidly developing, and should tend toward making the 4-year courses leading to the baccalaureate degree general but intensive engineering curricula which include as separate courses, some, but a distinctly limited amount, of the work outlined by Mr. Hellmund.

I am glad to note further that the paper under discussion presents material which can be used to a large extent by men teaching the strictly technical engineering courses pertaining to electrical machinery and does not of necessity require for its inclusion in an engineering curriculum the setting up of many separate courses dealing with economics only. For example, when a class is studying the technique of electrical-machinery design, it is entirely possible for the teacher to point out factors which influence design because of cost of materials, labor, test, inspection etc. Also, it is very easy to point out how designs may be modified without much sacrifice in electrical characteristics so that standard frames may be used for several machines.

My particular suggestion, therefore, would be that the teachers of engineering in discussing the design and operation of electrical machinery with students, supplement the technical phases of design and performance by discussion of the economic factors which influence the construction and operation of the machine and also by showing how the use of the machine influences the economic life of those who use it. In fact, it seems somewhat surprising to me that any teacher of electrical machinery can avoid so doing, because I recall quite distinctly the fact that one of the students in the first class in dynamo-electric machinery which I ever taught said to me one day: "Well, all of these facts are very interesting, but you seem to indicate that the final decision as to whether a machine will be built and installed and as to how it will be built is largely a matter of dollars and cents rather than electrical phenomena." That man became an outstanding sales engineer. But lest I lose caste with the technical men of my profession, may I also add that one of his classmates received a very different message from the things taught in the class and went out from the college with a desire to be a very skilled technician who reveled in the theory of the electrical circuit.

**R. E. Hellmund:** The extent of the discussion of my paper and the generally favorable reaction is very gratifying in that it definitely indicates an increasing interest in the subject on the part of the teaching profession. In some of the discussions it is pointed out that it will be difficult for the colleges to obtain suitable material for class work, particularly problems, and that it will be even more of a problem to find instructors prepared to carry on a course of this nature. It is of course true that some difficulties will be encountered in any new undertaking, but I do not feel that those arising in this particular work will be insurmountable. The only practical solution therefore seems to be to get started and to improve both the material and the teaching personnel as time goes on.

I know that a number of efforts along lines somewhat similar to those outlined in my paper have been under way at various schools, such, for example, as described by Putnam for the Case School of Applied Science, by Ayres for the University of Wisconsin, Coover for Iowa State College, Lovell for Ann Arbor, and others. The relative success and favorable reception of these efforts are in themselves evidence that something of value can be accomplished. It is quite natural that these efforts, each started independently of the other, should differ, and also that they should differ in certain respects from the course suggested in my paper. As a matter of fact, I believe that the trying out of certain variations in anything that is comparatively new is very essential for arriving at the most successful finial solution. My purpose in giving such a detailed outline was chiefly to assist those who wished to undertake some new work of this character and who might find it difficult to obtain appropriate material. In making variations from the suggested plan, however, I believe that the proposed comprehensive character of the course should not be lost sight of and that some phases of the work which have been neglected in the past in courses of this nature should be given careful consideration. As an illustration of this, the combination of courses mentioned by Professor Ayres would permit the use of much of the material outlined in my paper, but the titles of the courses in themselves do not indicate that sufficient attention will be given to such important matters as marketing, stock-keeping, obsolescence of stock, and standards. Again, the practice suggested by Professor Lovell of considering economic matters in connection with the course on the generation and distribution of power, while having certain advantages, is not likely to afford an opportunity for stressing the very important subjects just cited.

Some of the discussions bring up the question of whether the proposed course should be given during the four-year curriculum or as postgraduate work. Mr. Miner in his discussion gives a logical answer to this when he points out that since only a limited number of industries are in a position to organize classes, the work must necessarily be given in the regular college course if all of the students are to profit by it. I furthermore agree with Professor Ayres to the effect that in order to put strength into this move, the start must in general be made in college. This does not preclude the desirability of those schools located in industrial centers giving such material in a postgraduate course; in fact, plans along this line are now under way. Some of the discussions stress the fact that colleges should deal essentially with fundamentals, but it is also pointed out, and quite properly, that the fundamentals of economics are as important as other fundamentals. Professor Malti in particular points out that the principal purpose of education is to develop certain qualities and habits in the student. I myself have made similar statements too often to take any exception to this. However, even though this is very true, we must not overlook the equally true fact that engineers, like men of other professions, must have a great deal of knowledge if they are to carry on their work efficiently. It would be very foolish to ignore this fact entirely during the four-year course, and the present practice of imparting to the student as much knowledge as practically possible in addition to developing within him the qualities outlined by Professor Malti is very effectual. The only question then that can be raised is that of whether certain kinds of knowledge should best be acquired before or after graduation.

I have not commented in full on all of the discussions, but it is obvious that the various viewpoints of teachers of many years' experience, such as Professor Sorensen and others, as well as the experiences cited by Mr. Miner, should be given full consideration by those interested in the subject.

## Per-Unit Quantities

**Discussion and author's closure of a paper by Irven Travis presented for oral discussion at the education session of the summer convention, Milwaukee, Wis., June 22, 1937, and scheduled for inclusion in a special supplement to the annual TRANSACTIONS for 1937.**

**M. G. Malti:** See discussion, page 1400.

**B. R. Prentice** (General Electric Company, Schenectady, N. Y.): Mr. Travis has made a timely and valuable contribution to the literature of engineering education in his brief and clear exposition of per-unit quantities. I agree with him that per-unit representation is "confusing to the average student" and for another reason in addition to those he has given. Students are often introduced to per-unit at the same time that they take up the study of some new machine or subject, frequently, synchronous-machine theory. Added to the fresh concepts of the new theory are the novel ideas of per-unit, multiplying the confusion. Mr. Travis has aptly applied per-unit to well-known problems.

In developing the "theorem in dimensional analysis," it is tacitly assumed in equation 16 that the parameters and variables can be expressed in terms of not more than 4 fundamental dimensions, length, mass, time, and electric charge. It is then properly shown that "It is never possible to assign more than 4 independent bases." However, it is inferred that this last statement applies to physical problems generally instead of the limited class of problems covered by the tacit assumption. Obviously, if 3 or

5 fundamental dimensions had been assumed, the mathematical derivation would have resulted in a maximum of 3 or 5 independent bases, respectively. In general, pure mathematical proofs of the number of independent dimensions in other than specific problems cannot be given as dimensions are inherent physical things, and rest on experimental laws and arbitrary definitions. In one important class of problems, it is convenient and desirable to include a fifth fundamental dimension, temperature. Such problems are those involving heat flow as well as mechanical and electrical phenomena. I believe that, in such problems, the dimension temperature (or its substitute) can only be eliminated by recourse to kinetic theory which is outside the realm of most engineering problems.

The "theorem in dimensional analysis" is valuable for finding the number of independent bases and determining which specific ones are independent in any actual problem provided one knows the independent fundamental dimensions involved from physical reasoning.

**Irven Travis:** Mr. Prentice is entirely correct in his statement that the conclusions in the "theorem in dimensional analysis" apply to the limited class of problems described by the 4 fundamental dimensions; length, mass, time, and electric charge. In a preliminary draft of the paper, the theorem was set up for a system of $n$ independent dimensions; this was changed in an effort to simplify the derivation as much as possible for student consumption.

The general rule for assignment of bases is: Independent bases may be assigned to any group of quantities, providing the rank of the matrix formed by the exponents in the dimensional formulas for these quantities is equal to the number of bases to be assigned. It is evident that in the matrix described, the number of rows is equal to the number of bases, and the number of columns is equal to the number of fundamental dimensions. The greatest possible number of independent bases is, therefore, equal to the number of fundamental dimensions.

An error has been called to my attention by Mr. J. E. Hobson. In figure 2, under receiver, 10,000 kw should read 10,000 kva.

joy. The committee on education, in sponsoring these papers, has injected into the Institute an activity the need of which has long been felt by the Institute membership in general and by educators in particular.

## A New Magnetic Flux Meter

**Discussion and author's closure of a paper by George S. Smith published in the April 1937 issue, pages 441–5, and presented for oral discussion at the Instruments and measurements session of the summer convention, Milwaukee, Wis., June 22, 1937.**

**R. F. Edgar** (General Electric Company, Schenectady, N. Y.): Professor Smith's paper describes an instrument which should prove useful in many applications. Two achievements have been realized in the development. The first is the development of an instrument employing bismuth but having a zero indication which is not affected by temperature changes. Lack of this feature has been one of the biggest objections to the use of the bismuth spiral as a means of measuring magnetic field strength. The second lies in the ability of the instrument to measure flux densities in the range below 1,000 gauss.

The calibration curves of figure 3 show a very nearly linear characteristic from a full-scale value down to about 2,000 gauss. Are calibration curves for the lower ranges, say for a full scale value of 2,000 gauss, similar in shape, or do they curve to a greater extent throughout the range? Is the zero adjustment as stable for this low range as for the higher ones? What does Professor Smith consider to be the lowest range which it would be feasible to design the instrument for?

This method of measurement differs from that of using a search coil and galvanometer in that the latter is definitely directional and, in a uniform field, measures only the component perpendicular to the plane of the coil. Does the bismuth spiral exhibit any difference in its action which depends upon the direction of the magnetic field? Would the action of a straight piece of bismuth conductor be the same in a longitudinal field as in a transverse field?

**G. S. Smith:** The questions by Edgar and Sprague are quite opportune since the answers to some of them had not been discovered until after the paper had been published.

A meter just recently completed, was so made that 3 exploring bridges could be used with the same meter equipment. Table I shows the variation in design in these bridges.

Bridge number 3 was the most sensitive and was calibrated for a full-scale range of about 2,100 gausses. Bridge number 1 was calibrated for a maximum range of 22,000 gausses. It is evident that any of the bridges could be calibrated for any upper limit within the range of the calibrating equipment.

Answering Mr. Edgar's questions first, I would say that in the calibration curves for the higher ranges, the straight line portion of the curve occupies a little greater per cent of the full scale on the meter than in the lower ranges.

If an accurate zero adjustment is obtained it is very stable for all ranges on the meter. It is evident, however, that when using the lower ranges, the greater sensitivity available will cause a greater displacement from zero if any temporary resistance changes take place. Such variations can be caused by quick changes in temperature in one or more of the coils above or below the remainder. In the normal use of the meter such differences

**Figure 1. Effect of holding plane of bridge coils parallel to magnetic flux**

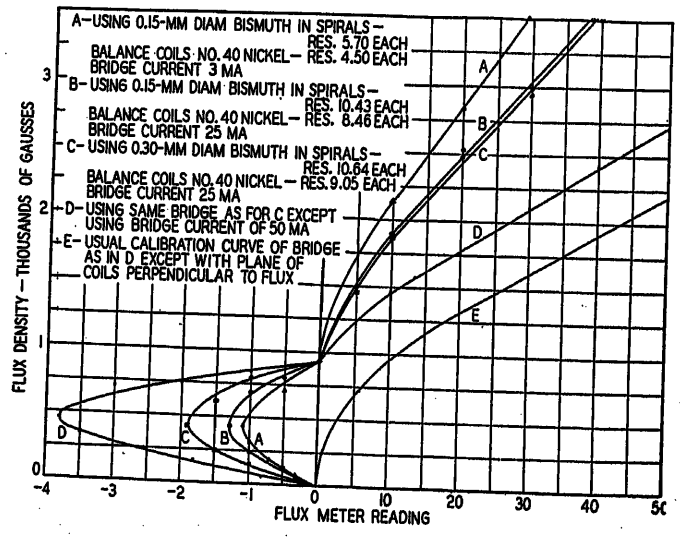



**Table I**

| | Number 1 | Number 2 | Number 3 |
|---|---|---|---|
| Diam. of bismuth wire used—millimeters | 0.15 | 0.15 | 0.30 |
| Approx. resistance of each spiral—ohms | 5.7 | 10 | 10 |
| Diameter of spiral—millimeters | 5 | 7.5 | 15 |

## Fundamental Concepts of Synchronous Machine Reactances

**Discussion of a paper by B. R. Prentice presented for oral discussion at the education session of the summer convention, Milwaukee Wis., June 22, 1937, and scheduled for inclusion in a special supplement to the annual TRANSACTIONS for 1937.**

**M. G. Malti** (Cornell University, Ithaca, N. Y.): These papers are in a class which the Institute might well foster. They are admittedly expository and contain recent developments in electrical engineering presented in a new, clear, and concise form which the student and the average engineer can read and thoroughly understand and en-

usually exist for only a few seconds, if at all, after which the true zero position of the meter is restored.

It is rather difficult to state the lowest feasible range for such an instrument. For a portable instrument, using the small inexpensive type of meters, and a bridge diameter of about one centimeter, a full scale range of about 2,000 gausses would probably be as low as could be expected. By using a more expensive meter, as the flux-reading meter, or more material in the bridge, or both, the full scale range might be reduced to 1,000 gausses or less. By using a sensitive galvanometer, in which case the meter would no longer be portable, the full scale range might be reduced well below 500 gausses. A vacuum-tube amplifier might also be used, though little has been done thus far in attemping this.

Previous researches have shown that less change in the resistance of bismuth takes place in a longitudinal field than in a transverse field. The curves *A*, *B*, *C*, and *D*, in figure 1 show the results of calibrations made when holding the plane of the spirals parallel to the magnetic field, while curve *E* is for the same bridge as used in *D* except holding the plane of the spirals perpendicular to the magnetic field. For low flux densities the readings for *A*, *B*, *C*, and *D* are negative, and for higher values displaced vertically from the usual calibration curve as in *E*. It should be noted that the scale in figure 1 is greatly magnified on the negative side. This negative effect may be due to some characteristic of the nickel wire used as balancing resistors in the bridge. Careful resistance measurements on a plain bismuth spiral placed first with its plane parallel to, and second, perpendicular to, the magnetic field, showed less change in the resistance in the first position than in the second, but showed no tendency toward a negative or lowering of the resistance at any flux density.

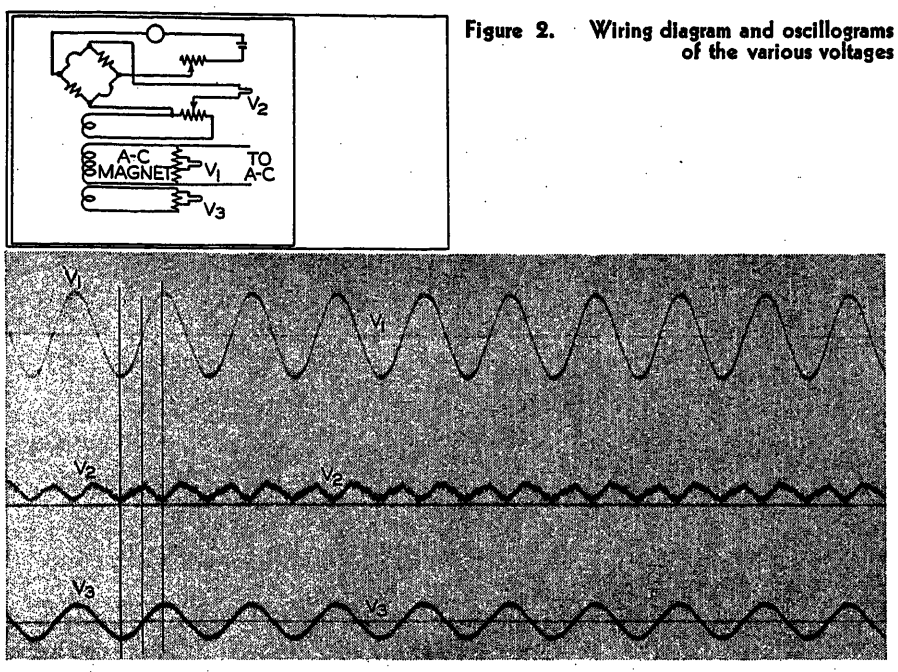



**Figure 2. Wiring diagram and oscillograms of the various voltages**

It is interesting to note that the changeover from negative to positive occurs at about the same value of flux density regardless of the size of wire or resistance used in the bismuth spirals. This might also be an indication that the negative effect is due to some characteristic of the nickel rather than the bismuth.

Mr. Sprague inquired about the use of the flux meter in alternating or transient fluxes. The bridge does give a reading for an alternating magnetic flux, but thus far too little has been done in this field to make any more definite statements.

A crude, but sensitive oscillograph vibrator was constructed and used as the flux indicator $V_2$ in the bridge circuit as shown in the wiring diagram in figure 2. Thus the $V_2$ wave in the oscillogram shows the flux variation due to an alternating magnetic field caused by the voltage shown in $V_1$. $V_3$ shows the voltage induced into a separate coil about the same field. As will be noticed in the wiring diagram, it was necessary to balance out a small component of alternating voltage induced into the bridge circuit since it apparently was not entirely noninductive in construction. Since the vibrator used was very crudely constructed, and not oil damped, it is scarcely feasible to attempt to explain the harmonics shown since they might have been due partly or wholly to other causes than flux variations.

Figure 3 shows the results of using the meter to measure the variations of the flux density in the air gaps of motors and generators. In these curves only the maximum and minimum values were measured, and the remainder of the curves sketched in. With a suitable instrument, the complete curves, accurate at every point, could be very quickly and easily obtained by photographic or curve drawing methods.

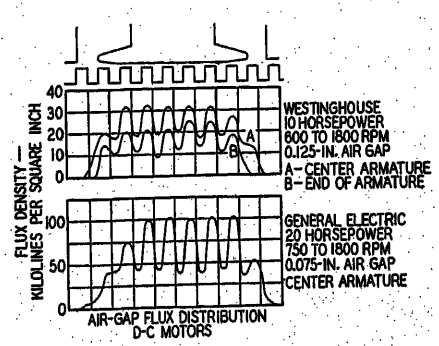



**Figure 3**

# A New High-Speed Cathode-Ray Oscillograph

**Discussion and authors' closure of a paper by H. P. Kuehni and Simon Ramo published in the June 1937 issue, pages 721–7, and presented for oral discussion at the instruments and measurements session of the summer convention, Milwaukee, Wis., June 22, 1937.**

**J. H. Hagenguth** (General Electric Company, Pittsfield, Mass.): The authors have given a very good description of the new oscillograph. One of these oscillographs has been in use in the high-voltage engineering laboratory, with which the writer has been connected, for the last year and a half. This oscillograph represents a great improvement in the oscillographic art chiefly from a mechanical point of view.

The compactness of the assembly combined with accessibility of the component parts permits easy handling of the oscillograph and provides for the least amount of trouble. The adaption of the completely sealed cathode-ray tube eliminates all delays inherent to the continuously evacuated type, resulting in a considerable saving of time. Several improvements in the tube design might be desired: First, the curvature of a d-c calibration line at the higher calibration voltages might be eliminated (see figure 4 of paper), second, the focusing of the beam might be improved, to give a more uniform and sharp definition of the beam on the front and on the tail of waves (figure 5 of paper).

Considering the low cathode excitation voltage of only 15 kv, as compared to 60 to 80 kv of the usual cold-cathode continuously evacuated oscillograph, the writing speed is excellent. At the higher rates of speed required for front-of-wave testing at 1,000 kv per microsecond or higher, the record on the film sometimes does not reproduce well on a blueprint, but the necessary data can be taken from the film directly so that the oscillograph can be used for all testing, which at present is required for high-voltage work.

The easily varied cathode-voltage supply enables the use of the oscillograph in connection with the transient analyzer for determining wave shapes for transformer impulse testing.

**Otto Ackerman** (Westinghouse Electric & Manufacturing Company, East Pittsburgh, Pa.): In the first part of their paper the authors give a very clear and interesting

review of the history of the cathode-ray oscillograph. They relate how, with the development of high-voltage metal oscillographs with internal photography, the art of measuring electrical transients has come to its height and has actually reached its limits. It was with instruments of this type that by far the biggest part of all impulse testing and research in the last 10 or 12 years has been carried out, which made the cathode-ray oscillograph an invaluable tool in science and industry. Since it is the very essence of our endeavor as engineers to obtain certain results in the simplest and most economical manner, the development on cathode-ray oscillographs has of course been continued, although types are already available which have as high a recording speed and accuracy as can be needed. It is, therefore, quite appropriate that any new appearance in this field be scrutinized as to whether it comes up to the standards in performance which the industry has already learned to expect.

One extremely important feature which has helped to make the cathode-ray oscillograph such a remarkable instrument is its instantaneous response to an external impulse. It is not clear why, in this new type, a time lag of about 20 microseconds is introduced before the timing sweep is started. Should the formation of the grid-controlled cathode beam require any such interval which practically excludes this type from the use of the recording of random phenomena?

Another feature which it appears to the writer entails many hidden difficulties, is the use of a great number of small sphere gaps. Five such sets are shown in figure 3. Their spacing can be only of the order of $^1/_{16}$ inch. They obviously need a great deal of attention for constant operation.

Whether it is the time lag in the formation of the beam or the variations in the system of small gaps, it appears to be necessary to definitely start the oscillograph before the surge generator or, in other words, start the surge generator by means of an impulse from the oscillograph.

Since the voltages available at the oscillograph circuit are comparatively low, an intermediate impulse amplifier must be added (see figure 7).

Regarding the oscillograph records themselves, the obtainable accuracy in voltage measurements is, of course, another important feature. It is partly determined by the ratio between the picture size and the width of the recording trace. Are the records as published about full size?

Of equal importance in this respect is the uniformity of deflection or calibration. The upper lines of the calibration record in figure 4 are quite definitely curved. This accentuates another problem in oscillograph design: The potentials applied to the deflecting plates influence the speed of the electrons passing between them. If the deflecting potentials are not negligible compared with the cathode voltage, the electron speed suffers changes which result in nonuniform deflections and are partly responsible for pattern distortion.

These features could be expressed in terms very much like those of speed and focal length when speaking of photographic cameras, which serve to compare their quality. If such terms were already used with cathode-ray oscillographs, they would establish some sort of rating for this type of equipment.

The writer, furthermore, likes to suggest that the apparent misprint in reference to a film speed of 500 feet per second be corrected. To unsuspicious readers, this figure might not seem extravagant with an instrument where one deals with fractions of microseconds and hundreds of kilometers per second of writing speed.

The writer finally would like to take exception to the inference on page 722, that the vacuum system on metal oscillographs need be a troublesome and unreliable feature. While it is true enough that the production of satisfactory pumping equipment and air-tight vessels requires a highly specialized technique, the reliability of the finished product cannot be doubted where porcelain solder seals by the millions and automatic pumping equipments, as for instance in mercury arc rectifiers, have proved their dependability in countless industrial applications.

**R. J. Donaldson** (Commonwealth Edison Company, Chicago, Ill.): The Commonwealth Edison Company has had one of the General Electric type *HC*-15 cathode-ray oscillographs for several months. Some of our operating experiences may be of interest to others.

In using the oscillograph with the rotary film drum, to make records of events occurring over a period of several cycles of a 60-cycle wave, it is sometimes desirable to have the cathode-ray beam stay on for an accurately predetermined time. If it is on for less time than this, the record may be incomplete, if it is on for more, there are unnecessary traces on the film.

The duration of the beam is determined by the time required for an adjustable capacitor to partially discharge through a Thyrite resistor in series with the anode circuit of a thyratron tube. Due to the temperature characteristics of this tube, it is not usually possible to be sure of the exact number of cycles the beam will be on. The duration of the beam is also affected to some extent by changing from one thyratron tube to another. It was thus desirable to have some means of determining the duration of the beam just prior to the making of an oscillographic record.

This was done indirectly by measuring the product of beam current and time, or $IT$. A capacitor was connected between the cathode-ray tube anode and the oscillograph case to which the anode is normally grounded. The potential built up on this capacitance by the beam current flowing for time $T$ is almost directly proportional to the duration of the beam. This is true where the capacitance is made sufficiently large so that the potential built up on it is very small compared with the cathode-ray tube voltage. The capacitor potential was $E = IT/C$ where $I$ is the beam current, $T$ the duration of the beam, and $C$ the capacitance in series with the tube anode. The potential on the capacitor was measured with a high-resistance d-c voltmeter. Each volt represented so many milliseconds beam duration, or so many cycles of a 60-cycle wave. If the same beam intensity and cathode-ray tube voltage were used, the meter could be calibrated directly in time or cycles duration.

For the *HC*-15 oscillograph the beam current at maximum intensity with 15 kv on the cathode-ray tube is about $^1/_5$ milliampere. The duration may be adjusted for various times up to about 20 cycles of a 60-cycle source or $^1/_3$ second. The capacitance used was 2 microfarads. This gave a value of

$$E = \frac{IT}{C} = \frac{0.0002 \times .33}{2 \times 10^{-6}} = 33 \text{ volts}$$

The voltmeter used in measuring this voltage was a microammeter in series with a 5-megohm resistor. This gave a time constant to the circuit of 10 seconds, sufficiently long to permit the meter to indicate the potential on the capacitor with fair accuracy before appreciable charge had leaked off.

A very interesting characteristic of the thyratron tube controlling the beam duration was noted while operating the oscillograph with the rotating drum film holder. In this particular test the thyratron circuit was adjusted to release the beam for a total time of about 20 cycles of a 60-cycle wave. On some of the oscillograms there were several missing sections in the wave as though the beam had been blocked for a moment and then released again. The thyratron tube can be tripped from either of 2 3-electrode spark gaps in the initiating circuit. The first gap is tripped by applying a few thousand volts to the middle tripping electrode from a 60-cycle transformer and this gap in turn trips the second gap a few microseconds later, starting the time sweep. Occasionally the 60-cycle potential on the middle electrode caused several successive sparks to the gap electrode to which the thyratron grid was connected while the beam was still released. If the impulse from these sparks was negative the beam was blocked until a positive impulse occurred releasing the beam again. This sometimes occurred several times during the 20 cycles being recorded. At first this appeared quite unusual, for the anode current in a thyratron is usually considered to be independent of grid potential after the tube is tripped. However, in an article in the December 1936 issue of ELECTRICAL ENGINEERING, Herbert J. Reich of the University of Illinois points out that the grid of a thyratron may be used to stop, as well as start, the flow of current provided the current is small.

The remedy for the interrupted beam, once the cause was found, was simple: readjust the gap to a spacing such that it will spark over only once during the recording time. Actually the solution was even more simple. When using the rotating drum the starting time can just as well be a few microseconds later and the thyratron can be tripped from the sweep circuit which never applies but one impulse. This merely involves changing a plug from one jack to another.

**W. F. Skeats** (General Electric Company, Philadelphia, Pa.): The authors mention that several multiple-element oscillographs are in use in the General Electric Company. One of these is in the circuit-breaker interrupting capacity test plant.

In this application multiple elements were desired partly to observe phenomena on the

3 poles of a 3-phase breaker and partly to observe the operation of different parts of a special circuit for determining the performance of breakers at short-circuit power beyond that available at the testing plant. The speed required was moderately, but not extremely, high, the maximum frequency anticipated being about 200,000 cycles, but on the other hand a long record was

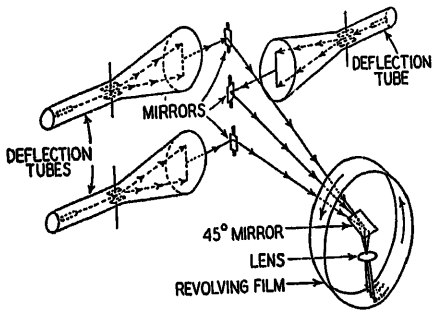



**Figure 1. Optical system of cathode-ray oscillograph**

necessary as it was desired to observe phenomena occurring two or three hundredths of a second apart. It was also desirable to have records available promptly after each operation with a minimum of delay before the instrument would be ready for another record.

Many of the unique features of the design will be evident from a diagram of the optical system which is shown in figure 1. Three sealed glass deflecting tubes with fluorescent screens are used. These deflect the beam in one dimension only giving a deflection proportional to the quantity being measured. A lens focuses the light from these

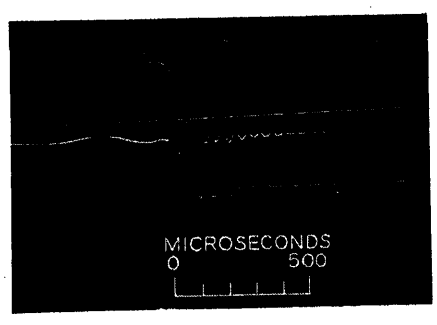



**Figure 2. Section of cathode-ray oscillogram**

screens upon a film mounted on the inside of a rotating drum. One mirror is used to make the necessary bend in the light beams on the inside of the drum, and in order to obtain compactness of the field of vision and reduce its size 2 deflecting tubes are placed on one side and one on the other of a central axis, individual mirrors being placed on this axis to reflect the three light beams into the same plane. These latter also provide an adjustment to line up the 3 spots with respect to each other on the film.

The film was placed on the inside of the drum in order to make high peripheral speeds available without the introduction of awkward clamping means or the possibility of breaking or loosening of the film on account of expansion resulting from its own centrifugal stresses.

The drum is 12 inches in diameter, and rotates at a maximum speed of 10,000 rpm. This gives a time scale of 6 microseconds per millimeter, stretching out one cycle of a 200,000-cycle wave over 0.8 millimeter. With a reduction of about 5 to 1 in the optical system, a sharply defined curve is obtained which can easily be read at this spacing.

Figure 2 shows part of a record obtained with this oscillograph indicating the voltages attendant upon the interruption of the last two phases of a 3-phase-to-ground fault on an ungrounded generator. The upper and lower traces are the voltages across the 2 poles of the breaker clearing at the time of the record and the center trace shows the voltage induced the phase which had cleared previously.

**A. T. Sinks** (General Electric Company, Lynn, Mass.): We have had in our laboratory at the West Lynn Works for about 8 months a cathode-ray oscillograph of the type described in this article. During this period the oscillograph has been in use at least 50 per cent of the time testing instrument transformers and has been of great value to us in designing transformers for higher impulse-voltage strengths.

I do not mean to imply that impulse testing was made possible only by this new oscillograph, as before its advent we made impulse tests for a number of years using the old type of oscillograph in which the film was inside the tube, and for the most part results obtained with this instrument were very satisfactory and we made quite valuable improvements in instrument transformer design on the basis of these results.

However, in our work, the new oscillograph has demonstrated its superiority over the old type in a number of ways. In the first place, with the new design, as the authors state, the time of pumping a vacuum and any question of having the right vacuum after replacing the film is eliminated. In the second place, one can see the wave at the same time a picture is taken. On the old type this was not possible and there was no way of knowing what happened when a surge was recorded on the film until the film was developed. When, as frequently occurs, one wishes to know what has happened before going further, it is obviously very much more convenient to be able to have some knowledge of what occurred without waiting to develop films and disassemble apparatus.

Another point of interest in the new oscillograph is that we have found the calibration of the cathode-ray tube to be very constant and consistent.

Since the whole apparatus including trip circuits and calibrating devices is co-ordinated in one design and made in one unit the operation of the apparatus is simplified.

When all is taken into account, we, therefore, feel that the new oscillograph design represents a valuable advance in the art.

**P. R. Benedict** (nonmember; Westinghouse Electric & Manufacturing Company, East Pittsburgh, Pa.): The development of this new self-contained, portable oscillograph is a noteworthy contribution to the technique of impulse testing. This device fills a need for a laboratory instrument which bridges the gap between the low-voltage cathode-ray oscillograph and the cold-cathode 60-kv constant-beam oscillograph. Two features of the instrument which are new are the simultaneous viewing and recording arrangement and the cathode beam initiating unit. In regard to the cathode-beam initiating system I would like to ask the authors what beam current is used in the tube. How is it measured for the short time the tube is in operation?

In recent years, more and more stress has been laid on front-of-the-wave testing and it has been necessary to improve the existing cold-cathode instruments. All reliable impulse data must be sealed from recordings of actual impulses applied to the test piece. Oscillations on the test wave tend to decrease the density of the trace and make suitable recording difficult. In order to get readable, reliable records, all spurious oscillations must be eliminated from the system. It has been my experience that nearly all spurious oscillations come from poor grounding arrangements. Grounding the test generator at only one point helps a great deal. All divider cables should be grounded at the generator ground. A copper-braid sheath over the lead sheath of the divider cable also helps to reduce superimposed oscillations on recorded test waves. The divider cable sheath should be insulated from ground over its whole length. Short heavy ground connections should be used at both ends of the cable. The authors show no damping resistors in the timing plate leads to the cathode ray tube. Such resistors placed at the timing plates help to cut out inductive pickup from the voltage leads and other parts of the oscillograph system. A resistance value of 3,000 ohms is about right. The timing calibration should be made with the resistors in. The unit described by the authors is very well shielded as the oscillograms show.

The oscillograph tube of this article uses electrostatic concentration methods for producing an intense beam. The cold-cathode instruments are much harder to focus in this way but satisfactory progress has been made in this country and in Europe. Field control at the cathode seems to offer the best solution of concentrating the beam electrostatically. The use of a magnetic concentrating coil between the cathode and anode, so placed that the beam is focused on the anode hole, 0.025 inches in diameter, improves the recording speed materially. I would like to ask the authors what the recorded trace width is. In high voltage it is imperative that the beam be intense but narrow. Assuming a trace width of 0.1 inch, and a deflection of 2 inches, the trace width is 5 per cent of the recorded voltage. Such a wide beam introduces errors in scaling oscillograms and while the recording speed may be increased by using a large diameter spot, a trace width of about 0.040 inches is desirable.

What is the actual deflection in inches of the records of figure 5 and figure 6? Also, what is the approximate voltage of figure 6? In high-voltage recording it is desirable to use about a 3-inch voltage deflection for satisfactory accuracy. A time deflection of about $2\frac{1}{2}$ inches per microsecond is also necessary for wave-front testing. The testing of lightning arresters and all apparatus

at short time to flashover values require such deflections for satisfactory scaling, especially where time to flashover curves are desirable.

The rotating-drum type of camera can also be applied to the cold-cathode type instrument and the loss of time due to repumping after each film is more than offset by the excellence of the record. In the modern high-voltage beam oscillograph 8 to 10 minutes are consumed in pumping to working vacuum after a film change. When taking time to break down curves, using roll film, as many as 150 records are taken on a 6-exposure film. The cold-cathode instruments may be used to cover the range of 10,000 microseconds to the shortest times obtainable in surge-generator circuits. Calibrations are permanent and accurate to about 1 per cent. While the authors state the writing speed of 10 inches per microsecond, the requirements of wave-front testing and short time to breakdown phenomena are such that 50 inches per microsecond is desirable in an instrument used for the collection of pertinent impulse data.

**H. P. Kuehni and Simon Ramo:** Mr. Ackerman's comments and questions about the new cathode-ray oscillograph are indeed very interesting and also highly pertinent and the authors welcome this opportunity to discuss here briefly some of the details which might not have been sufficiently clearly brought out in the paper.

The second, third, and fourth paragraphs of Mr. Ackerman's discussion are quite closely related from the point of view of the oscillograph design features and they may be answered as follows.

In order to serve as a fundamental background for the general discussion, it may perhaps be well here to state the basic requirements which guided the design of the new oscillograph.

(*a*). The oscillograph must satisfy practical impulse testing requirements. It must be capable of recording standard impulse testing waves.

(*b*). The oscillograph records shall show a portion of the sweep (zero line) before the wave record begins so as to obtain a full wave record. This result is to be obtained without the use of delay cables. Therefore, this feature makes it necessary to initiate the oscillograph sweep before the appearance of the impulse wave at the oscillograph deflection plates.

(*c*). In view of (*b*) above, the oscillograph shall include means for initiating an impulse generator and shall include proper timing equipment to release the cathode-ray beam, to start the sweep and to initiate the impulse generator at the correct time.

(*d*). The oscillograph shall also be capable of recording random phenomena whereby the cathode-ray beam and sweep are initiated by an incoming voltage impulse. For this application the response must take place within a fraction of one microsecond.

For reasons of economy and also to arrive at a compact design the internal oscillograph initiating circuits were limited to 7.5 kv with respect to ground, and 3 electrode gaps were selected to initiate these circuits. It is quite natural that Mr. Ackerman should question the reliability of low-voltage gaps of this kind and the authors share his skepticism in a general way. However, by the use of effective artifices the performance of these gaps was rendered reliable in service without necessitating undue critical gap adjustment. Tests have shown that small gaps of the type used may be made to perform very uniformly by ultraviolet light irradiation. The necessary gap irradiation is obtained from an auxiliary circuit and it is the main function of the primary initiating circuit, which is tripped by the 60-cycle transformer and push-button shown in figure 3, to supply the needed ultraviolet light at its spark gaps. As figure 2 shows, these gaps are mounted very close to the sweep-initiating-unit gaps. The time performance of the auxiliary circuit gaps obviously need not be accurate.

Inasmuch as a primary initiating circuit was used, it was decided to initiate with it also the cathode-ray beam. The time delay of approximately 20 microseconds, introduced between the primary initiating circuit and the sweep circuit, was quite arbitrary and was admittedly originally introduced to give the thyratron tube and the cathode-ray tube ample time to establish the cathode-ray beam before the initiation of the sweep. However, it was soon found that this precaution was quite unnecessary, because the cathode-ray beam could be initiated in a small fraction of a microsecond by applying a sharp voltage impulse to the thyratron grid. Nevertheless, the resistance between *M* and the sweep circuit midsphere was retained to prevent a voltage impulse of large magnitude at *M* and the thyratron grid *L* when the sweep circuit midsphere is tripped by an incoming voltage impulse applied at *O* as shown in figure 7. Also, this method of primary beam initiation provided a convenient means of initiating the cathode-ray beam in rapid succession for beam focusing purposes without having to wait 20 or 30 seconds for the sweep-circuit capacitors to charge through a high resistance.

Referring to the diagrams of figure 3 and figure 7, when the oscillograph is to be used for recording random phenomena, provisions are made, by means of a flexible lead and plug, to connect the thyratron grid lead at *O* of the sweep circuit instead of at *M* of the primary initiating circuit. In this case the incoming voltage impulse through *Q* is then used to initiate the gaps of the sweep circuit and the cathode-ray beam. By using a fairly large incoming momentary voltage impulse of, say, 50 kv, which is usually readily available in this type of recording, ultraviolet gap irradiation as described above is now not needed. Thus, it is not necessary to start the oscillograph before the surge generator. However, it is generally advisable to do so, whenever the impulse generator initiation is under control, as is the case in impulse testing and when a complete wave record is desired without the use of an artificial delay of the arrival of the voltage wave to be recorded.

In figure 7 there is shown between the oscillograph and the impulse generator an intermediate initiating circuit which was used, as pointed out by Mr. Ackerman, to amplify the 7.5 kv output from the oscillograph. Since the publication of the paper a simple inexpensive air-core type of transformer was developed to take the place of this unit, whereby the voltage of 7.5 kv is transformed into a voltage of 70 or 80 kv suitable for initiating directly the impulse generator. The polarity can easily be changed by simply reversing the output leads. This method has proved to be highly successful and precision timing was obtained.

The performance of this type of oscillograph in impulse testing work has been excellent and as many as 120 consecutive impulse records per day were taken.

The curvature of the d-c calibrating lines shown in figure 4 is due to the spherical curvature of the fluorescent tube screen. By simply superimposing the oscillograph wave records on this calibration chart this slight curvature should be of no consequence as far as the measurements of deflection amplitudes are concerned.

The oscillograph reproductions shown in figures 4 and 5 are approximately $\frac{1}{2}$ full size and the original films are $3\frac{1}{4}$ by $4\frac{1}{4}$ inches.

Mr. F. R. Benedict's interesting comments relating to the technique of building impulse testing circuits free from spurious oscillations agrees well with our own laboratory experience.

The exact magnitude of the beam current in the cathode-ray tube has not been measured. However, test evidence obtained by observing, by means of a cathode-ray oscillograph, the voltage drop across a suitable resistor in the cathode circuit indicated that the beam current is approximately one milliampere when the beam intensity control is adjusted to maximum at zero control grid bias.

The width of the recorded trace of the records shown in figure 5 is approximately $\frac{3}{32}$ inch where it is widest. The width depends on the cathode spot motion, it being somewhat larger when the cathode spot is moving slowly. However, the high-vacuum type of cathode-ray tube with electrostatic control grids leads itself to a very fine beam-intensity control.

The amplitude deflection of the records shown in figure 5 is approximately $1\frac{1}{2}$ inches. The records of figure 6 were taken with a small camera giving a record about $\frac{1}{5}$ full size. In our laboratory we project these records for analysis on a graduated screen by means of an enlarging camera with excellent results.

Mr. R. J. Donaldson's discussion refers to the use of the new oscillograph for rotating film drum recording. In the transient recording with stationary film and cathode beam sweep, the slight erratic shut off of the thyratron tube is, of course, of no consequence because the cathode-ray beam is already swept off the screen when the beam is finally shut off. Mr. Donaldson has made a very interesting contribution in the form of his current times time number of cycle indicator.

The authors wish to rectify here an omission in the bibliography of the paper and attention is here called to an excellent paper by Messrs. K. B. McEachron and E. J. Wade entitled "Study of Time Lag of the Needle Gap" published in the AIEE TRANSACTIONS, volume 44, pages 832–42, June 1925. This paper is one of the earliest describing the application of the high-voltage internal-photography cathode-ray oscillograph to practical electrical engineering problems.

# Sixty-Cycle Calibration of the 50-Centimeter Sphere Gap

**Discussion and authors' closure of a paper by C. S. Sprague and G. Gold published in the May 1937 issue, pages 594–6, and presented for oral discussion at the insulation co-ordination session of the summer convention, Milwaukee, Wis., June 22, 1937.**

J. R. Meador (General Electric Company, Pittsfield, Mass.): The authors have described what appears to be a very practical method of measuring high a-c voltages that lends itself particularly well to calibration purposes.

While making 60-cycle spark-over tests on grounded sphere gaps ("Calibration of the Sphere Gap," J. R. Meador. ELECTRICAL ENGINEERING, June 1934) in 1933 at Pittsfield, the writer had occasion to take a few check points on a 50-centimeter isolated sphere gap. The results were not published at that time due to the small number of spacings tested and to the fact that only one size of sphere was used. Since the calibration points checked the values in Standards Number 4 to within 2 per cent to 3 per cent, there did not appear to be an urgent need for further investigation. The more complete investigation conducted by Messrs. Sprague and Gold seems to indicate that a slight revision of Standards Number 4 for isolated spheres would be desirable.

The calibration points that were obtained by the writer are compared in table I with those for nonirradiated spheres given by the authors and with Standards Number 4.

It will be noted that the maximum difference between the Pittsfield points and those

**Table I**

| Sphere-Gap Spacing (Centimeters) | Spark-Over Voltage (Kilovolts Crest) Nonirradiated | | |
|---|---|---|---|
| | Meador | Sprague and Gold | Standards No. 4 |
| 10 | 262 | 266 | 265 |
| 15 | 370 | 374 | 381 |
| 20 | 468 | 465 | 475 |
| 25 | 555 | 545 | 557 |
| 30 | 626 | 624 | 632 |
| 40 | 755 | 764 | |

of the authors is 1.8 per cent which is very good agreement for measurements of this nature.

My voltage measurements were made with a voltmeter coil and vacuum tube crest voltmeter. I fully agree with the authors that the crest voltmeter is a very satisfactory and convenient instrument for this type of voltage measurement.

P. H. McAuley: (Westinghouse Electric & Manufacturing Company, East Pittsburgh, Pa.): The authors have made another contribution to the improvement in sphere-gap calibrations on which a great deal of work has been done in the last few years. It is gratifying to note that their values for the nonirradiated ungrounded gap are mostly within 2 per cent of the present standard values.

In a general way the method of measurements used appears satisfactory when the precautions mentioned in the paper are taken. Much depends on the vacuum-tube crest voltmeter, for which, unfortunately, no details are given. Some Westinghouse testing transformers are equipped with a crest voltmeter operating on the bushing charging current. The same principle was used by Fortescue and Farnsworth in their original fundamental calibration of the sphere gap. It is perhaps appropriate to describe the method briefly at this time.

If $Q$ is the charge of a condenser at a crest voltage $E$, 2 $Q$ is the change in charge from a voltage $+E$ to $-E$. The change per cycle is 4 $Q$. The average current, disregarding sign, is the charge flowing in coulombs per second. If $C$ is the capacity of the condensers, the average current is $4\ Qf = 4\ CEf$, where $f$ is the frequency. To obtain an indication of the average current, the condenser charging current is rectified and measured with a D'Arsonval type of meter. Either a mechanical or a thermionic type rectifier may be used.

This furnishes a simple and reliable method of measuring high voltages, especially when the testing transformer is equipped with condenser bushings. It is of course customary to check the crest voltmeter against the sphere gap to guard against changes in capacity with voltage. Once its performance is determined, however, it can be relied upon for most testing conditions. It is sensitive to disturbances in the high voltage circuit and, with a thermionic rectifier, trouble may develop in tests causing high frequencies or excessive harmonics. Methods of overcoming these troubles have been described (D. F. Miner, *Electric Journal*, December 1925). An outstanding feature of this crest voltmeter is that it is independent of the load on the testing transformer.

It would be interesting to have the authors report the results of their study of the effect of voltage on the capacities of the bushings. It has been our experience that the effective capacity increases as much as 2 per cent at the higher voltages.

C. S. Sprague and G. Gold: In response to Mr. McAuley's request for more detailed information on the crest voltmeter employed by the authors, the following brief description will be given here.

The working range of the crest voltmeter proper is about 30 volt crest, hence its use on high voltages requires a capacitance divider of known ratio, of which the condenser-type bushing conveniently supplies the high-voltage capacitor. Low alternating voltage up to 30 volts is supplied to the grid circuit of a vacuum tube having a sufficiently high input impedance so as not to disturb the potentiometer ratio. Full-wave rectification of the a-c component is provided by a duodiode in the plate circuit, by which means 2 series condensers, connected as in a voltage-doubler circuit, are each ultimately (after several cycles) charged to a d-c potential proportional to the crest value of the voltage applied to the grids. This d-c potential is in turn applied to the grids of a d-c push-pull amplifier with a milliammeter and a differential shunt in its output circuit, the reading of this milliammeter being a function of the crest voltage of the alternating wave applied to the instrument.

The instrument proper has no inherent calibration but it can be accurately calibrated at low voltage. It is not sensitive to occasional high frequencies but indicates the average value of the applied crest voltage over a number of cycles. Since the indications depend upon the change in plate current, that is, upon the slope of the $E_g$-$I_g$ curve, and not upon the absolute values of plate current, the instrument is insensitive to changes in the supply voltage.

With proper design, the instrument responds quickly to any change in the applied voltage and is independent of wave shape and sustained harmonics or tooth ripples, even under the most extreme conditions.

When first built the possibility of error due to changes in the characteristics of the vacuum tubes was considered. However, with operation of the vacuum tubes well within their ratings, no trouble of this sort has been experienced in continued operation over periods of a year or more. As with the rectified charging current type of crest voltmeter, the device when used with a capacitance potentiometer can be occasionally checked against a sphere gap. Also with either type of crest voltmeter the capacitance of the condenser-type bushing should be accurately known.

With regard to the change in capacitance of the bushing with voltage the authors are glad to present the following data. The bushings were designed for operation at 300 kv effective. The capacitance was constant up to approximately 55 per cent of this value. Between 55 per cent and 100 per cent the capacitance increased, at first slowly, then more rapidly, ultimately showing a total increase of approximately 1.1 per cent.

Mr. Meador's discussion presents comparative data showing a close check between Mr. Meador's results and those of the authors for nonirradiated spheres. Such a check is always gratifying to both parties.

# Basic Impulse Insulation Levels

**Closure of a paper by the EEI-NEMA joint committee on system insulation co-ordination, published in the June 1937 issue, pages 711–12, and presented for oral discussion at the insulation co-ordination session of the summer convention, Milwaukee, Wis., June 25, 1937. Previous discussion of this paper appeared in the October 1937 issue, page 1298.**

Philip Sporn: Setting up insulation levels on a voltage basis has laid the foundation for carrying on the more important work of the Joint Committee in specifying the insulation strength of all classes of equipment in the established levels and in allocating these levels to the normal system of voltages.

General agreement on the basic levels as indicated in table I, was reached, of course, only after certain compromises and minor

differences of opinion. As mentioned by Mr. Foote and as pointed out in the report, consideration should be given to increasing the 100-kv impulse level in the 15-kv class. The apparent lack of agreement here appears to be due to the fact that the 100-kv level really corresponds to the 13.8-kv class (if such were recognized) as can be readily shown by plotting the basic levels against the rated voltage classification. It is planned to give this matter further consideration in the committee.

The heading of column 1 of table I "maximum rated voltage classification" was the heading agreed upon by the committee. As Mr. Foote points out, however, it may be desirable to change this wording if there is confusion, as there apparently is, interpreting the present heading to mean that basic impulse levels are definitely tied up only with system voltages having numerical values given in column 1. A way of clearing up this entire matter might well be by referring to the different basic impulse insulation levels by letters or numbers independent of the system voltage on which they may be applied.

This report covers the progress so far made by the committee in the insulation co-ordination problem. There is still a great deal of work to be done and this may perhaps constitute the major part. If it had been found possible to recount in detail the various discussions within the committee prior to adoption of these levels, a clearer understanding of how the values given in table I were arrived at would be evident. As Mr. Foote points out, "the basic levels are intended to be reference levels." This appears to clearly define what these basic levels are supposed to represent.

Mr. Vogel assumes that these levels are "purely arbitrary since the foundation which is the voltage level which can be maintained by protective equipment is lacking." In other words, a basic level is a benchmark on which all other insulation and protective equipment in the system is based. If I understand Mr. Vogel's comments correctly, he believes that protective devices should be standardized and that transformers and other equipment should be based on the performance of the protective device. Further, if Mr. Vogel's remarks are understood correctly, he would design a piece of apparatus self-protected and place it in a system with the firm belief that the apparatus would perform satisfactorily regardless of whether the system itself functions as a unit or not. This is exactly the type of thing that insulation co-ordination is intended to prevent, that is, the throwing together of a mass of equipment such as power transformers, circuit breakers, instrument transformers, bus insulators, etc., each made to the pet ideas of the individual designer or manufacturer as regards construction and protection without consideration of the broad point of view of the protection of the system as a whole when this equipment is installed and has to work as a unit. Experiencing situations of this kind frequently and in actual practice has been one of the principal factors in giving insulation co-ordination the large amount of attention and consideration that it has been given up to the present time and is still receiving.

It makes little difference where the basic level is set; whether at the protective device, the transformer, the station entrance, or elsewhere, but once set, the problem becomes one of selecting and using margins between the various steps of insulation where these steps are desirable and economically justified. The bases on which these insulation levels were selected were distinctly not arbitrary, but have been co-ordinated so far as information has been available with present-day protective devices. A close study of data published in papers by Messrs. Foote and North and Messrs. Sporn and Gross show clearly that consideration has been given to the protective devices at present available.

As the work of the committee progresses in "carrying out its purpose and scope in:

1. Specification of insulation strengths, and
2. Allocation of insulation levels as mentioned in the paper"

it is believed that the co-ordination of insulation on a power system will become much less difficult. The proper use of the principles of insulation co-ordination will, it is confidently believed, result in more economical power systems.

## Insulation Strength of Transformers

**Closure of a report of the transformer subcommittee of the AIEE committee on electrical machinery published in the June 1937 issue, pages 749–54, and presented for oral discussion at the insulation co-ordination session of the summer convention, Milwaukee, Wis., June 25, 1937. Previous discussion of this report appeared in the October 1937 issue, pages 1297–8.**

**I. W. Gross:** This paper was intended to give a historical record of the development of the insulation strength of transformers, particularly the impulse strength. In so doing, it was desirable to recount the various steps which were taken in setting up impulse tests on transformers, and in conclusion, the paper gave impulse-test values (tables II and III) of transformer and bushings, together with a brief outline of the proposed method of test where it differed from past procedure.

The fact that a question has arisen since the report was published (as pointed out by Mr. Montsinger) regarding the magnitude of test voltages seems to indicate that perhaps the report was not entirely clear in this respect. It may be well, therefore, to briefly summarize the entire aspect of impulse tests on transformers.

It is recognized that a transformer in service may be subjected to 3 different types of impulses, namely, a full wave, a wave chopped on the tail, and a wave chopped on the front. Impulse testing of transformers has developed today to the point where it is perfectly safe and practical to impose on a transformer in the factory tests with full waves and waves chopped on the tail. Some work has been done and still is in progress on applying tests with waves chopped on the front, that is, front-of-wave tests. The standard wave used to test transformers is the $1\frac{1}{2} \times 40$ wave, and it, of course, may either be of a positive or negative polarity. Since the first of the year when the test procedure was clarified by speaking of impulse-test voltages in terms of their crest value instead of inches of gap—which, of course, was only a test device—the recommended impulse test on transformers boils down to the application of full-wave and chopped-wave applications. Following past procedure, the test now recommended calls for 2 chopped waves but of equal value followed by the full-wave test. The magnitude of impulse-test voltages correspond, in general, to the voltages permitted by the test gaps formerly specified. In accord with action taken by the transformer subcommittee at its meeting in Milwaukee, June 25, it was agreed that the test values indicated in table II of the paper should be recommended, subject to the changes indicated in Mr. Montsinger's discussion above, namely, that distribution transformers in the 15-kv class be subject to a full-wave test of 95 kv and a chopped wave test of 110 kv. Likewise, it was agreed at that meeting to recommend the bushing characteristics given in table III with the change that the 15-kv-class bushing impulse flashover value be changed from 110 kv to 105 kv. These tables II and III with the 3 changes indicated are the latest recommendations of the committee on magnitudes of impulse tests on transformers and their bushings, the sequence of application being 2 chopped waves of equal magnitude followed by one full wave.

While the above 3 changes in voltage values in the 15-kv class from those given in tables II and III have been agreed upon, there is still a feeling by some of the members of the committee that the values should be retained as given in the table. However, since entire agreement could not be obtained it was felt better to go along with the lower tentative values in the 15-kv class than hold up the entire matter until agreement had been reached.

Considerable discussion has developed over the gaps on transformer bushings. Mr. North points out that "gaps mounted directly on bushings are very undesirable and should be discontinued." Others in the industry have voiced the same sentiment, and it seems quite likely that the development of standards for transformers, together with their bushings, will eliminate the bushing gap entirely. It seems perfectly clear that the matter of setting up and testing insulation strength of transformers is one thing and the protection of that transformer is another, whether it be protected by gaps, lightning arresters, or some other device. The 2 problems are, of course, interrelated and should be co-ordinated.

It has been clearly brought out in the discussions that there is a hazard in mounting gaps on bushings due to the possibility, and in many cases almost certainty, that the power arc, which will develop over the surface of the bushing when these gaps break down, will damage the bushing. Actual experience has shown this to be true. It is believed, however, that where gaps are used in connection with transformer protection, they should not be close enough to the bushing to result in a destructive arc on the bushing itself.

Answering Mr. North's question regarding the definition of "a directly grounded circuit," which appeared in the 1930 AIEE Transformer Standards. As near as can be determined at the present time, this definition was set up to accomplish several things;

first, to make it impossible to consider a system's neutral solidly grounded if it had a small grounding bank or potential transformer bank Y-connected with the neutral physically attached to ground. Another point considered appears to have been that the system neutral would be held sufficiently close to ground potential to consider the system grounded if the requirements set up in the footnote were followed. Further, it was considered improbable that troublesome oscillations would be set up in the system due to transient voltages resulting from arcing grounds if the procedure outlined in the footnote were followed in defining the system as directly mounted or isolated.

## Application of Arresters and the Selection of Insulation Levels

**Authors' closure of a paper by J. H. Foote and J. R. North published in the June 1937 issue, pages 677–82, and presented for oral discussion at the insulation co-ordination session of the summer convention, Milwaukee, Wis., June 25, 1937. Previous discussion of this paper appeared in the October 1937 issue, pages 1293–6.**

J. H. Foote and J. R. North: The large amount of constructive discussion of these papers is appreciated and we are especially glad to have the various phases of this matter of insulation co-ordination amplified by others who have been working actively with the problem.

We would like to call attention to 2 corrections which should be made in our paper. On page 680, item (*b*) should not mention fault resistance and should read: "(*b*). The ratio of zero-sequence impedance (including neutral impedance) to positive-sequence impedance...."

The ratio $Z_0/Z_1$ is indicative to some extent of the effectiveness of the neutral grounding. The voltage during fault conditions from sound phase to ground may range from less than $E_n$ to more than $E$ line-to-line, depending upon the netural conditions. In many cases, it will be found that an 80 per cent arrester may be used if the ratio $Z_0/Z_1$ is equal to 2 or less and that a 70 per cent arrester may be used if this ratio is equal to one or less; however, it should be distinctly understood that this approximation of the arrester rating is only a general "rule of thumb."

Mr. Halperin has questioned the necessity of the arrester voltage rating being at least 10 per cent above the calculated maximum sound phase voltage-to-ground. The rating of an arrester is based upon the 60-cycle voltage at which it will cut off after discharge. Considering the possibility of a line-to-ground fault coincidental with the surge, it was felt that arresters should have a margin of at least 10 per cent above any such voltage which it might be called upon to clear. The ability of an arrester to clear itself is influenced to some extent by the voltage recovery rate and experience has indicated that the performance is much better on systems having a moderate ratio of reactance to resistance. Then, too, arresters in the lower-voltage classes tend to have a higher factor of safety than those in the higher-voltage classes.

Messrs. Piepho, Ross, and Vogel have inquired as to the characteristics of present day arresters when discharging currents above 5,000 amperes. The value of 5,000 amperes was used in the paper since comparable data regarding the performance of different types of arresters was available at this current value but not generally at the higher values of discharge current. Practically, this is not of great moment since the voltage across the arresters during discharge does not increase lineally with increasing discharging current. The characteristic curve is a logarithmic exponential function and the voltage across one design of arrester during discharge of 20,000 amperes is only approximately 15 per cent higher than that at 5,000 amperes. While arresters of different designs have differing characteristics at high discharge rates, it is generally held that currents much in excess of 5,000 amperes can be discharged before the voltage drop across the arrester reaches the basic impulse insulation level. We are highly sympathetic to the plea for comparable manufacturers' data of arrester performance characteristics at higher values of discharge current and it is to be hoped that this information will be made generally available in the near future. Similar data should also be made generally available regarding the performance characteristics of older designs of arresters and arresters which may have deteriorated in service.

The adequacy of the value of one kv per circuit foot assumed for the short-time potential gradient has been questioned. This value is equivalent to an incoming wave having a front of 1,000 kv per microsecond and without reflection. In particular cases, the assumption of higher values may be necessary but it has generally been felt that one kv per foot represented a reasonably average value considering the actual lengths of circuit feet, circuit connections, and surge conditions as found in practice.

Mr. Sels has discussed the matter of insulation steps and the relative importance of different types of insulation. The relative insulation values of bus insulators, transformer bushings, etc., as given in the figures in the paper, were intended to merely illustrate certain existing insulation levels and were specifically not intended to represent necessary marginal steps between different types of insulation. Fundamentally, it seems to us that there are only 2 major steps of margins required in insulation co-ordination. First, the margin between the performance of the surge protective device under the conditions as assumed and the surge insulation level of the weakest or most important class of equipment; second, the margin between the maximum dynamic voltage-to-ground and the lowest low-frequency flashover or puncture value of insulation under the worst condition of dirt and moisture. Marginal requirements are matters of experience and economics. Transformers have generally been taken as having the limiting minimum insulation strength because of the cost involved and because preferred practice is to place the arresters or other surge protective devices as closely as possible to the transformers. Bushings and insulators have generally been selected with higher impulse insulation strengths because of the relatively small additional cost involved and due to the fact that they are subjected to dirt and moisture and in addition are often located many circuit feet from the protective device.

We fully agree with Mr. Sels that the margins should generally be greater than 10 per cent between the protective device and the apparatus. Furthermore, in our opinion, the margins should properly be expressed in terms of "( ) kv + ( ) per cent" rather than strictly on a percentage basis over the range of voltage characteristics normally considered from the distribution voltage to the highest transmission voltages. It is not apparent that marginal steps are particularly necessary between classes of apparatus in a given basic insulation level except to insure that under the worst conditions assumed for specific classes of apparatus the insulation strength will be in excess of the basic insulation level requirements.

## Insulation Co-ordination

**Authors' closure of a paper by Philip Sporn and I. W. Gross published in the June 1937 issue, pages 715–20, and presented for oral discussion at the insulation co-ordination session of the summer convention, Milwaukee, Wis., June 25, 1937. Previous discussion of this paper appeared in the October 1937 issue, pages 1296–7.**

Philip Sporn and I. W. Gross: It has been some 7 years since the subject of insulation co-ordination has been present in an organized and comprehensive manner and thoroughly discussed, as has been done in this group of papers. The extensive discussions which the papers have brought forth show not only that the subject is very much alive but also give the electrical industry an opportunity to observe what has been done during recent years in the development of thinking on co-ordination, the thoughts behind the development, and the progress made in its application.

The question of establishing margins between different types of apparatus, to obtain co-ordination, is an important one and has been discussed from several points of view. It is particularly interesting to know what some of the operating companies are doing in arriving at these margins. Mr. Sels, for example, is allowing 30 per cent margin between lightning arresters and transformers as he feels that margins of 10 per cent are not adequate. Mr. Foote's analysis of margins between arresters and transformers is extremely interesting as it brings out some of the variables which have to be considered in arriving at and recommending insulation margins. The practice of Mr. Sels' company in making the transformer the strongest piece of equipment in the station, with the bus itself graded lower, is, as pointed out, exactly opposite to that of our company. Situations of this kind show clearly the need for establishing classes of insulation levels so that they may be adapted to the individual needs and practices of the various users. Certainly at the present time no one can say that either one of these practices is right and the other wrong; and for the conditions met within

service it may be that each of these practices, although exactly opposite in principle, is economically sound in application.

Mr. Vogel has mentioned the self-protected transformer in the distribution-voltage class where protective devices are built into the transformer itself. This, of course, is similar to the practice of some companies today in locating lightning arresters directly on the transformer tank, a practice which we started as early as 1928. The question immediately arises, therefore, if distribution transformers are to be equipped with protective devices, why should not power transformers also be so equipped? This would mean that power transformers might be supplied complete with lightning arresters attached thereto, as standard equipment.

In connection with the impulse testing of transformers it has been our practice in recent years to not only equip power transformers with lightning arresters placed directly on the transformer make but also to impulse test practically all of these larger transformers. In addition to the standard impulse tests which have been developed during the past few years we require an additional impulse test on the entire unit including the arrester. That is, an impulse is applied to the transformer with the lightning arrester connected to it. The purpose of such a test is to observe the voltage characteristics permitted on the transformer by the lightning arresters under conditions simulating as nearly as possible actual field conditions. Impulse test voltages which would rise to something in the order of 3 times the magnitude permitted by the transformer test code, if the arrester were not present, have been applied to transformers in combination with arresters, the rate of voltage rise in some cases being considerably in excess of 1,000 kv per microsecond.

In addition to testing the impulse strength of the transformer itself under commercial conditions we are strongly in favor of this practice in applying a severe impulse to the transformer equipped with a lightning arrester as the installation will actually be made in the field. We would suggest that some thought be given in our technical committees in setting up the standard procedure for applying impulse tests to transformers equipped with lightning arresters.

A great deal of the discussion has apparently centered around the possibility of obtaining 100 per cent protection against impulses. We wish to refer again to that part of our paper which states the problem of "insulation co-ordination" centers around economy. This means that working out the problem of protecting equipment, while technically we may be able to protect apparatus practically 100 per cent against breakdown from impulse, it may not be the economical thing to do, and therefore we face the possibility of an occasional failure under severe impulse conditions rather than build into the apparatus itself insulation strength and into the protective device sufficient protection to eliminate failure for almost any conceivable type of impulse.

It is believed that, with the work which has already been done, and the field experience which is now being accumulated, we are fast collecting a store of information which will make this insulation co-ordination problem much simpler to handle in the future, giving us a set-up finally where it will be possible to predict the operating results of applying these principles with a considerable degree of accuracy.

## Application of Spill Gaps and Selection of Insulation Levels

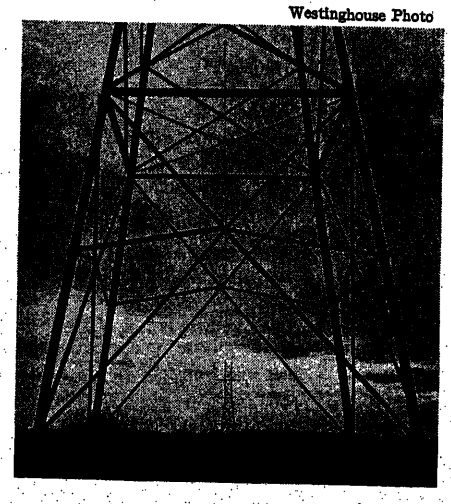
**Authors' closure of a paper by H. L. Melvin and R. E. Pierce published in the June 1937 issue, pages 689–94, and presented for oral discussion at the insulation co-ordination session of the summer convention, Milwaukee, Wis., June 25, 1937. Previous discussion of this paper appeared in the October 1937 issue, pages 1290–3.**

**H. L. Melvin and R. E. Pierce:** In the discussion by Messrs. Foote and North the criticism as to the use of the term "level" as being applicable to a spill gap is well taken. It is perhaps unfortunate that the term "insulation levels" was ever applied to gaps and insulators in view of the many later attempts to picture these insulation levels as fixed or uniform values of voltage regardless of time. The origin of the term was of course closely associated with the idea of defining insulation levels in terms of "inches of rod gap."

The authors believe that the experience cited justifies the first conclusion in the paper, namely, that "spill gaps are effective as a means of establishing and co-ordinating insulation levels on lines and stations, and affording dependable protection to equipment and insulation, against failure from lightning." It is of course brought out in the paper that spill gap settings and equipment insulation strengths must be properly co-ordinated. Also instances are cited where spill gaps were set too wide to protect equipment probably in the short time zone.

The wide range of gap settings used for the same operating voltage in different locations is more the result of different methods and stages of experimentation with gap settings under service conditions rather than of calculations or complete tests to determine minimum practicable gap settings. It is therefore, doubtful if detailed explanatory data on such items as insulation strengths of apparatus and system sequence impedances would be pertinent for most of the situations cited. For the one 110-kv substation in Louisiana, however, where definite and more complete tests were carried out to determine the minimum gap settings permissible, the 110-kv system neutral is effectively grounded and the ratio of zero-sequence impedance to positive-sequence impedance is in the order of from 0.7 to 1.0 under most operating conditions. Experience has shown that designers' estimates of the impulse insulation strength of specific transformer units have been gradually lowered over a period of years as additional failures have occurred and more has been learned regarding the co-ordination of the design of the complicated insulation structure within a transformer.

Westinghouse Photo



The experience of the South Texas Company with the use of fused spill gaps as described by Mr. M. H. Lovelady is of decided interest and is further confirmation of the authors' second conclusion, namely, that minimum permissible spill gap settings are less than those previously considered possible.

With reference to table I in the paper, showing the operating record of spill gaps in Texas, it is understood that the only means used to determine whether or not these gaps operated was by periodic visual inspection.

Mr. Rorden raised the question as to whether experience indicates that most insulation failures are associated with a single severe surge, such as a direct stroke, or if there are a fair percentage of failures that occur with strokes of lesser magnitude and current, such as traveling waves, also Mr. Ross inquires if experience indicates the relative destructive effect of switching surges, induced surges, and direct strokes. The authors believe experience has fairly definitely shown that direct strokes are the only real concern as far as destruction of equipment from impulse voltages is concerned, and that the destructive effect of switching surges and induced surges are fully guarded against if the design of equipment and its protection from direct strokes is adequate. However, there are so few instances of insulation failures in which all of the facts are known that it is probably more a matter of opinion that most insulation failures are associated with a single severe direct stroke nearby, rather than from direct strokes to the line at some distance, which appear at the substation as traveling waves.

Answering the other question by Mr. Ross, the authors have no definite test data relative to the wave shape of switching surges. However, it is also our opinion that many, if not all, switching surges have characteristics intermediate between 60-cycle voltages and relatively slow rate of rise impulse voltages.

Answering the questions raised by Mr. McEachron, the fused gaps used on the 110-kv system discussed on page 691 were rated 8 amperes. The repeater type fuse operates in from 15 to 30 cycles. There are, of course, plain back-up rod gaps used in connection with all of the repeater fused gaps, having slightly higher settings, which prevent loss of protection during the interval required for the repeater fuses to come into position. Where permanent installations are made of several fused gaps in multiple, the loss of even the difference in degree of protection between the fused and back-up gaps is prevented until all fuses have operated.

# News

## Of Institute and Related Activities

# Important Developments in Publication Policy Announced

By I. Melville Stein, Chairman AIEE Publication Committee

TO MEET the definitely expressed wishes of the Institute's membership for a broader publication service, the AIEE publication committee has been studying publication policies during the past year or so.

An initial step in this direction was taken, upon the committee's recommendation, in January of this year when the board of directors approved an additional appropriation for the publication in ELECTRICAL ENGINEERING of more articles of broad general interest during the remainder of the appropriation year ending September 30, 1937. Since that time, the publication committee has continued its study of publication and related policies with a view toward improving still further the value of the Institute's publications to the membership. To assist the committee in better determining and meeting the wishes of the membership, the subject was discussed at some length at the conference of officers, delegates, and members held during the Institute's 1937 summer convention in Milwaukee, Wis. The AIEE technical program committee also has studied the situation as it affects the work of that committee, and has made certain recommendations.

As an outgrowth of these various deliberations the publication committee has completed plans for some important developments in publication policy and procedure, which were approved by the board of directors at its meeting on October 28, 1937. These developments are outlined in the following paragraphs.

The policy of including in each issue of ELECTRICAL ENGINEERING a substantial number of articles of broad general interest will be continued, and it is expected that the changes in policy just adopted will make possible an appreciable improvement in this section.

Advance copies of all papers approved by the technical program committee for national conventions and District meetings will be provided for the use of the technical program committee and the convenience of others interested. These advance copies will be in the form of reproduced manuscripts of accepted papers, these manuscripts being subject to revision before final printing. They will be available at headquarters or at the registration desk at meetings or conventions at a price of 5¢ each; by mail the price will be 10¢ each. ELECTRICAL ENGINEERING regularly will carry announcements of advance copies as they become available.

Technical program papers will be published in a segregated section of ELECTRICAL ENGINEERING after they have been presented and finally reviewed (instead of before presentation as at present), so that the approved discussions can be correlated and published with their respective papers. Some highly technical papers that are considered to be of limited interest will be abstracted in ELECTRICAL ENGINEERING and will not appear there in full. (Such papers will be published in full in the TRANSACTIONS.) For the present it is contemplated that approximately two-thirds of the regularly approved technical program papers will be published in full in this segregated section of ELECTRICAL ENGINEERING.

The TRANSACTIONS will include only finally reviewed papers and correlated discussions approved by the technical program committee, but all formal papers presented on the technical programs at national meetings and those approved by the technical program committee for presentation at District meetings will be included except in rare special cases.

The publication committee believes that these modifications in policy and procedure should result in an improved publication service to the membership, and in a reduction of the time elapsing between the submission of a technical paper manuscript and its presentation at a national convention or District meeting. The new policy will be made effective with the January 1938 issue of ELECTRICAL ENGINEERING.

Comments and criticisms will be sincerely appreciated by the publication committee.

# 1938 International Management Congress

The Seventh International Management Congress will be held at Washington, D. C., September 19 to 23, 1938, under the auspices of the International Committee of Scientific Management (CIOS), of which Lord Leverhulme of Great Britain is president. Authorities on industrial and commercial management from about 40 countries are expected to attend. An American Congress Council has been formed with Willis H. Booth, honorary president of the International Chamber of Commerce, as chairman, to sponsor the gathering.

Discussions of the latest developments in management and the social and economic aspects of management, based upon more than 200 papers selected competitively from experts all over the world, will comprise the congress. Six sections, convening simultaneously, will deal with management problems in production, administration, distribution, personnel or labor relations, agriculture, and the home. Leaders in business are expected to take part in the discussions, together with invited governmental representatives. Extensive tours for foreign visitors through the plants and offices of industrial and commercial establishments, noted for their application of scientific management, are planned.

The congress will be under the direction of the National Management Council of the United States of America, affiliate of the international committee. It is composed of the following organizations: American Management Association, The American Society of Mechanical Engineers, The Association of Consulting Management Engineers, International City Managers Association, Life Office Management Association, National Office Management Association, Personnel Research Federation, and Society for the Advancement of Management. A co-ordinating committee, of which W. L. Batt, president of SKF Industries, Inc., and past-president of ASME, is chairman, has been formed with the following officers: *vice-chairmen*—Harry Arthur Hopf, William H. Gesell, Thomas R. Jones, Henry P. Kendall; *treasurer*—Charles G. Smith; *general secretary*—John J. Furia. Sectional chairmen include James O. McKinsey, for administration, Ralph E. Flanders for production, Leon C. Stowell for distribution, W. W. Kincaid for agriculture, and Marie M. Meloney for the home. American Engineering Council's executive committee, on the request of the co-ordinating committee, has authorized the secretary of AEC, F. M. Feiker (M'34), to serve as Washington secretary of the congress.

Previous congresses have been held at Prague (1924), Brussels (1925), Rome (1927), Paris (1929), Amsterdam (1932), and London (1935).

**New NEMA Bulletins.** The National Electrical Manufacturers Association has issued 2 new publications: (1) INDUSTRIAL CONTROL STANDARDS, publication number 37–44; and (2) INSTRUCTIONS FOR CARE AND OPERATION OF TRANSFORMERS, publication number 37–46. The first bulletin is a revision of a previous publication on the same subject, and the second contains instructions for the care of both distribution and power transformers. Copies of these pamphlets may be obtained from the headquarters of the National Electrical Manufacturers Association, 155 East 44th Street, New York, N. Y.

# Industrial and Other Topics Feature Busy Sessions at Akron—Students Take Active Part

SUPPORTED by an unusual variety of inspection trips to many different types of industrial plants, there was a very effective industrial flavor to the general meeting of the AIEE Middle Eastern District held in Akron, Ohio, October 13–15, inclusive. About a third of the 23 papers on the program dealt with problems of an industrial nature in which electrical engineers are directly interested through the development, application, or operation of a wide variety of machinery and control equipment. Also afforded a place on the program were timely papers and discussions concerning such topics as radio interference, transportation, electrical machinery, electronics, and power transmission.

This was the ninth District meeting to be held by the Middle Eastern District, and the first since 1932. Other meetings that have been held by the District are (attendance indicated in parentheses): Washington, D. C., January 1925 (212); Cleveland, O., March 1926 (430); Bethlehem, Pa., April 1927 (400); Baltimore, Md., April 1928 (400); Cincinnati, O., March 1929 (270); Philadelphia, Pa., October 1930 (500); Pittsburgh, Pa., April 1931 (500); Baltimore, Md., October 1932 (240).

Chairman A. O. Austin of the Akron Section opened the initial session, introducing Mayor Lee D. Schroy who welcomed the visitors and outlined some of the local features that he deemed to be of interest to engineers. In responding to Mayor Schroy Vice-President I. Melville Stein cited the fact that 3 of the renowned pioneers in the electrical industry were born in Ohio: Theodore N. Vail, Thomas A. Edison, and Charles F. Brush.

Presiding at the various technical sessions were: I. Melville Stein, vice-president from District 2 and past chairman (1927–28) of the Philadelphia Section; Russell Krammes, past-chairman (1931–32) of the Akron Section; A. M. MacCutcheon, past-chairman of the Cleveland Section (1920–21), one time director (1928–32), and past-president (1936–37); J. R. Martin, Cleveland; G. R. Fink, Philadelphia; F. W. Funk, Akron.

Doctor W. E. Wickenden, president of Case School of Applied Science, and past-chairman (1936–37) of the Cleveland Section presided and acted as toastmaster at the concluding banquet, where President W. H. Harrison spoke briefly prior to the introduction of the guest speaker, Commander C. E. Rosendahl. To Harold L. Brouse (A'32) electrical engineer, B. F. Goodrich Company, and chairman of the general committee for the Akron meeting, special tribute was paid by Toastmaster Wickenden and all those assembled. Confined for some time by illness, Mr. Brouse was a listener-in on the program through the medium of a microphone pick-up and a special direct wire. R. A. Hudson (A'30) efficiency engineer with Goodyear Tire and Rubber Company, was credited with effective "pinch-hitting" for Mr. Brouse.

**Analysis of Registration at Akron Meeting**

| Classification | Location: Akron | District No. 2* | Other Districts | Totals |
|---|---|---|---|---|
| Members | 30 | 165 | 35 | 230 |
| Students | 6 | 125 | 1 | 132 |
| Men Guests | 7 | 40 | 7 | 54 |
| Women Guests | 12 | 32 | 4 | 48 |
| Totals | 55 | 362 | 47 | 464 |

* Outside of Akron Section

## Radio Interference

On the increasingly important subject of radio interference, one formal published paper and 2 informal papers prepared especially for the Akron meeting were presented and actively discussed:

A Review of Radio Interference Investigation, Frank Sanford (A'28, M'34) and Willard Weise; both are employed by the Cincinnati Gas and Electric Company (published, October issue pages 1248–52).

Notes on Radio Interference, Grover Lapp (A'22), chief engineer for the Lapp Insulator Company, Inc., LeRoy, N. Y. (not published).

Radio Disturbance Measurements, W. S. Jennens and C. J. Miller, Jr., Barberton, Ohio, electrical engineers; both are employed in the Ohio Insulator Company Division of the Ohio Brass Company (not published).

Brief review of the subject was given by Messrs. Sanford and Weise who described radio interference elimination as "essentially the co-ordination of this use of electricity with its other uses for light, heat, power, and transportation, in order that the growth of each may not be restricted by the requirements of the other," and who consider as practical an approach to the problem similar to the effective approach to the problem of inductive co-ordination with reference to wire communication. Effective co-operative control measures experimentally developed in Cincinnati were briefly described.

G. W. Lapp analyzed conditions contributing to radio interference, with particular reference to transmission line insulators, and to the various methods now being followed on modern power systems for control or elimination. He pointed out that at least one by-product of interference control that is of direct value to the operating utility has been the discovery and elimination of points of incipient failure. In discussing radio characteristics of insulators he stressed the continuing importance of field tests to supplement laboratory tests and developments, considering the variation in contamination of atmosphere in different localities. He emphasized the fact that "considerable information is now available from actual cases, so that insulators can be specified with confidence to meet unusual types of severe conditions," and concluded that "the problems of satisfactory freedom from radio interference on insulators have been met as the needs have appeared and in such a way that future demands can be taken care of as they arrive."

Messrs. Jennens and Miller called attention to the method outlined by the National Electrical Manufacturers' Association for measuring radio interference on high-voltage insulators, describing it as "probably the most satisfactory method now available for laboratory use"; they stated—that this method "probably will be used by most of the insulator manufacturers, and eventually radio interference data will be correlated between the various laboratories." They pointed out, however, that before the NEMA method can be used to determine radio interference, it is necessary to correlate the microvolts across the insulator as measured by the NEMA method with the field strength of radio interference that the insulator will create when used on a transmission line. They gave various correlation data and described testing equipment and methods used.

## Mine Ventilation

"Improvements in Mine Ventilation" were described by Doctor Theodore Troller of the Guggenheim Airship Institute. As indicative of the train of beneficial development resulting from well-organized basic research, Doctor Troller described several noteworthy advances in equipment and technique of mine ventilation that have grown directly from the fruits of research originally directed toward aeronautical problems.

Doctor Troller outlined briefly the peculiar requirements of mine ventilation, citing it as typical relatively low-pressure high-quantity (20,000 to 300,000 cubic feet per minute) service, and one where notable improvements in fans have been made and more may be expected. He cited the case of one coal company where the electric power bill for mine ventilation amounts to as much as $150,000 per year, pointing out that in such a case each one per cent improvement in the efficiency of fan or related electrical equipment meant a reduction of $1,500 per year in the ventilation power bill. He reported the modern trend toward the use of propeller type fans because of their adaptability to the peculiar and varying requirements of mine ventilation, stating that "maximum efficiencies of 80 to 85 per cent can be combined with a power characteristic having the maximum power required at or near the point of maximum efficiency." He stated further that "in a few years the propeller type fan should be developed from the laboratory state to practical installation so that 90 per cent efficiency will be a regular feature, and its weight and size further reduced by about 30 per cent."

## Industrial Switchgear

"The Advance in Industrial Switchgear" was treated at some length by V. L. Cox

(A'28) of the switchgear division, General Electric Company, Philadelphia, Pa., emphasizing the necessity for continuing advance in the development of switchgear to meet the ever more complex and rigorous requirements of modern industry. Mr. Cox traced the steps followed in laying out electrical equipment for the modern plant. He described and illustrated numerous varieties of factory-built and assembled equipment which in many cases includes the complete complement of related auxiliary, control, and metering devices.

### Rubber Industry

The rubber industry came in for its share of consideration in 2 papers; the first was "Electrical Applications in Rubber Mills," by John Grotzinger (A'24), chief electrical engineer, and R. S. Ferguson and W. A. Brown of the Goodyear Tire and Rubber Company, Akron. Mr. Grotzinger and his co-authors presented a general outline of the major processes of a manufacturing plant producing rubber tires and tubes, and described the more important items of equipment used. They listed the principal power requirements for a typical plant and described methods of pre-determining energy requirements and maximum demands for plants of any capacity. Opportunities for generating power from process steam were briefly reviewed, and evidence furnished indicated that fully 50 per cent of energy requirements could be met in such a manner. (Figures given indicated a power requirement of about 0.55 kva per tire for plants capable of producing 10,000 or more tires per day, whereas a plant having a capacity of 300 tires would require about 2.2 kva per tire.)

"Recent Developments of Electrical Equipment for the Rubber Industry" were discussed by C. W. Drake (M'21) industrial sales engineer, Westinghouse Electric and Manufacturing Company, East Pittsburgh, Pa. Supplementing the previously mentioned paper which covered the matter of applications, Mr. Drake discussed the engineering and related problems involved in the development of electrical equipment to meet the peculiar requirements of the rubber industry.

In this discussion Mr. Drake covered 2-speed motors for Banbury mixers, and dynamic-braking starters for synchronous-motor mill-line drive. The motors discussed were synchronous machines rated at 600–1,200 or 450–900 rpm, and they were discussed in connection with various related control and protective equipment. Under the subject of dynamic-braking starters, he described and illustrated new assemblies or arrangements of equipment intended to be "of special value in connection with the present trend toward enclosed or cubicle-type equipment and the mounting of such control in remote locations," covering recent developments of several combinations of electrically operated circuit breakers "to provide forward and reverse operation with dynamic braking, performing the same functions as older types of control, but having numerous advantages from the standpoint of installation, maintenance, and especially compactness."

### Iron and Steel Industry

An insight into some of the electrical and related problems in the many ramifications of the iron and steel industry was given through the medium of 3 descriptive papers, all of which were published in the September issue:

Some High Lights in the Use of Electricity in Steel Mills, E. G. Fox (M'20), Freyn Engineering Company, Chicago, Ill.

Carbon Brushes for Steel Mill Equipment, W. C. Kalb (M'15), advertising department, carbon sales division, National Carbon Company, Cleveland, Ohio.

Tension Measurement and Control in Cold Strip Rolling, C. M. Hathaway (A'29), and F. Mohler, mechanical engineers, general engineering laboratory, General Electric Company, Schenectady, N. Y.

In addition to describing some of the more interesting features of steel mill electrification, Mr. Fox pointed out that approximately one-tenth of the investment in the American steel industry is in electric plants, and that the power consumption of steel mills is increasing; that about two-thirds of this power is generated within the plants, but that there is a tendency toward an increased purchase of power. He mentioned also that electric melting furnaces supply a small but growing increment of total steel production; that high-frequency heating is finding some uses; that new types of electric furnaces are being installed for heat treating and annealing operations.

Messrs. Hathaway and Mohler described a device called a "tensiometer" designed for the measurement of the tension in steel strips during rolling in a cold-rolling mill, and for the indication of any difference in tension between the 2 edges of the strip. They reported that "the tensiometer can function in connection with auxiliary control equipment for the automatic maintenance of the total tension to any desired value."

Mr. Kalb discussed problems associated with brush application on commutating types of equipment in the iron and steel industry, in relation to type of equipment and conditions encountered in service; discussed also a newly defined measure of brush performance, termed "commutation factor" which "provides an improved basis for control of the performance characteristics of brushes." He mentioned also the development of electrographitic grades designed to prevent the formation of troublesome surface film on commutators exposed to the contaminating atmospheric conditions frequently encountered in steel-mill applications.

### Steam Turbines

"Some Recent Applications of Steam Turbines in Industrial Plants Showing Upward Trend in Pressures and Temperatures" were described by K. S. Kramer of the South Philadelphia Works of the Westinghouse Electric and Manufacturing Company. Concerned primarily with problems incident to industrial plants where the requirements of steam for processing purposes are of prime importance, Mr. Kramer described typical installations, pointing out that the wide diversity in requirements for process steam had led turbine manufacturers for the past 10 or 15 years to build industrial turbines to special order. He reported that both condensing and noncondensing turbines have "been built for extraction of steam nonautomatically at one or more pressures, and automatically at one or two pressures in addition to nonautomatic extraction. Turbines have been built for induction as well as extraction of steam and, in some cases, extraction at one pressure and induction at another. Inlet pressures may be as low as several pounds; in some instances turbines were supplied with inlet steam at 2 pressures. Most turbines can be designed for initial operation with low pressures and temperatures, and later by minor changes made suitable for efficient operation with much higher pressures and temperatures."

### Railway Electrification

Two different problems incident to railway electrification were covered in papers presented:

The Design and Test of a High-Speed High-Interrupting - Capacity Railway Circuit Breaker, W. F. Skeats (M'36), and H. E. Strang (A'28), both of the General Electric Company, Philadelphia, Pa.

Pennsylvania Railroad Electrification, H. C. Griffith (M'35), electrical engineer, Pennsylvania Railroad Company, Philadelphia, Pa.

Mr. Skeats described and illustrated a circuit breaker designed for 25-cycle 1,500-ampere 15-kv normal service and capable of interrupting a fault current of 65,000 amperes with an over-all short-circuit duration of one cycle. He reported that "being intended for railway trolley service, which is rather severe from the standpoint of frequency of short-circuit operation, it is expected to handle 50 short-circuit operations without internal inspection or change of oil...this breaker operates upon the impulse principle." A spring-driven system forces a blast of oil through a special passageway which causes the oil to sweep directly across the arc path, a departure in design from the earlier breakers which used a "radial" blast of oil. Mr. Skeats described test methods and results.

Mr. Griffith described the scope and character of the main-line electrification project now being actively prosecuted by the Pennsylvania Railroad. Electrified lines now in operation, including the trackage used for suburban service, covers 373 miles of line, involving 1,343 miles of electrified track between New York and Washington, and from Philadelphia to Paoli, Pa., on the main line west. The project now

## Future AIEE Meetings

**Winter Convention**
New York, N. Y., January 24–28, 1938

**North Eastern District Meeting**
Pittsfield, Mass., Spring 1938

**Summer Convention**
Washington, D. C., June 20–24, 1938

**Pacific Coast Convention**
Portland, Ore., date to be determined

**Southern District Meeting**
Miami, Fla., Fall 1938

under way will complete the main-line electrification from Paoli through Lancaster to Harrisburg for passenger service, and various main freight lines east of Harrisburg. This new work will add to the Pennsylvania system some 315 miles of electrified line involving some 773 miles of track. Mr. Griffith reported that "upon completion of the new work, the Pennsylvania Railroad system will have a total of 2,677 miles of electrified track, or 41 per cent of the total electrically operated standard railroad trackage in the entire United States."

### Electrical Machinery

"Single-Phase Induction-Motor Performance" was discussed in mathematical terms by A. F. Puchstein (A'20, M'27) and T. C. Lloyd (A'31) respectively chief engineer and development engineer, Robbins and Myers, Inc., Springfield, Ohio. This paper was published in full in the October issue. In discussing their subject at Akron, the authors reported: "In a search for labor saving methods for predicting the pull-out torque (or its equivalent, the number of primary-winding turns) and the performance curves of the single-phase induction motor from design-sheet data with satisfactory precision, it became necessary to examine as much of the existing literature as could be found" (the work of 25 or more writers on the subject since 1895), and stated that "the present paper was an attempt to reduce greatly the labor of numerical application, while maintaining the accuracy within the limits dictated by modern practice."

"Recent Trends in the Design of Power Transformers" were described and illustrated in some detail by L. H. Hill (A'22, M'29) engineer-in-charge, transformer division, Allis-Chalmers Manufacturing Company, Milwaukee, Wis. Mr. Hill stated that "during the past 15 years ... there have been more changes in power transformer design than in all the years prior to that time." He called attention to such modern trends as improved internal mechanical construction, designing for impulse strength and the related tendency to use dielectric flux control to reduce internal oscillation, and reported a trend toward "increased use of tap changing under load both in straight transformers and in regulating units, increased use of phase-angle control under load, forced-air-blast equipment, inert-gas protection, design for oiltightness, use of large 3-phase units, and multiwinding units."

### Electronics

"Low-Current Ignitors" were described by A. H. Toepfer (A'31) research engineer, Westinghouse Electric and Manufacturing Company, East Pittsburgh, Pa. He outlined briefly the various developments that have grown from the initial work of Slepian and Ludwig incident to the design and operation of the so-called ignitron tube, devoting principal attention to the problem of proper materials and design of the ignitor tip. This paper was published in full in the July issue.

The "Regulation of Grid-Controlled Rectifiers" was discussed at some length by L. A. Kilgore (A'29) and J. H. Cox (A'25) respectively design engineer and section engineer, Westinghouse Electric and Manufacturing Company, East Pittsburgh, Pa. They reported that "this paper discusses several factors which have not been included in the previously published regulation formulas and which should be considered in the practical application of rectifiers. Approximate solutions are given to take into account system reactance and the load inductance." Consideration also is given to the effect of grid pick-up characteristics on regulation, and means of modifying the inherent regulation characteristics by regulators or compensators. This paper was published in full in the September issue.

In discussing "The Igniter-Type Mercury Arc Rectifier as a Power-Conversion Unit," A. Lee Barrett, Pittsburgh Coal Company, Pittsburgh, Pa., reviewed briefly the changes since 1930 in coal-mining operations which have changed materially the problems of electric power supply. Strong tendencies toward mechanization, toward concentration of actual mining operations in smaller areas within a given mine, and toward multiple-shift operations have had at least 2 important effects upon requirements for electric supply: first, increasing the electric load at the working faces from the earlier total of about 25 per cent of the total mine load to the present figure of from 50 to 60 per cent of the total mine load; second, requiring more frequent relocation of underground substations. He reported some economic and mechanical details incident to recent and projected installations of underground rectifier substations of the igniter or multiple-tank type, stating that these "would seem to provide the mining industry with a substation no more expensive than contemporary substations. . . much more portable . . . efficiency is substantially better than anything heretofore available."

The use of "Mercury Arc Rectifiers in Chlorine Production" was described and explained by L. J. Rimlinger, chief electrical engineer, Columbia Chemical Company, Barberton, O. Mr. Rimlinger described a 7,000-kw 500-volt d-c rectifier installation recently placed in operation involving 2 2,000-kw 12-anode double-6-phase units each connected to an individual supply transformer, and one 3,000-kw unit involving 2 tanks operating on one transformer, 12 anodes each, and double-6-phase. To meet the requirements of electrochemical service he explained that "mercury arc rectifiers were selected for converting equipment because of their low operating cost, high efficiency, and their suitability in corrosive atmosphere."

### Lightning Versus Power Transmission

Lightning still is given a prominent position in discussions pertaining to electric power transmission. Three of the Akron papers dealt directly with this subject.

"Lightning-Proof Transmission Lines" of the Pennsylvania Water and Power Company were described by Edwin Hansson (A'19, M'35) and A. F. Bang (A'11) respectively transmission engineer and superintendent of operation for that company. The method of lightning protection described "consists of the proper combination of overhead ground wires, low tower-footing resistances obtained by means of a counterpoise, and ample insulation. Its successful application is illustrated by operating records . . . Performance of any given line can be predicted if the tower-footing resistances are known." Theory of protection outlines: "(1) that overhead ground wires must be placed so as to shield the conductors completely from direct strokes, thus eliminating flashovers from conductor to tower; (2) that the ground wires and towers must be so connected to earth that the current from the lightning stroke will be drained off without raising the potential of the structure to a value which will cause a flash from tower to conductor." Results cited: (1) 5 years operation of a 92-mile single-circuit 230-kv line with one lightning operation; (2) 3 years' operation of a 4-circuit 32-mile 132-kv line with no lightning operation; (3) $1\frac{1}{4}$ years' operation of a 2-circuit 23-mile 69-kv line with no lightning operation; "all lines located in severe lightning territory . . . average storms per year respectively, 62, 42, 39." This paper was closely related to a paper by S. K. Waldorf (A'27, M'36) test engineer of the same company, "Probable Outages of Shielded Transmission Lines," published in the May 1937 issue.

In discussing "Lightning Strokes in Field and Laboratory," P. L. Bellaschi (A'29, M'34) section engineer in charge of transformer engineering, Westinghouse Electric and Manufacturing Company, Sharon, Pa., concerned himself principally with the fundamental aspects of the problem, particularly with the characteristics of the lightning-stroke channel. He gave data and findings revealing further the nature of the channel core and of the resulting column, and submitted field observations for comparison purposes. This paper was published in full in the October issue.

"Cross-Catenary Transmission Lines for Lightning and Fog Conditions" were described by A. O. Austin (A'04, F'25) consulting and manufacturing engineer, Barberton, Ohio. Mr. Austin discussed 2 methods of achieving electrical reliability against lightning interruption: "In one method the ratio of the arcing voltage to the impedance in the lightning-diverting path constitutes the index of reliability where the line is equipped with ground wires. In the second case the high arcing voltage together with the limitation of current due to high ground resistance or other means produces a high resistance in the path to ground and prevents the follow-up of normal-frequency current." He further states that: "The ease of obtaining a high arcing voltage to ground with the cross-catenary type of construction makes it possible to develop either type to its maximum. The very high arcing voltage to ground with limited insulation between phases results in smaller structures and lower cost for a given standard. The double insulation in the cross-catenary construction provides a high degree of reliability not possible with single insulation. . . . The relative advantage is appreciable at lower voltages, but increases materially with the voltage. Clearance between phases or between conductors and ground which would be prohibitive with the usual types of construction can readily be obtained with the cross-catenary type. The development of low-capacitance high-voltage radio strain insulators removes the previous electrical and mechanical limitations of insulation for the cross span." Mr. Austin cited the "wide use of guyed cross-catenary construction for the Penn-

## Membership—

Mr. Institute Member:

The coming winter activities in national, District, and local groups will provide you with a strong appeal to your fellow workers when you speak to them about AIEE membership. An invitation to participate with you in these meetings and other affairs, when permissible, should prove helpful in creating a better understanding of Institute aims and activities. If one or more of your associates should indicate an interest in joining, and if you feel he or they would make desirable members, please let your membership committeeman know about it.

C. M. Foust

Vice-Chairman, District No. 1
National Membership Committee

sylvania Railroad for its recent electrification" as showing "a growing trend toward the use of the cross-catenary construction."

### D-C Transmission

"Possibilities of Direct-Current Power Transmission Using Electrically Controlled Rectifiers and Inverters," were discussed by O. K. Marti (A'21, M'27), engineer in charge of rectifiers and railway equipment, Allis-Chalmers Manufacturing Company, Milwaukee, Wis. He outlined some of the problems of power system stability; he stated that "from preliminary considerations it would appear that these difficulties in transmitting power would be overcome if direct current were used, and it therefore seems justifiable to look carefully into the possibility of transmitting power by means of direct current. This is particularly true since it appears to be possible by means of the latest development of the grid-controlled electric power valve to convert a-c power to d-c at high-voltage, for d-c transmission, and invert the d-c power back into a-c of any desired frequency and voltage, without great cost and with little loss of power." He reported briefly the high lights of 30 years of operating experience with the 275-mile 125-kv d-c transmission system between Mougiers and Lyon, France, in connection with which were put into practical application the original development of Rene Thury, the Swiss consulting engineer, who is generally regarded as the father of d-c high-voltage transmission.

Mr. Marti stated that "it seems now that the argument between the proponents of direct and alternating currents will again be revived. The principal reason for this is the fact that the electronic power valve has reached a stage of development where it can be employed without difficulty to handle the high voltages and currents coming into consideration for the commercial transmission of electric power."

### Student Program

More than 130 electrical-engineering students—nearly a third of all those attending the Akron meeting—contributed to the effectiveness of the general program and themselves held a technical session that drew not only full attendance from their own group, but also a good many practicing engineers from the general session that was held in parallel. General arrangements for the students' participation in the program were under the direction of J. T. Walther (A'19, M'26) professor of electrical engineering, and counselor of the Student Branch at the University of Akron, and past-chairman (1924–25) of the Akron Section.

The 6 papers presented on the student technical session program were as follows:

Measurement of Reverberation Time with the Cathode-Ray Oscillograph, H. W. Lensner, Case School of Applied Science.

We, The Students, Nelson A. Powell, Ohio University.

Pressure Insulated Conductor for High-Voltage Transmission, J. B. Adams, Jr., Johns Hopkins University.

The Telephone Inverter, Frank Andrix, Ohio State University.

An Engineer's Training, A. H. Graham, West Virginia University.

Saturable Core Reactor, Robert F. Miller, University of Akron.

Subsequent to the technical session, the chairmen and the student counselors of the various Student Branches in the Middle Eastern District gathered in separate groups for conferences and an exchange of ideas concerning the effective conduct of Student Branch activities. Following these conference group meetings, a general luncheon of the 2 groups was held, supplemented by others interested in student affairs including President W. H. Harrison, National Secretary H. H. Henline, Past-President A. M. MacCutcheon, Past-Chairman O. W. Eshbach of the AIEE committee on education, and Editor G. R. Henninger. Actions reported at this meeting included:

1. Decision to hold 1938 student conference at Bucknell University, Lewisburg, Pa.; date to be announced later.

2. Selection of Doctor A. C. Seletzky, faculty counselor of the Student Branch at Case School of Applied Science, Cleveland, as chairman of the District committee on student activities, for the year beginning August 1, 1938.

3. Selection of Professor J. T. Walther to serve as the District student-counselor representative at the 1938 summer convention in Washington, D. C.

Asked for a "few remarks," President Harrison spoke briefly but forcefully and effectively on the subject "Minding Our Own Business." The theme of his brief address was to the effect that the important engineering requirements of the modern world can be met best by seasoned engineers having a broad background of experience. He urged engineering students to give primary attention to the acquisition of a sound and fundamental technical training, rather than to be led too far afield into other subjects during student days.

### Inspection Trips and Entertainment

The variety of important industrial activities to be found in the vicinity of Akron afforded excellent opportunities for interesting and instructive inspection trips.

The principal event was the all-afternoon-and-evening trip to Nela Park, Cleveland, where some 300 of those attending the meeting were the guests of the General Electric Company. The program included escorted tours through the laboratories devoted to the experimental development and manufacture of electric lamps of various sizes, demonstration lectures on commercial and industrial illumination for the men and on home economics and illumination for the women, a generous dinner, and as a finale a demonstration lecture in the auditorium of the General Electric Institute covering briefly the evolution of illumination and some of the major contributions made by scientific research.

Another general event, heavily-attended was an evening trip to the Daniel Guggenheim Airship Institute where men and women alike enjoyed the inspection and demonstration of the vertical wind tunnel and its 110-mile-per-hour blast, various equipment for the pursuit of aeronautical research, and small-scale test models of dirigible aircraft. Although originally founded for research in the field of lighter-than-air craft, the Guggenheim Institute is now using available time and facilities for research in other suitable fields, such as mine ventilation as reported by Director Troller at one of the technical sessions.

A large group interested in power-plant equipment took advantage of the opportunity to visit the Barberton plant of the Babcock and Wilcox Company where the various fabrication processes incident to the manufacture of boilers, pulverized-coal equipment, and other power-plant equipment were witnessed in full swing under shop conditions. Of particular interest were the large and extremely heavy boiler drums being manufactured for new power plants where new levels of high pressures and temperatures are being pioneered.

A large crowd likewise attended the all-afternoon trip through the Barberton plant of the Ohio Brass Company, where the many steps in the manufacture of porcelain insulators of various types were followed through from their beginnings in raw material to their finishing, high-voltage testing, and packing into crates for shipment. The afternoon's program was topped off by a demonstration of the high-voltage labora-

tory equipment, featuring both commercial testing and some of the more spectacular high-voltage phenomena.

Automobile tire manufacture was followed through from crude rubber to finished product by a group that enjoyed the hospitality of the B. F. Goodrich Company. Various other special trips were arranged for other groups.

The women in attendance were generously provided for in the special features of the entertainment program. In fact, they were kept quite busy with a program starting with a guest luncheon Wednesday noon and providing a continuous series of activities that ended only with the concluding general banquet, Friday evening. The progam included an afternoon garden pilgrimage through the estates of F. A. Seiberling and L. A. Laurson, games and luncheon at the Portage Country Club, inspection of the Akron Air Dock and guest excursion on one of the Goodyear blimps, and a bridge-tea at the home of Mrs. A. O. Austin in Barberton.

### Commander Rosendahl Defends Dirigibles

Commander C. E. Rosendahl of the United States Navy, widely renowned for his pioneering efforts and leadership in the field of air navigation, spoke at the banquet on the subject "Lighter-Than-Air Craft." Commander Rosendahl carried all in the crowded banquet room along with him as he described and explained some of the more important features of lighter-than-air craft, and outlined his opinion of their inevitable and vitally important place in the field of modern transportation. He drew a convincing word picture of such craft in what he strongly termed "proper place"—as an important adjunct to other modes of transportation in the air and on the land and sea, and in both commercial and naval use.

In commercial transportation, Commander Rosendahl pictured the dirigible airship as a logical mode of long-distance high-speed travel, particularly on transoceanic routes where their "pay load" capacity and their long-range cruising ability he considers as already well-demonstrated by the world tour of the "Graf Zeppelin" and the long service of such craft in trans-Atlantic commercial service between Germany and South American ports. He emphatically assigned the "Hindenburg" disaster to the inflammability of hydrogen rather than to any defect in craft or handling. He stated that by its ability to maintain a continuous day and night air speed of about 85 miles an hour the modern dirigible aircraft could cross the Pacific in 4 days whereas the heavier-than-air craft now in that service require 6 days because of the necessity for intermittent flying and in spite of their higher speed when in the air.

For naval service, Commander Rosendahl considers the dirigible airship to be a vital part of the intelligence and scouting service, leaving the fighting to be done by planes and surface crafts better fitted for that service. The commander's talk was thoroughly understandable and well received.

### District Executive Committee Meeting

The Middle Eastern District executive committee met in Akron, Saturday morning, October 16, following the District meeting, for a busy session involving a wide range of matters incident to District affairs and activities. Attendance at the meeting was recorded as follows:

I. Melville Stein, vice-president AIEE, presiding
H. A. Dambly, District secretary
M. W. Smith, District vice-chairman, membership committee
L. S. Billau, chairman, Baltimore Section
J. A. Noertker, chairman, Cincinnati Section
F. E. Harrell, chairman, Cleveland Section
W. L. Everitt, secretary, Columbus Section
W. D. Bearce, secretary, Erie Section
E. F. De Turk, chairman, Lehigh Valley Section
J. B. Harris, Jr., chairman, Philadelphia Section
W. A. Furst, secretary, Pittsburgh Section
H. S. Smith, chairman, Sharon Section
H. R. Daykin, secretary, Toledo Section
A. G. Ennis, representing Washington Section

## Wichita Section Holds First Meetings

The organization meeting of the AIEE Wichita Section, authorized by the Institute's board of directors on June 24, 1937, was held September 16, 1937, at Wichita, Kans., with an attendance of 17. By-laws were adopted, and R. R. Miner (A'30) electrical engineer for the Kansas Gas and Electric Company, and W. A. Wolfe (A'30, M'36) relay engineer for the same company, were elected chairman and secretary-treasurer, respectively, to serve until August 1, 1938. Other members of the executive committee are E. E. Powell (A'37), G. LeRoy Quigley (A'32), and J. A. Rupf (A'33).

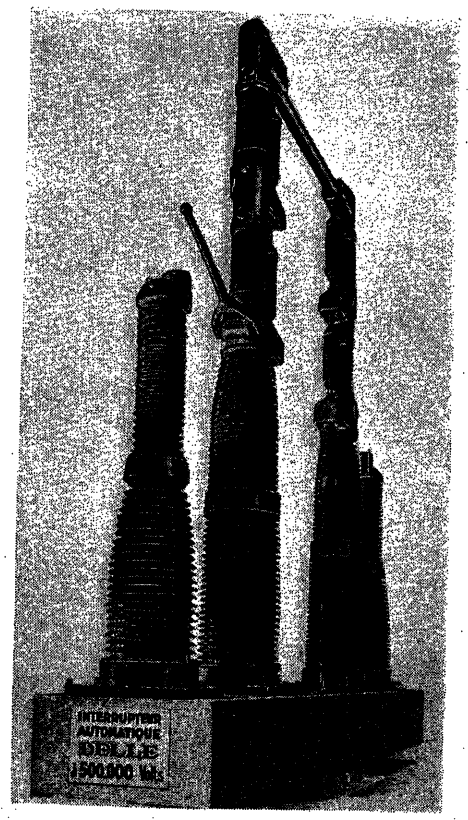
On September 30 a dinner meeting was held with 34 members and guests present. Doctor W. M. Jardine, president of the University of Wichita and former Secretary of Agriculture, was toastmaster, and speakers included L. T. Blaisdell (A'20, M'22) AIEE vice-president, whose subject was "The AIEE and the Electrical Engineering Profession."

Section committee chairmen are H. E. Margrave (A'37) membership; P. S. Colby (A'37) meetings and papers, and R. B. Gow (A'35) arrangements.

**Former Edison Secretary Dead.** At the age of 84, W. H. Meadowcroft, former secretary to Thomas A. Edison, died October 15, 1937, at his home in Boonton, N. J. Mr. Meadowcroft was born in Manchester, England, May 29, 1853, where he received his common and high school education. He came to the United States in 1875, and for the succeeding 6 years he was employed by the law firm of Carter and Eaton in New York City, being admitted to the New York bar in 1881. In that year he became affiliated with the Thomas A. Edison enterprises, and from 1910 until Edison's death in 1931 he was assistant and confidential secretary to Mr. Edison. Mr. Meadowcroft was founder and historian of the Edison Pioneers, of which organization he served as president in 1927. He was honorary vice-president of the Thomas Alva Edison Foundation, Inc., which was established in 1935 for the purpose of creating a living tribute to the inventor. He was the author of several books.

**Training of Skilled Workers.** A recent survey by the National Industrial Conference Board indicates that 4 out of every 5 companies have adopted some form of training for industrial work in order to meet present and future needs for skilled workers. The results of the board's survey, which included 473 companies in various industries and in different sections of the United States, are presented in a report, "Training for Industry." This report shows that training on the job is the method generally used, only 8.5 per cent of the companies surveyed maintaining so-called vestibule schools. Systematic apprentice training is reported by 272 companies, the time required ranging from one week to more than 5 years. Compensation is shown to be at least 50 per cent of the regular rate in over 90 per cent of the companies surveyed, and 80 per cent of the regular rate in about 32 per cent of the companies. Training is given to mature persons and regular employees as well as to youths and beginners, but in most companies not to persons under 18. Women as well as men are offered training opportunities in some companies.

## Large Circuit Breaker Exhibited at Paris Fair



CONSTRUCTED by Ateliers de Constructions Electriques de Delle, Villeurbanne, France, the circuit breaker and disconnecting switch shown here is being exhibited in the Palace of Light of the International Exposition of Paris. This unit, said to be the largest in the world, is designed for operation at 500 kv at 500 amperes and has an interrupting capacity of 5,000,000 kva.

# Nomination of AIEE Officers for 1938 Election; Members' Suggestions Invited Until December 15

FOR the nomination of national officers to be voted upon in the spring of 1938, the AIEE national nominating committee will meet during the winter convention, January 24–28, 1938. To guide this committee in performing its constituted task, suggestions from the membership are, of course, highly desirable. To be available for the consideration of the committee, all such suggestions must be received by the secretary of the committee at Institute headquarters, not later than December 15, 1937.

In accordance with the provisions in the constitution and by-laws, as amended during 1935 and quoted in the following paragraphs, actions relative to the organization of the national nominating committee are now under way.

**Constitution**

28. There shall be constituted each year a national nominating committee consisting of one representative of each geographical district, elected by its executive committee, and other members chosen by and from the board of directors not exceeding in number the number of geographical districts; all to be selected when and as provided in the by-laws. The national secretary of the Institute shall be the secretary of the national nominating committee, without voting power.

29. The executive committee of each geographical district shall act as a nominating committee of the candidate for election as vice-president of that district, or for filling a vacancy in such office for an unexpired term, whenever a vacancy occurs.

30. The national nominating committee shall receive such suggestions and proposals as any member or group of members may desire to offer, such suggestions being sent to the secretary of the committee.

The national nominating committee shall name on or before January 31 of each year, one or more candidates for president, national treasurer, and the proper number of directors, and shall include in its ticket such candidates for vice-presidents as have been named by the nominating committees of the respective geographical districts, if received by the national nominating committee when and as provided in the by-laws; otherwise the national nominating committee shall nominate one or more candidates for vice-president(s) from the district(s) concerned.

**By-Laws**

SEC. 22. During September of each year, the secretary of the national nominating committee shall notify the chairman of the executive committee of each geographical district that by December 15 of that year the executive committee of each district must select a member of that district to serve as a member of the national nominating committee and shall, by December 15, notify the secretary of the national nominating committee of the name of the member selected.

During September of each year, the secretary of the national nominating committee shall notify the chairman of the executive committee of each geographical district in which there is or will be during the year a vacancy in the office of vice-president, that by December 15 of that year a nomination for a vice-president from that district, made by the district executive committee, must be in the hands of the secretary of the national nominating committee.

Between October 1 and December 15 of each year, the board of directors shall choose 5 of its members to serve on the national nominating committee and shall notify the secretary of that committee of the names so selected, and shall also notify the 5 members selected.

The secretary of the national nominating committee shall give the 15 members so selected not less than 10 days' notice of the first meeting of the committee, which shall be held not later than January 31. At this meeting, the committee shall elect a chairman and shall proceed to make up a ticket of nominees for the offices to be filled at the next election. All suggestions to be considered by the national nominating committee must be received by the secretary of the committee by December 15. The nominations as made by the national nominating committee shall be published in the March issue of ELECTRICAL ENGINEERING (Journal of AIEE), or otherwise mailed to the Institute membership not later than the first week in March.

INDEPENDENT NOMINATIONS

Independent nominations may be made in accordance with provisions in Section 31 of the constitution and Section 23 of the by-laws, which are quoted below:

**Constitution**

31. Independent nominations may be made by a petition of twenty-five (25) or more members sent to the national secretary when and as provided in the by-laws; such petitions for the nomination of vice-presidents shall be signed only by members within the district concerned.

**By-Laws**

SEC. 23. Petitions proposing the names of candidates as independent nominations for the various offices to be filled at the ensuing election, in accordance with Article VI, Section 31 ( constitution), must be received by the secretary of the national nominating committee not later than March 25th of each year, to be placed before that committee for the inclusion in the ballot of such candidates as are eligible.

On the ballot prepared by the national nominating committee in accordance with Article VI of the constitution and sent by the national secretary to all qualified voters during the first week in April of each year, the names of the candidates shall be grouped alphabetically under the name of the office for which each is a candidate.

(*Signed*) H. H. HENLINE,
November 1, 1937 *National Secretary*

# Lehigh Valley Section Sponsors Joint Meeting

An engineers' dinner meeting, attended by more than 400 persons, was held at the Jermyn Hotel, Scranton, Pa., October 9, 1937, under joint sponsorship of the AIEE Lehigh Valley Section, the local sections of the American Institute of Mining and Metallurgical Engineers, and The American Society of Mechanical Engineers, and the chambers of commerce of Scranton, Wilkes-Barre, Hazleton, and Pottsville. A report of the meeting was made available by W. H. Lesser (M'24) of J. H. Pierce and Company, Scranton, a past-chairman of the Lehigh Valley Section, who was chairman of the committee on arrangements and who also acted as toastmaster and presiding officer at the meeting.

Following the dinner those attending heard 3 addresses; 2 speakers dealt with the anthracite coal industry, one of the chief industries of the Lehigh Valley Section, and the other was concerned with one phase of the electrical industry. In the first talk of the evening Philip Sporn (A'20, F'30) vice-president and chief engineer of the American Gas and Electric Company, New York, N. Y., outlined broadly, yet using some specific examples to illustrate his assertions, the operation of electric power systems on an interconnected and co-ordinated basis. He stated that "the development of the electric utility systems of the United States on an interconnected and co-ordinated basis has resulted in giving the United States a preeminent position in the field of electric power supply." In the next address, Cadwallader Evans, Jr., vice-president and general manager of the Hudson Coal Company, Scranton, spoke on "Looking Ahead in Anthracite," outlining some of the operating problems in the coal-mining industry and sketched its future as it appears today. The latest efforts of the anthracite industry to promote the sale of its product were described by the third speaker, Frank W. Earnest, Jr., president of Anthracite Industries, Inc., New York, N. Y. He emphasized the improved competitive position of the anthracite industry, and painted a bright picture of the future of that business. This was the second of 2 such jointly sponsored meetings, the first having been held in October 1935 at Wilkes-Barre, Pa.

# Winter Convention to Include General Session

Because the "general session" held during the Institute's 1937 summer convention at Milwaukee, Wis., evoked so much interest, a somewhat similar session is being arranged for the forthcoming 1938 AIEE winter convention to be held in New York, N. Y., January 24–28. According to present plans, a speaker of national repute will address the session on a subject of broad interest to the engineering profession, and to electrical engineers in particular. A special committee to make the necessary arrangements for the session has been appointed consisting of the following: H. S. Bennion, C. R. Beardsley, L. W. W. Morrow, H. S. Osborne, and W. E. Wickenden.

Although the technical program is still in the formative stage, sessions on the following subjects are tentatively scheduled: electronics, communication, electrical machinery, power transmission and distribution, protective devices, transportation, instruments and measurements, education, electric welding, research, and basic sciences. In addition, several technical conferences are expected to be held; 3 such conferences already have been tentatively scheduled, one on active networks under sponsorship of the committee on communication, and 2 under sponsorship of the committee on basic sciences.

Details concerning these and other features of the convention program will be included in a later issue of ELECTRICAL ENGINEERING.

**New ASTM Standards.** At a recent meeting of committee *E*-10 on standards of the American Society for Testing Materials, 11 new tentative standards were recommended. Among these were the following, covering specifications and test methods for electrical materials:

1. SPECIFICATIONS FOR PHENOLIC LAMINATED SHEET FOR RADIO APPLICATIONS (*D* 467–37 *T*).
2. METHOD OF TESTING PIN-TYPE SODA-LIME GLASS INSULATORS (*D* 468–37 *T*).
3. METHODS OF TEST FOR RUBBER INSULATED WIRE AND CABLE (*D* 470–37 *T*).

# Fifth Annual Meeting of ECPD Held; Accrediting of Engineering Curricula Extended

THE fifth annual meeting of Engineers' Council for Professional Development was held October 1, 1937, in the Engineerng Societies Building, New York, N. Y. Election of officers, appointment of committees, and presentation of the annual reports of Council's committees constituted the principal items of business. Council approved the accrediting of additional curricula in engineering schools, as recommended by the committee on engineering schools, making a total of 442 curricula now accredited in 127 institutions (see tabulation elsewhere in this report).

Excerpts from the complete reports of the committees on student selection and guidance, professional training, and engineering schools follow the item on election of officers and appointment of committees; the report of the committee on professional recognition was held over as an order of business for a later meeting of ECPD executive council, and was referred back to the committee for further consideration.

Chairman Chas. F. Scott (A'92, F'25, HM'29, past-president) in opening the meeting presented a prepared review of ECPD's activities to date, calling attention to its principal objectives and outlining various possibilities for increased effectiveness of ECPD's efforts as a joint agency for the engineering societies. "Supplementing 'general objectives' in our charter," said Doctor Scott, "is an 'immediate objective'—the development of the young engineer for some 10 years from high school to professional recognition. It is in several stages. In the pre-freshman stage ECPD is to present 'the responsibilities and opportunities of engineers'; in engineering schools it is to 'formulate... a sound educational foundation for the practice of engineering'; and after graduation it is to 'further personal and professional development of young engineering graduates.' "

## Elections and Appointments Reported

Chas. F. Scott, professor of electrical engineering emeritus, Yale University, was re-elected ECPD chairman. A. B. Parsons, secretary of the American Institute of Mining and Metallurgical Engineers, was elected secretary, and C. E. Davies, secretary of the American Society of Mechanical Engineers, was re-elected assistant secretary of Council. Chairmen of 3 ECPD committees were re-elected as follows: student selection and guidance, R. L. Sackett, dean emeritus of college of engineering, Pennsylvania State College; engineering schools, Karl T. Compton (F'31), president, Massachusetts Institute of Technology; and professional recognition, C. N. Lauer, president, Philadelphia (Pa.) Gas Works. O. W. Eshbach (A'17, F'37) American Telephone and Telegraph Company, New York, N. Y., was appointed chairman of the committee on professional training; he has served as acting chairman since the death of General R. I. Rees, former chairman of the committee.

Executive committee members reappointed were: J. P. H. Perry, representing the American Society of Civil Engineers; C. F. Hirshfeld (A'05, F'36) representing the American Society of Mechanical Engineers; L. W. W. Morrow (A'13, F'25, director) representing the AIEE; H. C. Parmelee, representing the American Institute of Chemical Engineers; and D. B. Steinman, representing the National Council of State Boards of Engineering Examiners. Members newly appointed to the executive committee were: D. C. Jackson (A'87, F'12, past president) representing the Society for the Promotion of Engineering Education [alternate R. E. Doherty (A'16, M'27)]; and W. B. Heroy, representing the American Institute of Mining and Metallurgical Engineers.

Appointments of representatives of the participating societies for the 3-year term 1937–40 were announced as follows: ASCE, J. P. H. Perry (reappointment); ASME, A. R. Stevenson, Jr. (reappointment); AIME, W. B. Heroy; AIChE, B. F. Dodge; SPEE, R. E. Doherty; AIEE, F. Ellis Johnson; NCSBEE, J. S. Dodds.

## Report of Committee on Professional Training

O. W. Eshbach, Acting Chairman

The untimely death, during the past year, of the chairman, General R. I. Rees, seriously affected progress toward the objectives expressed in previous reports. His full time activity being essential to the realization of the year's program, it became necessary to adjust the work of the committee to more restricted projects.

The program recommended in the 1936 report may be simply expressed in terms of 3 general objectives.

1. To prepare and distribute information which would stimulate and assist junior engineers in self-development.

2. To give assistance in local organization of juniors so as to provide means of achieving their objectives.

3. To study the desires and needs of younger engineers as their activities develop and ideas crystallize, so that additional efforts can be made most effective.

While substantial progress has been made in the first 2 objectives, not much has been achieved in obtaining a better understanding of future needs. By nature, this is a continuing problem, varying in time and locality. It requires an accumulation of experience and the constant attention of the committee as local activities develop.

*Local Organizations and Activities.* At the 1936 annual meeting, the committee considered as its second major undertaking for 1936–37 the stimulation of programs similar to that at Providence in an increasingly large number of centers, having local sections of the constituent bodies and junior engineers form the basis of operations. The success of the Providence trial organization, which has continued its activities during the past year and reports of their experience given wide circulation, prompted General Rees to plan a trip in October and November, 1936, to Cleveland, Chicago, St. Louis, Detroit, and Pittsburgh to discuss the development of junior programs in these areas. Plans were interrupted by his sudden death in Detroit, on November 23. Through the voluntary assistance of Doctor C. F. Hirshfeld, joint meetings with representatives of local engineering societies and the national societies were held in both Detroit and Chicago, completing the itinerary. As a result of these visits, active organization work has been undertaken and plans are in progress for this fall to initiate further progress in junior activities. In addition to the activities started by General Rees, junior committees have been formed in Hartford and Boston and are being considered by the Worcester Engineering Society.

During the spring and summer the committee has been studying the trend of junior organization developments. From reports of the participating societies and other sources, it was found that some form of junior organization, sponsored either jointly or separately by local sections of the national societies, was in existence or being formed in 39 localities.

While recent in origin most of these organizations have come about through the normal activities of the sections of national societies. In most cases they are sponsored by a single society but include in their membership juniors of other affiliations. The spontaneity of these developments is encouraging. They present opportunities for co-operation which should be considered jointly by the sections in the several localities.

*Principles of Organization of Local Activities.* The principal objective of local organization has been to afford opportunity for personal development in accord with the ideals set forth by the ECPD. The general and sequential procedure in starting junior activities has been as indicated in many letters and reports as follows:

1. The selection of experienced engineers of the community who have expressed interest and willingness to act as advisors and a group of junior engineers representative of different professional interests.

2. Effecting an organization of juniors which gives opportunity for them to frame their own ideas as to the form it takes.

3. Encouraging the development of a serious and effective program of activity consistent with the wishes of the group and the ideals of the purpose.

While this general statement typifies the procedures followed, the initiation by the advisors or originators may come in 3 different ways.

1. Local engineering clubs may sponsor the junior organization through representatives of their professional divisions and thus effect co-ordination with the section activities of the national engineering societies.

2. Representatives of the several sections of the national societies may undertake to start and co-ordinate junior activities by forming a special joint activity or junior advisory committee.

3. The sections of national societies may act independently and not concurrently.

The first 2 ways have the advantage of co-ordination in programs of social and pro-

fessionally common interests. The last has the advantage of flexibility and speed in getting underway but the disadvantage of lack of co-ordination in matters of common interest and united effort toward the stimulation of professional unity.

In whatever manner these organizations originate it seems desirable that they should be the accomplishment of local sections of the constituent bodies of ECPD and that the committee on professional training should aim to give the constituent bodies such assistance as necessity requires and is reasonable to provide. In this connection there is at present no common committee organization within local sections, and no common classification of membership which together with reasonably uniform section areas would greatly enhance the opportunity for local and national co-operation.

*Junior Committee Recommendations.* The annual report of the junior committee in 1936 stresses as important problems:

1. Stimulation of junior interest in the entire ECPD program.
2. Organization of groups in local areas.
3. Development of training material.
4. Development of means of qualifying for professional recognition.

During the year progress has been made by ECPD in the first 2 problems. During the coming year the committee on professional training plans to study the junior programs now in progress and give attention to such needs as are in evidence.

*Publications and Their Distribution.* Since the organization of ECPD the committee on professional training has prepared and published the following pamphlets, among others:

"Suggestions to Junior Engineers." A personal appraisal blank to assist in planning a definite program of development; supplemented by a nontechnical reading list, classified under 10 general subjects.

"Selected Bibliography of Engineering Subjects." A selection of widely recommended texts, mostly of college grade, prepared with the co-operation of over 100 practicing engineers and teachers in 1937:

I. Mathematics, mechanics, and physics
II. Aeronautical and civil engineering
III. Chemical and industrial engineering
IV. Electrical and mechanical engineering
V. Metallurgical and mining engineering

"University Extension Facilities." A list of 24 institutions with description of nontechnical courses given by class study or by correspondence. Prepared by the junior committee in 1935.

During the past year considerable effort was spent in the final editing of the "Selected Bibliography of Engineering Subjects" and its distribution. Copies were sent to all who co-operated in its preparation, the deans of engineering schools, selected publishers of trade magazines, and librarians. The listing of all ECPD publications in the sections of the bibliography was called to the attention of the recipients with the purpose of affording teachers and others the opportunity of directing the attention of students to the interest of the profession in their development, and expediting individual efforts in organizing programs of self-development after graduation. Thus there have been made available at nominal fees an aid for self-analysis, references for both cultural and technical study, and suggestions of study facilities through university extension. To further publicize the program of Council and emphasize the need for continued development, the committee has prepared a small folder, appendix *C*1, and recommends a wide distribution of it to fill the need which has been felt for a short account of the organization, purpose, plans and accomplishment of ECPD. The reprinting of selected articles, both by ECPD and in engineering magazines, is also recommended to aid in reports of progress and better understanding of aims and activities. In this connection 2 articles were reprinted by the committee and several appeared in national societies' publications. A particularly well-prepared article on "The Providence Experiment in Junior Engineers' Development" was reprinted from *Chemical and Metallurgical Engineering*, volume 44, March 1937, and distributed through the national societies to the sections of their societies. It is hoped that as progress in other localities is reported the details of their experiences may be publicized in similar manner.

## Report of Committee on Student Selection and Guidance

R. L. Sackett, Chairman

*English and Mathematics Tests.* The study of the academic history of entering engineering students who were given the co-operative tests in English and mathematics in 1933 and 1934 has been continued. Results noted in previous reports are confirmed by the evidence from the 12 institutions giving the tests. Of those students who discontinued, the larger proportion dropped out voluntarily because of dissatisfaction with themselves, lack of finances, or other conditions. It is safe to say that some had little or no effective guidance and if they had received good counsel, would not have undertaken an engineering education. Scholarship, sound objectives, the will to win, or other qualifications were lacking. The English and mathematics tests indicated that these individuals were invariably low grade for educational refinement. That the lack of the scholarship which is required for reasonable success in engineering education can be detected by such tests, or others, or by examination of the high-school record, is beyond dispute.

*Engineering: A Career—A Culture.* The more general use of the pamphlet of this title is a source of satisfaction. The subcommittee has revised the material and is prepared to submit a copy for a new and improved edition as soon as the present one is exhausted.

*Guidance Manual.* The "Manual on Guidance," prepared by the committee, is being used increasingly and is helpful to the committees of engineers, to colleges, and to high schools. It has been mimeographed and distributed, without charge, to those vitally interested.

*High-School Guidance.* A notable increase in interest in the subject of guidance for high-school students has been observed. Articles in magazines and in the daily press are evidence of the growing appreciation of the economic and social importance of sound vocational counsel.

*Selection by the College.* To cull some 20,000 prospective engineering freshmen from hundreds of thousands of seniors, in thousands of high schools, for entrance to 150 engineering schools, is a mighty task. Upon it, however, depend the careers of individuals, the efficacy of engineering schools, the quality of the engineering profession, and its contribution to the interest of the general public. The usefulness of the engineer depends on personality as well as technical proficiency.

The increase in college enrollments has brought financial and social problems of grave importance.* Limiting enrollments has been suggested but no generally accepted basis for restriction has yet been found. Various methods have been used, such as college board examinations and batteries of training and aptitude tests. There is no doubt that limiting enrollment in engineering to those of high scholastic standing, judged by the 4-year high- or preparatory-school record, is distinctly helpful.

In order to assist in better precollege guidance, engineering schools have been urged to use their influence and faculties in promoting better guidance in the high schools within their spheres of influence.

*Guidance by Engineering Societies.* The national engineering societies have been urged to organize local committees of interested engineers who approach the public-school authorities and offer their services as counselors to students who are interested in engineering. The purpose is to bring the student into closer contact with the realities of engineering education and the practical work which the engineer does—especially the young engineer. Among the cities which have made a notable success of such joint efforts are Detroit, Denver, Milwaukee, Kansas City, Rochester, and St. Louis.

*Selective Tests.* Search, experiment, and evaluation of tests suitable for extracting aptitudes of importance in the prospective engineering student are being conducted by various psychologists and committees. The validity has not yet been established or the committee has not yet had data submitted to it to establish the value of new tests or small groups of tests. That tests of value have been or will be established is beyond doubt. That they may be of great assistance in guidance and selection is equally certain. But discretion in their use and judgment are also necessary in their application. A large measure of responsibility will still rest on those using tests to evaluate personal qualities which tests cannot be expected to expose, at least in the present state of the art.

*Guidance in Public Schools.* City schools are organizing public programs followed by personal counsel for those desirous of entering one of the professions. The majority of the better high schools have counselors and are developing guidance for those thinking of engineering or other vocations. In some of them there is a definite need for an experienced approach to the subject. This, the practicing engineer can supply if he has the interest and an understanding of what youth needs in the way of information about the demands made on the novitiate and the later rewards. More emphasis should be placed on interests, aptitudes, ambitions, and personal qualities and less on "how much does it pay?"

* W. M. Kotschnig, *The Educational Record*, July 1937.

# List of Undergraduate Curricula of Educational Institutions Accredited by ECPD

(As of October 1, 1937, and subject to continual revision)

**University of Alabama:** Aeronautical, civil, electrical, industrial, mechanical, mining

**University of Arizona:** Civil, electrical, mechanical, mining

**University of Arkansas:** Civil, electrical, mechanical

**Armour Institute of Technology:** Chemical, civil, electrical, mechanical

**Brown University:** Civil, electrical, mechanical

**Bucknell University:** Civil, electrical

**University of California:** Civil, electrical, mechanical, metallurgical (metallurgy), mining, petroleum

**California Institute of Technology:** Aeronautical (6-year course), chemical (5-year course), civil, electrical, mechanical

**Carnegie Institute of Technology:** Chemical, civil (*a*), electrical (*a*), industrial (management) (*a*), mechanical (*a*), metallurgical (*a*)

**Case School of Applied Science:** Chemical, civil, electrical, mechanical, metallurgical

**University of Cincinnati:** Aeronautical, chemical, civil, electrical, mechanical

**The Citadel:** Civil

**Clarkson College of Technology:** Civil, electrical, mechanical

**Clemson Agricultural College:** Civil, electrical, mechanical

**College of the City of New York** (*a*): Civil, electrical, mechanical

**University of Colorado:** Architectural, civil, electrical, mechanical

**Colorado School of Mines:** Geological, metallurgical, mining, petroleum

**Columbia University** (*b*): Chemical, civil, electrical, industrial, mechanical, metallurgical, mining

**Cooper Union Institute of Technology** (*c*): Civil, electrical, mechanical

**Cornell University:** Chemical, civil, electrical, industrial (administrative), mechanical

**Dartmouth College:** Civil

**University of Delaware:** Civil, electrical, mechanical

**University of Detroit:** Aeronautical, architectural, civil, electrical, mechanical

**Drexel Institute:** Chemical, civil, electrical, mechanical

**Duke University:** Civil, electrical, mechanical

**University of Florida:** Civil, electrical, industrial, mechanical

**Georgia School of Technology:** Aeronautical, civil (*d*), electrical (*d*), mechanical (*d*)

**Harvard University** (*e*): Civil, communication, electrical, industrial (engineering and business administration), mechanical, metallurgical (physical metallurgy), sanitary

**Howard University:** Civil, electrical, mechanical

**University of Idaho:** Civil, electrical, mechanical

**University of Illinois:** Architectural, ceramic (technical option), chemical, civil, electrical, general (*f*), mechanical, metallurgical, mining

**Iowa State College:** Agricultural (*g*), architectural, chemical, civil, electrical, general (*f*), mechanical

**State University of Iowa:** Chemical, civil, electrical, mechanical

**Johns Hopkins University:** Civil, electrical, mechanical

**University of Kansas:** Architectural, civil, electrical, mechanical, mining

**Kansas State College:** Agricultural (*g*), architectural, civil, electrical, mechanical

**University of Kentucky:** Civil, metallurgical, mining

**Lafayette College:** Civil, electrical, industrial (administrative), mechanical, metallurgical, mining

**Lehigh University:** Chemical, civil, electrical, industrial, mechanical, metallurgical, mining

**Louisiana State University:** Civil, electrical, mechanical, petroleum

**University of Louisville:** Chemical, civil, electrical, mechanical

**University of Maine:** Civil, electrical, general (*f*), mechanical

**Marquette University:** Civil, electrical, mechanical

**University of Maryland:** Civil, electrical, mechanical

**Massachusetts Institute of Technology:** Aeronautical, architectural, building engineering and construction, chemical, civil, electrical, electrochemical, general (*f*), industrial (business and engineering administration), mechanical, metallurgical (metallurgy), mining, naval architecture and marine engineering, public health, sanitary

**University of Michigan:** Aeronautical, chemical, civil, electrical, engineering mechanics, mechanical, metallurgical, naval architecture and marine engineering, transportation

**Michigan College of Mining and Technology:** Civil, electrical, mechanical, metallurgical, mining

**Michigan State College:** Civil, electrical, mechanical

**University of Minnesota:** Aeronautical, chemical, civil, electrical, mechanical, metallurgical, mining (excluding mining in geology option), petroleum

**University of Missouri:** Civil, electrical, mechanical

**Missouri School of Mines and Metallurgy:** Ceramic, civil, electrical, metallurgical, mining (mine) (excluding mining geology option)

**Montana School of Mines:** Geological, metallurgical, mining

**Montana State College:** Civil, electrical, mechanical

**University of Nebraska:** Agricultural (*g*), architectural, civil, electrical, mechanical

**University of Nevada:** Electrical, mining

**University of New Hampshire:** Civil, electrical, mechanical

**University of New Mexico:** Civil, electrical, mechanical

**New York University:** Aeronautical, chemical (*h*), civil (*a*), electrical (*a*), mechanical (*a*)

**New York State College of Ceramics** (at Alfred University): Ceramic

**Newark College of Engineering:** Civil, electrical, mechanical

**North Carolina State College:** Ceramic, civil, electrical, mechanical

**University of North Dakota:** Civil, electrical, mechanical, mining

**Norwich University:** Civil, electrical

**Ohio State University:** Ceramic, chemical, civil, electrical, industrial, mechanical, metallurgical, mining (mine)

**University of Oklahoma:** Architectural, civil, electrical, mechanical, petroleum (production option)

**Oklahoma Agricultural and Mechanical College:** Civil, electrical, industrial, mechanical

**Oregon State College:** Civil (excluding business option), electrical (excluding business option), mechanical (excluding business option)

**University of Pennsylvania:** Chemical, civil, electrical, mechanical

**Pennsylvania State College:** Architectural, chemical, civil, electrical, electrochemical, industrial, mechanical, sanitary

**University of Pittsburgh:** Chemical, civil, electrical, industrial, mechanical, metallurgical, mining, petroleum, petroleum refining

**Polytechnic Institute of Brooklyn:** Chemical (*h*), civil (*a*), electrical (*a*), mechanical (*a*)

**Princeton University:** Chemical, civil, electrical, mechanical

**Purdue University:** Chemical, civil, electrical, mechanical

**Rensselaer Polytechnic Institute:** Chemical, civil, electrical, mechanical

**Rhode Island State College:** Civil, electrical, mechanical

**Rice Institute:** Civil, electrical, mechanical

**University of Rochester:** Mechanical

**Rose Polytechnic Institute:** Civil, electrical, mechanical

**Rutgers University:** Civil, electrical, mechanical, sanitary

**University of Santa Clara:** Civil, electrical, mechanical

**South Dakota State College:** Civil electrical, mechanical

**South Dakota State School of Mines:** Civil, electrical, metallurgical, mining

**University of Southern California:** Petroleum

**Stanford University:** Civil, electrical, mechanical, metallurgical, mining, petroleum

**Stevens Institute of Technology** (*f*): General

**Swarthmore College:** Civil, electrical, mechanical

**Syracuse University:** Civil, electrical, industrial (administrative), mechanical

**University of Tennessee:** Civil, electrical, mechanical

**University of Texas:** Civil, electrical, mechanical, petroleum (petroleum production)

**Agricultural and Mechanical College of Texas:** Civil, electrical, mechanical, petroleum

**Texas Technological College:** Civil, electrical, mechanical

**Tufts College:** Civil, electrical, mechanical

**Tulane University of Louisiana:** Civil, electrical, mechanical

**Union College:** Civil, electrical

**University of Utah:** Civil, electrical, mechanical, metallurgical, mining

**University of Vermont:** Civil, electrical, mechanical

**University of Virginia:** Civil, electrical, mechanical

**Virginia Military Institute:** Civil, electrical

**Virginia Polytechnic Institute:** Civil, electrical, industrial, mechanical

**Washington University:** Architectural, civil, electrical, industrial (administrative), mechanical

**University of Washington:** Aeronautical, ceramic, chemical, civil, electrical, mechanical, metallurgical, mining

**State College of Washington:** Civil electrical (basic and hydroelectric, options), mechanical (basic option), metallurgical, mining (excluding mine administration and petroleum engineering option)

**Webb Institute of Naval Architecture:** Naval architecture and marine engineering

**West Virginia University:** Civil, electrical, mechanical, mining

**University of Wisconsin:** Chemical, civil, electrical, mechanical, metallurgical, mining

**Worcester Polytechnic Institute:** Civil, electrical, mechanical

**Yale University:** Chemical, civil, electrical, mechanical, metallurgical

(*a*). Accrediting applies to both the day and evening curricula.

(*b*). Accrediting applies to the 4-year and 5-year curricula leading to the bachelor of science degree.

(*c*). Accrediting applies to day curriculum only. Action on evening curriculum deferred pending granting of degrees.

(*d*). Accrediting applies to both regular and co-operative curricula.

(*e*). Accrediting applies only to curriculum as submitted to ECPD and upon completion of which a certificate is issued by Harvard University certifying that the student has pursued such a curriculum.

(*f*). The accrediting of a curriculum in general engineering implies satisfactory training in engineering sciences and in the basic subjects pertaining to several fields of engineering; it does not imply the accrediting, as separate curricula, of those component portions of the curriculum such as civil, mechanical, or electrical engineering that are usually offered as complete professional curricula leading to degrees in these particular fields.

(*g*). All curricula in agricultural engineering which appear in this list have been provisionally accredited for a period of 2 years. The reason for this is twofold; in the first place it appears to ECPD that the final year of the 4-year programs fails to build, in adequate manner, upon the engineering basis laid in the first 3 years; secondly, it is the feeling of ECPD that curricula in agricultural engineering might more properly be given as options under one of the major engineering branches (that is, civil engineering, electrical engineering, or mechanical engineering).

(*h*). ECPD has not received from its subcommittee on chemical engineering a recommendation with respect to the evening curriculum in chemical engineering.

*Cost of Lack of Guidance.* For lack of adequate guidance a considerable number of boys drop out at the end of or during the first year. There is a definite financial loss in each case. Much has been said about the intangible profit of going to college even one year. The statistics of engineers do not show tangible values for one or 2 years of college life. On the contrary, the moral and psychological effects of failure are serious and real. The sense of defeat is a handicap at a critical period in the life of youth struggling for a foothold.

Some 20,000 students, more or less, are asking admission to engineering colleges this fall. Two things should be done to prevent economic loss and to protect the engineering profession. First, there should be conscientious guidance provided by the schools, by colleges, and with the aid of the profession. Second, colleges should abandon competition for numbers and accept only those who can meet certain well-defined standards which promise a fair measure of achievement in engineering education and in their future business and professional careers.

## Report of Committee on Engineering Schools

Karl T. Compton, Chairman

The committee on engineering schools is expected, as its broad responsibility, "to formulate criteria for colleges of engineering, which will insure to their graduates a sound educational background for practicing the engineering profession." In order that the committee might carry out most effectively its broad program, the decision was made during its first year that the early efforts of the committee should be directed solely toward the accrediting of undergraduate curricula in engineering. There seemed to be a pressing need for a thoroughly representative and authoritative accrediting agency. While the committee recognized that the theoretical desirability of accrediting might be subject to considerable differences in opinion, it further recognized that various factors, including state licensing laws, were resulting in numerous unco-ordinated efforts to establish lists of accredited engineering colleges. In ECPD there seemed to exist an organization representing the entire profession, and thus ideally constituted to administer a plan for accrediting engineering curricula both uniformly and in a manner consistent with the high ideals of the engineering profession. (The basis for accrediting was published as part of report of the fourth annual meeting of ECPD in ELECTRICAL ENGINEERING for November 1936, pages 1280–5.)

In October 1936, an initial list of the curricula in 2 regions of the United States, judged by ECPD to be worthy of accrediting, was released for publication. Arrangements were made in the early spring of 1936 to extend the program into the remaining regions of the United States and to examine the institutions in the first 2 regions which had not applied in time for consideration during 1935–36. Ninety-five institutions submitted curricula, involving visits of inspection to 88 institutions during the year 1936–37. The remaining 7 institutions have asked for inspection during the year 1937–38.

*Summary of Institutions and Curricula Inspected.* Since the accrediting program was inaugurated in 1935, a total of 134 degree-granting engineering schools have submitted 642 curricula for accrediting. Of this number 127 institutions have been visited to date and recommendations prepared on 617 curricula. The records of the committee show that 20 degree-granting engineering colleges have not yet responded to the invitation of the committee.

*Summary of Recommendations.* The following is a summary of the actions recommended to ECPD by the committee for the 617 curricula inspected up to the present time:

| | |
|---|---|
| To accredit | 373 |
| To accredit provisionally for a limited period | 69 |
| To defer action | 35 |
| Not to accredit | 140 |
| Total | 617 |

Provisional accrediting has ranged from periods of one to 3 years and involves a revisit at the end of the period of accrediting. (In all other cases review is left entirely to the discretion of ECPD and its committee on engineering schools.) Deferred action has been taken where degrees have not yet been conferred, or where recommendations in regard to curricula in chemical engineering are still under consideration by the committee on chemical engineering education of the American Institute of Chemical Engineers. A complete list of the accredited curricula by institutions may be found elsewhere in this report.

*By-Products of Accrediting.* The main objective of the accrediting program, of course, has been to draw up a list of engineering curricula which, in the opinion of ECPD, represent sound and adequate instruction in the several branches of engineering. A second objective, however, has come to be regarded as being fully as important, namely, to be of the greatest possible aid to the institutions offering curricula for accrediting.

Almost without exception the visiting committees have been asked by the administrative officers of the institutions visited to give them suggestions and advice. The committees have endeavored to comply with these requests, and throughout the discussions of the regional committees, and of the general committee later, a great deal of attention has been given to the consideration of directions along which substantial improvements might be made which would increase the effectiveness of the teaching program of the institution. In many instances the opinion of the ECPD committee has been the deciding factor in making long-desired changes or improvements possible. In other cases the wide experience and fresh perspective of the delegatory committee members have made it possible to call to the attention of the officers of administration undesirable conditions which had remained unnoticed or neglected. That the suggestions of the committees have been appreciatively received may be seen both from the letters which have been written, and from the way in which the suggestions have been acted upon.

At present there is every indication that the accrediting program will result not only in a generally accepted accredited list, for which there is a real need, but also in a definite stimulation to higher excellence in our engineering schools, and a wide distribution among the institutions, particularly among the various officers of administration, of some of the best ideas in engineering education.

*Activities in Prospect.* Since the organization of the committee on engineering schools in 1932, attention has been focused almost solely upon the accrediting program. It has seemed recently that this project is now sufficiently well in hand to permit the consideration of other ways in which the committee could be of service. Accordingly, during the past year the committee has discussed several activities in which it might engage over a period of perhaps 5 years. Not all of these activities would, or could, be undertaken at once. Their possibilities are, however, being further studied, and the consideration of them will require a substantial portion of the committee's time during the ensuing year. These activities are:

(*a*). Continuation of accrediting program. The committee must necessarily make this its first concern. Plans for the periodic review and reinspection of accredited curricula were outlined roughly during the past year, and these will shortly be put into operation.

(*b*). Investigation of graduate study. The committee has recently considered this aspect of accrediting and come to the conclusion that there may be other more effective means of enhancing the status of graduate study.

(*c*). Study of admission with advanced standing. During the consideration of undergraduate curricula, it has become evident to the committee that the qualifications of an engineering student who transfers to an engineering school with advanced standing, in particular from an institution of a different type, such as a college of liberal arts or a junior college, are dependent to a considerable extent upon the quality of the instruction which he received in the institution from which he is transferring. It further is evident that the quality of work maintained at any institution is affected by the standards at other institutions which prepare students for entrance with advanced credit. It appears, therefore, to be within the scope of the committee to consider ways and means of improving standards at the junior colleges, colleges of liberal arts, other engineering schools, and divisions serving as feeders for institutions which have had curricula accredited by ECPD. A committee has been appointed to pursue the study of this problem.

(*d*). Advisory service to institutions. In view of the considerable experience and background which the delegatory committee members have gained during the course of the accrediting program, the committee should be in a position to be of material assistance to institutions offering engineering curricula by making available to interested institutions an informal advisory service. Recognizing that its experience creates a responsibility in this direction, the committee is prepared to perform such a function and is ready, on request, to advise or confer with representatives of engineering colleges in reference to any phase of their work related to accrediting.

(*e*). Survey of engineering education. During the course of its operations, the committee has assembled a great deal of valuable information on the status of engineering education. It appears highly desirable that this material be analyzed and published while it is yet fresh.

**Index to ASTM Proceedings.** A complete subject and author index covering the contents of volumes 31 to 35, inclusive, of the ASTM *Proceedings*, issued from 1931 to 1935, is now available from the American Society for Testing Materials, 260 South Broad Street, Philadelphia, Pa. Prices may be obtained from the society.

# Chemistry Subcommittee of NRC Insulation Committee Meets at Rochester

UNDER auspices of the physical and inorganic division of the American Chemical Society, at its annual convention at Rochester, N. Y., the subcommittee on chemistry of the insulation committee of National Research Council held a symposium on insulation materials, September 9, 1937. Kenneth S. Wyatt (A'32) research engineer for The Detroit (Mich.) Edison Company, and chairman of the subcommittee, who furnished the material from which this report was prepared, presided over the session, at which 5 papers were presented:

1. DIPOLE POLARIZATION AND DIELECTRIC LOSS IN CERTAIN LIQUIDS AND SOLIDS, S. O. Morgan, Bell Telephone Laboratories, Incorporated, New York, N. Y.

2. ELECTRIC BREAKDOWN OF SOLID AND LIQUID INSULATORS, A. von Hippel (M'37), Massachusetts Institute of Technology, Cambridge.

3. THE INFLUENCE OF GASEOUS ELECTRIC DISCHARGE ON HYDROCARBON OILS, L. J. Berberich (A'30, M'36) Westinghouse Electric & Manufacturing Company, East Pittsburgh, Pa.

4. METHODS OF MEASURING THE ELECTRICAL PROPERTIES OF SOLIDS, R. M. Fuoss, General Electric Company, Schenectady, N. Y.

5. ELECTRICAL AND CHEMICAL STUDIES OF OIL OXIDATION, J. C. Balsbaugh (A'23, M'25), Massachusetts Institute of Technology, Cambridge.

In a brief introductory outline of the objectives of the symposium Chairman Wyatt pointed out that "insulating materials find an extremely wide and indispensable place in the electrical industry, and that the development and research leading to improved insulating materials, the manufacture and processing of present materials, and the study of deterioration in service are to a large extent chemical problems. Yet the burden of the attack so far has rested on the shoulders of electrical engineers and physicists rather than chemists. To insure the most rapid progress it will be necessary to enlist to a greater extent the services of the chemists."

## TECHNICAL SESSION

*Dipole Polarizations and Dielectric Loss.* S. O. Morgan, in presenting his paper, asserted that although generally the function of dielectrics is considered to be the hindering of current flow from one conductor to another, or from a conductor to its surroundings, for many purposes the function of dielectrics is to permit the flow of alternating current.

"No insulator permits the flow of current without at least a small amount of energy being dissipated as heat. One of the tasks of the engineer is to obtain a maximum permittivity or dielectric constant with a minimum of dielectric loss. Dielectric theories predict that a high dielectric loss is a necessary consequence of a high dielectric constant. Experimental data for a wide variety of materials bear out this prediction."

Mr. Morgan described the relationships between the chemical composition and dielectric loss and dielectric constant and interpreted these quantities in terms of the motions of the electrons, atoms, and molecules making up the dielectric. The various kinds of motion are translational, vibrational, and rotational, and the motion of molecules containing electric dipoles influence both dielectric constant and dielectric loss of the material.

*Breakdown of Solid and Liquid Insulators.* A. von Hippel's paper showed that: "The extrapolation of Paschen's law from gases under normal pressure up to the high densities of solids and liquids would predict the field strength of electric breakdown in these condensed systems 10 to 100 times higher than observed. The main reasons for this discrepancy are the following: in gases of low density the excitation of the electronic system of the particles acts as the important barrier, which stops the acceleration of the electrons before they reach ionizing velocities. With tight packing of the atoms and molecules these excitation levels become practically destroyed and the excitation of vibrations remains as the decisive mechanism of friction. Hence the study of the excitation functions of vibrations is the most important step for the formulation of the theory of electric breakdown in condensed systems. Next, one has to consider changes of the field distribution and of the structure of the matter itself by charged particles. The field emission of the cathode plays a dominating part to lower the breakdown strength of insulators. Fragile material may crack by mechanical stresses, produced by changes of the particles forming the solid. Hence the total phenomenon is often a very complicated one and the simple theory of heat breakdown, widely accepted, seems to be inadequate."

*Influence of Gaseous Discharge on Hydrocarbon Oils.* "The new and revolutionary solvent-refining processes now rapidly being adopted by the whole oil industry make possible the production of better oils in most respects than was formerly possible," according to L. J. Berberich. "In the application of such oils to the insulation of high-voltage equipment, however, they were found to possess a serious disadvantage. It was discovered that they were vulnerable to attack by the gaseous electric discharges which occur unavoidably in some high-voltage apparatus. Through research it has been discovered that one class of hydrocarbon molecules, known as the aromatics, is particularly resistant to the action of the discharges, and now it has been found that this same class of hydrocarbons when added to the oil in small percentages reduces the formation of gases markedly. Thus again, a bit of knowledge is added which may result in the transmission of electric power more economically and reliably."

*Methods of Measuring the Electrical Properties of Solids.* "The essential difference from the point of view of measuring technique between solids and liquids is that the former do not in general give perfect electrical contact with metallic electrodes, which results in the presence of 2 large air capacitances in series with the unknown. A simple mathematical analysis shows that the film capacitances can produce serious experimental errors, which are dependent on the average thickness of the air film, the thickness of the sample, and the dielectric constant and conductance of the sample." R. M. Fuoss described several methods of eliminating such errors, using measurements on typical insulating materials as examples.

*Electrical and Chemical Studies of Oil Oxidation.* "One of the most important types of high-voltage insulation is the combination of oil and paper. During use, this insulation is subjected to elevated temperatures and high electrical stresses, so there are reactions of the various oil constituents among themselves, with traces of oxygen and water remaining in the cable and with the copper conductor and the lead sheath. One attack on this problem has been the investigation of oil oxidation. By the application of solvent refining methods to the oils, and by the addition of several tests to those now in common use, it is hoped that some new light may be shed on the entire problem. J. C. Balsbaugh discussed the relations between oxidation stability, acid formation, power factor, colloidal content, Grignard test, oil source, and refining methods. He further pointed out that many problems concerning the chemical and electrical aspects of this problem are still without any satisfactory explanation.

## DINNER MEETING

Following the symposium, which was attended by about 150 guests and members of the subcommittee, a dinner was held for the subcommittee, at which Doctor T. Smith Taylor (M'21) Diehl Manufacturing Company, Elizabethport, N. J., delivered an address on "Plastics for Electrical Insulation." At this dinner, held at the University Club in Rochester, about 80 people were present.

The joint meeting with the American Chemical Society seemed to direct much interest and enthusiasm toward the problems of insulation research. As a result, the subcommittee has received requests to hold similar symposia each year under the auspices of other divisions of the American Chemical Society.

**Diederichs, Engineering Dean, Dies.** Herman Diederichs, dean of college of engineering at Cornell University, Ithaca, N. Y., died August 31, 1937. Born at Muenchen-Gladbach, Germany, August 12, 1874, he was graduated from Cornell University in 1897 with the degree of mechanical engineer. The following year he became an instructor in experimental engineering at that university, and in 1902 was made assistant professor. Five years later he was appointed professor, and in 1921 became director of the school of mechanical engineering. Since 1936 he had been dean of the college of engineering. He was appointed John E. Sweet professor of engineering in 1928. Dean Diederichs was the author, with others, of several engineering books. He was a member of The American Society of Mechanical Engineers, Society of Automotive Engineers, American Society for Metals, and Verein deutscher Ingenieur; in 1930 he received the Melville Medal of the ASME.

## District 9 Award for Branch Paper

Prize for Branch paper in the AIEE North West District (No. 9) for the period from January to June 1937, inclusive, has been awarded to Thomas Y. Merrell and Edward A. Rich, Enrolled Students, for their paper "Investigation of Losses in Single-Phase Induction Motors," which was presented at a meeting of the University of Utah Branch on May 19, 1937. The award was made in accordance with the revision of prize rules recently adopted by action of the AIEE board of directors, by which the prizes for Branch papers are awarded on the basis of the academic year from July 1 to June 30, inclusive. Excerpts of the rules for prize awards were given in the April 1937 issue of ELECTRICAL ENGINEERING, page 492.

**Naval Architects to Meet.** The Society of Naval Architects and Marine Engineers will hold its 45th annual meeting at the Waldorf-Astoria Hotel, New York, N. Y., on November 18 and 19, 1937. Among the papers to be presented is "Ship Propulsion by the Emmet Mercury Vapor Process," by W. L. R. Emmet (A'93, M'94, HM'33, Edison Medallist '19, past vice-president, member for life). Other papers will discuss such subjects as the burning of fuel oil, fire control, United States Coast Guard cutters, and alloys in shipbuilding.

**ASME Elects Officers for 1938.** New officers for 1938 of The American Society of Mechanical Engineers were elected on September 28, 1937, and will assume office on December 10, 1937. They are: *President*—H. N. Davis, president, Stevens Institute of Technology, Hoboken, N. J. *Vice-Presidents*—F. O. Hoagland, master mechanic, Pratt and Whitney division, Niles Bement-Pond Company, Hartford, Conn.; B. M. Brigman (M'28) dean, Speed Scientific School, University of Louisville, Ky.; Harte Cooke, mechanical engineer, McIntosh and Seymour Corporation, Auburn, N. Y.; W. H. McBryde, consulting engineer, San Francisco, Calif.; L. W. Wallace, director, division of engineering research, Association of American Railroads, Chicago, Ill. *Managers*—Carl L. Bausch, vice-president, Bausch and Lomb Optical Company, Rochester, N. Y.; S. B. Earle, dean, school of engineering, Clemson Agricultural and Mechanical College, Clemson College, S. C.; F. H. Prouty, partner, Prouty Brothers Engineering Company, Denver, Colo.

## Co-operative Educational Program Announced

A co-operative educational enterprise which will link the Westinghouse Electric and Manufacturing Company and the Carnegie Institute of Technology in a new program of undergraduate engineering training was announced recently by President Robert E. Doherty (A'16, M'27) of Carnegie, formerly chairman of the AIEE committee on education. To make this project possible the Westinghouse company has appropriated $200,000 to the Carnegie Institute of Technology.

The new co-operative program, which will go into effect at the beginning of the next school year, will make it possible for a number of students with superior qualifications to take the usual technical courses for a degree at Carnegie, and, during the same period, to get extensive shop and engineering experience and training in the Westinghouse plant. Of the group of students who will be selected to follow the co-operative course, a number, perhaps 10 each year, will receive George Westinghouse scholarships. A George Westinghouse professorship of engineering also will be established, and one of the duties of the holder of this position will be the supervision of the co-operative program.

The program of study will cover 5 years, of which 4 academic years will be spent at Carnegie. The summer months and 2 college semesters, one in the third and one in the fourth year, will be spent at the Westinghouse plant. Of the students selected for the course, those designated as Westinghouse scholars will receive an income of $50 per month during the 5-year training period from the company. Students will pursue courses not only in electrical engineering, but in the other engineering branches as well. Applications for admission to the co-operative program will be received after January 1, 1938.

## Standards

**Test Code for Polyphase Induction Machines.** There is now available an approved edition of the "Test Code for Polyphase Induction Machines." This is the first of the test codes developed by the AIEE to receive formal approval. (The other codes, which are still in preliminary report form, are "Test Code for Transformers," "Test Code for Synchronous Machines," "Test Code for D-C Machines," and "Test Code for Apparatus Noise Measurement.") The purpose of these test codes is to provide in convenient reference form the more generally applicable and accepted methods of conducting and reporting tests of a commercial nature, which apply to the fulfillment of performance guarantees and to acceptance tests. Copies of the approved code, No. 500, can be obtained from AIEE headquarters at 50 cents each, with 50 per cent discount to AIEE members on single copies.

**Safety Code for Elevators.** In July 1937 the American Standards Association approved the revised fourth edition of the "Safety Code for Elevators, Dumbwaiters, and Escalators." This code of safety standards covers the construction, inspection, maintenance, and operation of elevators, dumbwaiters, escalators, and their hoistways with certain exceptions. This latest edition was prepared by a sectional committee fully representative of the building, manufacturing, insurance, governmental, and other interests. The committee was sponsored by the National Bureau of Standards, the American Institute of Architects, and The American Society of Mechanical Engineers. The code may be obtained through the ASME, 29 West 39th Street, New York, N. Y., at one dollar per copy.

**Manual for Inspection of Elevators.** In July 1937 the American Standards Association approved as American recommended practice an "Inspectors' Manual for the Inspection of Elevators." This manual is intended to serve as a guide for the general use of elevator inspectors and is based on the requirements of the "Safety Code for Elevators, Dumbwaiters, and Escalators." The manual may be obtained through The American Society of Mechanical Engineers, 29 West 39th Street, New York, N. Y., at 75 cents per copy.

## American Engineering Council

### AEC Annual Assembly and Conference of Secretaries

The eighteenth annual assembly of the American Engineering Council and the eighth annual conference of secretaries of engineering associations, clubs, councils, institutes, and societies in the United States are scheduled for January 13, 14, and 15, 1938. The meetings are to be held at the Hotel Mayflower in Washington, D. C. Problems of common concern to the engineering and allied technical professions are being considered by the committees, and the programs, which include the all engineers' dinner, are expected to hold unusual interest for all branches of engineering.

### AEC Committee on Merit System

A meeting of the committee on the merit system of American Engineering Council was held in New York, N. Y., September 16, 1937, on the call of Chairman R. L. Sackett. There were present A. W. Berresford (A'94, F'14, past-president, member for life), F. L. Bishop, H. H. Henline (A'19, M'26, national secretary), and J. C. Hoyt of the committee and F. M. Feiker (M'34), *ex-officio*. The committee concurred in the idea of devising ways and means of forwarding the merit system by preparing a plan of procedure whereby state and local societies could sponsor the merit system for employment of engineers in states and municipalities as well as to continue to forward, in the public interest, the general desirability of merit as a basis for federal employment.

# Letters to the Editor

CONTRIBUTIONS to these columns are invited from Institute members and subscribers. They should be concise and may deal with technical papers, articles published in previous issues, or other subjects of some general interest and professional importance. ELECTRICAL ENGINEERING will endeavor to publish as many letters as possible, but of necessity reserves the right to publish them in whole or in part, or reject them entirely.

ALL letters submitted for consideration should be the original typewritten copy, double spaced. Any illustrations submitted should be in duplicate, one copy to be an inked drawing but without lettering, and other to be lettered. Captions should be furnished for all illustrations.

STATEMENTS in these letters are expressly understood to be made by the writers; publication here in no wise constitutes endorsement or recognition by the American Institute of Electrical Engineers.

## Synchronous Motor Effects in Induction Machines

*To the Editor:*

The effects noted by E. E. Dreese in the paper "Synchronous Motor Effects in Induction Machines" (AIEE TRANSACTIONS, July 1930, pages 1033–40) are not very common and, having run across a case of the same trouble, I believe it should be brought to the attention of induction-motor designers.

This case was brought up when several polyphase motors refused to come up to speed satisfactorily on production test. The rating was $^3/_4$ horsepower, 60 cycles, 220 volts, 4 poles, 1,725 rpm, 2 phase. The motors had 36 stator slots and 32 rotor slots, and were of normal design. Upon making careful investigation, it was discovered that the trouble was due to a synchronous cusp at 225 rpm, $^1/_8$ synchronous speed, similar to that described in the paper by Dreese.

Curve *A* of figure 1 shows the speed-torque characteristic of this motor. Curve *B* shows the same motor with the resistance rings turned smaller, and the air gap increased. Curve *C* shows the motor with a new rotor with more skew, but otherwise the same as the rotor of curve *B*.

One of the peculiar characteristics of this type of cusp was very definitely portrayed by these motors. If a motor has an ordinary induction cusp, such as would be shown by a curve similar to the dotted portion of curve *B*, it will not accelerate any load greater than that shown by the minimum torque point of the cusp. The synchronous cusp acts quite differently. If the synchronous goes to zero or negative, the motors seem to accelerate poorly even on light loads, but will usually come up to speed most of the time if several trials are made. If, however, the synchronous does not fall to zero, and has even half full load torque for a minimum value, the motor seems to accelerate very well. In fact, it is almost impossible to detect by ordinary starting and pull-up tests, that anything is wrong with the motor at all. On a number of motors which had a minimum point of 36 ounce-feet torque, all easily passed a minimum pull-up limit of 54 ounce-feet. Yet if the motors were allowed to slow down with a brake load of 38 ounce-feet, and the switch closed again when the speed had dropped very close to 225 rpm, they would all definitely lock in at the cusp, and refuse to accelerate again until the load was reduced to 36 ounce-feet.

Upon referring to page 1040 of Dreese's paper, we find that with

$$\frac{N \text{ (rotor slots)}}{p \text{ (poles)}} = \frac{32}{4} = 8$$

table II predicts a cusp at $^1/_{16}$ forward speed, and table III predicts one at $^1/_8$ backward speed, for 3-phase motors. However, upon referring to tables IV and V, for 2-phase motors, we find that $N/p = 8$ does not appear, and no cusp is expected.

On page 1041, C. J. Koch quotes P. L. Alger as finding that cusps would be expected at $p/N$ speed, and would be positive or negative depending on whether the motor were 3 or 2 phase, and whether the rotor or stator had the greater number of lots.

We then tested a similar 3-phase motor, and found a very pronounced cusp at −225 rpm as shown in figure 2. Again I wish to point out that in spite of the magnitude of this cusp, the motor would only lock in when the switch was closed at almost exactly this speed. The motor was loaded with considerable inertia load, and reversed time and time again, passing through the cusp speed quite slowly, and in no case would it lock in except when the switch was closed at just about the correct speed.

The rules of Alger seem to fit these 2 cases, whereas those of Dreese only partially

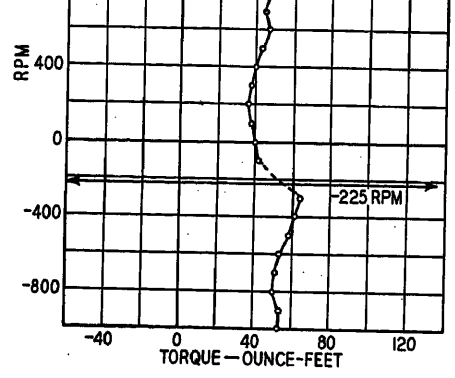



**Figure 2. Speed-torque curve of 3-phase motor**

Stator slots 36 Rotor slots 32

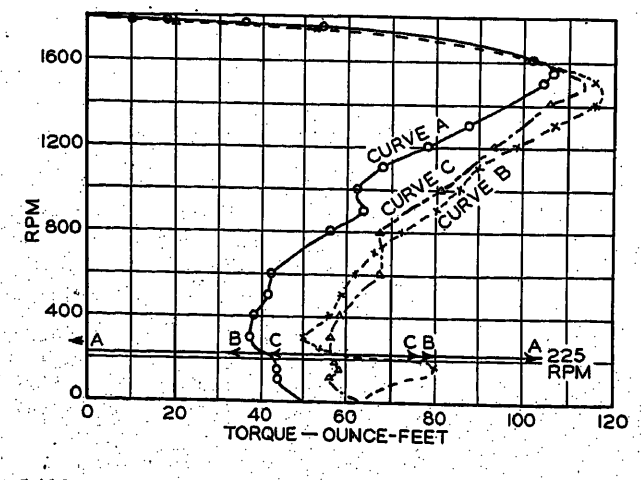



**Figure 1. Effect of air gap, skew, and rotor resistance on synchronous cusp of 2-phase motor**

| Stator slots 36 | Rotor slots 32 | | |
|---|---|---|---|
| Curve | Air Gap | Skew | $r_2$ |
| *A* | 0.020 | 0.313 | 2.48 |
| *B* | 0.030 | 0.313 | 3.25 |
| *C* | 0.030 | 0.500 | 3.25 |

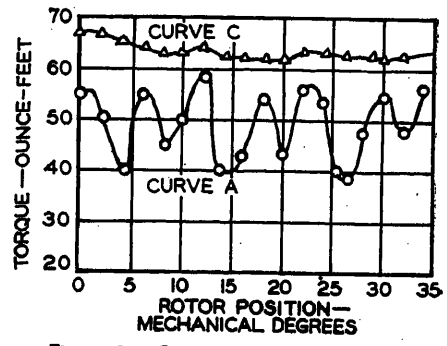



**Figure 3. Cogging of 2-phase motor**

| Stator slots 36 | Rotor slots 32 | | |
|---|---|---|---|
| Curve | Air Gap | Skew | $r_2$ |
| *A* | 0.020 | 0.313 | 2.48 |
| *C* | 0.030 | 0.500 | 3.25 |

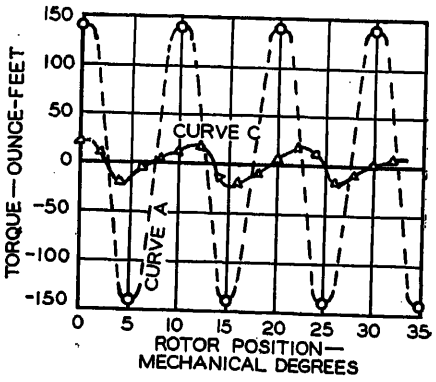



**Figure 4. Single-phase cogging of 2-phase motor with one phase open**

| Stator slots 36 | Rotor slots 32 | | |
|---|---|---|---|
| Curve | Air Gap | Skew | $r_2$ |
| *A* | 0.020 | 0.313 | 2.48 |
| *C* | 0.030 | 0.500 | 3.25 |

agree. We found the cusp at $^1/_8$ backward speed, but not at $^1/_{16}$ forward speed, and we did have the 2-phase case.

There was one other curious phenomenon which is illustrated in figures 3 and 4. The cogging or variation of starting torque with rotor position was very noticeable, particularly if one phase was opened. However, the cogging was practically eliminated by the changes which were made in air-gap, rotor resistance, and skew, whereas the synchronous cusp was not.

Very truly yours,

P. H. TRICKEY (A'30, M'36)
Design Engineer, Diehl Manufacturing Company, Elizabethport, N. J.

## Engineering Education and Democracy

*To the Editor:*

I have read with much interest R. E. Doherty's article entitled "Engineering Education and Democracy," in the September 1937 issue of ELECTRICAL ENGINEERING. This impressed me as being one of the most able articles by an engineer that I have read on this very important subject. The author certainly has discovered some of the principal underlying problems and has made some concrete suggestions for a solution.

Such a plan of broadening the education of engineering students and engineers is most commendable and, as he implies, some of our more energetic engineers have acquired something of the type of training, in one way or another, which he has so well described. The constructive point which I would like to raise in connection with the article is: Where are we to get the competent teachers to lead students to this broader outlook?

My own observations are to the effect that comparatively few men in the engineering profession, either in college or out of college, are prepared to furnish the leadership needed to carry forward such a splendid program as Doctor Doherty has outlined. Perhaps it will be necessary to start with the few who are capable as teachers and leaders and gradually develop a force of men trained to furnish this leadership.

All so-called educated people, including the professions, should give thought to the broad economic and governmental problems and it is encouraging to note that an increasing amount of thought and an increasing number of thoughtful articles by engineers are appearing in the various periodicals, and this in itself is a very encouraging sign.

Again expressing my appreciation for this splendid article, I am

Very truly yours,

J. L. HAMILTON (M'15, F'21)
Assistant to the General Manager, Century Electric Company, St. Louis, Mo.

*To the Editor:*

Robert E. Doherty's paper "Engineering Education and Democracy" strikes a responsive cord with me because he so ably has championed a program of engineering education which my colleagues and I have been endeavoring to carry out for more than a quarter of a century. Our program, first proposed and planned by Doctor George E. Hale, has been a great success even though it may be that some of us in our technical subject class rooms have failed to stress sufficiently the human side of engineering. Also, as I read Doctor Doherty's paper, I have been brought to realize that we, along with all others engaged in engineering, have been a bit slow in anticipating the need on the part of engineers for giving more "thought to consequences" which come about as a result of the technical development which has been so great during the last 1 or 2 generations. Indeed, I quite agree with President Doherty that, unless we are careful, there will be reason to become less optimistic about the outcome, for it is high time that we all gave heed to the idea conveyed by a statement which, more than 20 years ago, I once heard made by Doctor J. A. L. Waddell. The statement to which I refer is: "It is not difficult for me to find men who know how to build bridges, but it is tremendously difficult for me to find men who are able to determine whether or not the bridge should be built."

Referring, for purposes of illustration, to the sentence just quoted: As engineers we naturally, in trying to determine "whether the bridge should be built," apply first the laws of economics to see how the cost of the bridge may be paid. During the bad business period through which we have just been passing, we have learned that many persons use factors other than the rules of technical feasibility and economic value to arrive at a decision as to whether an engineering project shall be carried out.

In considering Doctor Doherty's comments concerning the balance between technical subjects content and humanities content in engineering course curricula, I am prompted to recall a striking incident in my own experience which, briefly summed up, resulted in the discovery of a mountaineer with eyes and hands so skillful that he was able to hew a true timber about 8 feet long and 3 by 4 inches in cross section, without the use of any tools other than an adz and an axe. Quite a contrast to the all-too-frequently-employed craftsman who comes with a trunk full of tools and can't turn out a true-surfaced board with square corners.

Good engineering is the measure of the man and not the measure of the number of tools in his kit. My 27 years of teaching experience makes me think that, on the whole, the man with a 4-year engineering course comprising a lot of what we have called the humanities (At California Institute of Technology 20 per cent of a student's time throughout the 4-year course and during the fifth year when the student is working toward the master's degree, is allotted to the study of what we call the humanities.) and which President Doherty has designated as the "social stem" is better prepared for life at the end of his college course than is the man who has given practically all his time during his 4-year college course to the study of technical subjects and to increased specialization. In fact I think such a course as has been described is the ideal education for any citizen of today whether he plans to be an engineer, a business man, or is preparing to engage in some other profession than engineering, such, for example, as the law, medicine, or the ministry. Curricula of this type naturally compel the prospective engineer to acquire most of his professional education after the regular 4-year college course has been completed; and I quite agree with Doctor Doherty that, for the majority of engineers, this follow-up professional education should be obtained in industry rather than by continuation in college. Such a conclusion, of course, is based on the assumption that industry will provide channels through which the student, as he works at being a junior engineer, can obtain the added education needed to make him, in his more mature years, a competent engineer.

Doctor Doherty's 6 phases of education are excellent, but I think there should be an addition to the list of subjects given under number one, making that statement read, "a clear historical understanding of the parallel growths of religion and philosophy, of science and of engineering; because we should not forget that the primary value of a man in the engineering field, as in any other field of endeavor, is determined by that man's ability to live a righteous life whereby he may know how to use correctly the Golden Rule in all his relations with his fellow men." The educational program in which I have had a part has accomplished well the task of teaching all the 6 phases mentioned by Doherty, unless it be number 4, for I must admit that somehow no key has yet been found whereby the teacher may enable every student in his classes to use the English language effectively.

Near the end of his article Doherty has said that a program such as he has suggested may be considered by some as too expensive. Comparatively speaking, such a program is expensive if desired results are obtained, because the 6 points of a rounded education such as he has outlined can be effectively made a part of a student's life only by having the students come in close contact with men of real ability who themselves are examples of what proficiency in those 6 points can do. To do this there must be many teachers and small classes. Young men who have an interest in technical matters and plan to be engineers can be interested in literature and kindred subjects but the teachers of those subjects must be men of outstanding achievement who are inspired with enthusiasm for the subjects which they teach.

Doctor Doherty has concluded his paper with this question: "For what is to be gained by preparing engineers to continue their building of a physically magnificent structure only to have it torn down ultimately by the uncontrolled, unintelligent forces of selfish interests and vandalism?" I should like to supplement that question by another: Is it not the first duty of the engineer as a citizen of his country to make his first question regarding any project be "What does the construction of this project mean to the future of America when considered in the light of its whole influence upon us, our children, and our children's children?" If the answer to that question is satisfactory, then, and only then, has the engineer a moral right to proceed with the design and construction of the project.

Very truly yours,

ROYAL W. SORENSEN
(A'07, F'19, director)
Professor of Electrical Engineering, California Institute of Technology, Pasadena

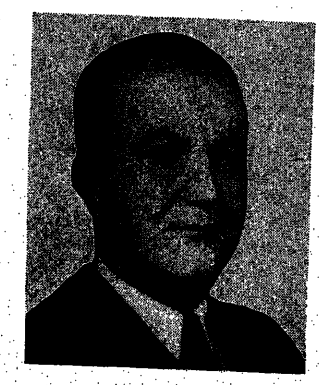
# Personal Items

E. E. DREESE (M'25) professor of electrical engineering and chairman of the electrical engineering department of The Ohio State University, Columbus, has been appointed chairman of the Institute's committee on basic sciences for the year 1937–38. Professor Dreese was born at Edmore, Mich., September 10, 1895, and was graduated from the University of Michigan in 1920 with the degree of bachelor of science in electrical engineering. In the following year he was appointed to the electrical engineering faculty of the University of Michigan as an instructor. At the same time he enrolled in the graduate school and in 1925 received the degree of master of science in electrical engineering, following which he was appointed chief engineer of the Lincoln Electric Company, Cleveland, Ohio. Professor Dreese remained with that company for 5 years, and during that time received the honorary degree of electrical engineer from the University of Michigan. In 1930 he was appointed professor of electrical engineering at The Ohio State University and made chairman of the department of electrical engineering. He is an active participant in the local affairs of the AIEE Columbus Section, and has been secretary (1933–34) and chairman (1934–35) of that Section; moreover, for the last 2 years he has been active in committee work of the Institute. He has been a member of the committee on basic sciences (formerly electrophysics) since 1935, and is entering his second year of service on the committees on education and student Branches. Professor Dreese is the author of 2 papers presented before the Institute. He is a member of the Society for the Promotion of Engineering Education, Tau Beta Pi, Eta Kappa Nu, and Sigma Xi.

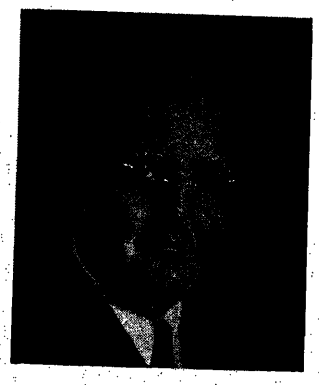
WILLS MACLACHLAN (A'08, F'21, past vice-president) consulting electrical engineer, Toronto, Ont., Canada, has been appointed to serve as chairman of the Institute's committee on safety for the term 1937–38. Mr. Maclachlan was born August 3, 1885, in Toronto, and received the degree of bachelor of applied science at the University of Toronto in 1907. For one year following his graduation he was employed by the Canadian Westinghouse Company as erection engineer before becoming electrical superintendent of the Dominion Government Grain Elevator at Port Colborne, Ont. After serving other companies in various positions from 1910 until 1913, he was appointed engineer-in-charge of the Electric Power Company, Toronto, in the latter year, and remained in that capacity until 1915, when he became inspector for the Electrical Employers Association of Ontario. Mr. Maclachlan's work for that association has been continuous, and has been concerned with accident prevention in several private and municipal utility companies. Since 1917 he has been consultant on employee relations to the Hydro Electric Power Commission of Ontario and has served as Safety adviser to several other organizations in Ontario. Mr. Maclachlan was vice-president of the Institute during 1919–20, served as a member of the committees on mines (now applications to mining work), 1919–20, and law (now constitution and by-laws), 1920–21. He has been a member of the committee on safety since 1920, and during 1920–21 was a member of the special committee on geographical division and election procedure. Mr. Maclachlan has been active in the committee and administrative work of other organizations, including the former National Electric Light Association, Edison Electric Institute, National Safety Council, Canadian Engineering Standards Association, Canadian Electrical Association, Royal Canadian Institute, and others, and is the author of many papers and articles dealing principally with electric shock and remedial measures.

A. M. MACCUTCHEON (A'12, F'26, junior past-president) engineering vice-president of the Reliance Electric & Engineering Company, Cleveland, Ohio, has been appointed chairman of the Institute's committee on Institute policy for the term 1937–38. Mr. MacCutcheon was born at Stockport, N. Y., December 31, 1881, and was graduated from the State Normal College at Albany in 1901. After teaching mathematics and science in high schools until 1904 he entered the electrical engineering school at Columbia University and was graduated in 1908. From 1909 until 1914 he was affiliated with the Crocker-Wheeler Company, Ampere, N. J. In 1914 he took charge of all new design work of the Reliance Electric & Engineering Company, was appointed chief engineer in 1917, and in the fall of that year entered the United States Navy. Following his release in 1919 he returned to his former position, and in the following year was elected a director of the Reliance company. Since 1923 Mr. MacCutcheon has held the position of vice-president in charge of engineering. He was a director of the Institute from 1928 until 1932, president during 1936–37, and has served as a member of the following committees: general power applications, 1916–18, 1924–33 (chairman 1925–28); electrical machinery, 1924–34; meetings and papers (now technical program) 1925–29; electric welding, 1928–30; applications to iron and steel production, 1928–33; Edison Medal, 1929–31; executive, 1930–31; standards, 1922–36 (chairman 1931–34) and Lamme Medal, 1934–37 (chairman 1935–36). He is now a member of the executive committee and the Edison Medal committee, and is the Institute's representative on the United States National Committee of the International Electrotechnical Commission, the electrical standards committee of the American Standards Association, the standards council of the same organization, and the John Fritz Medal board of award. Mr. MacCutcheon is a member of several technical and engineering organizations.

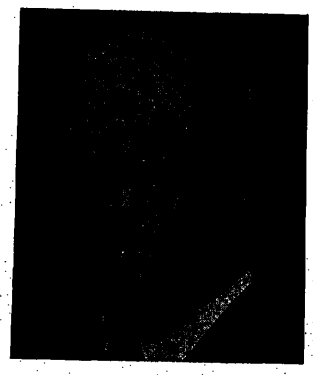
W. M. YOUNG (A'24, M'34) formerly research engineer for the Taylor Instrument Companies, Rochester, N. Y., has been appointed dean of the college of applied science of Ohio University, Athens. Doctor Young was born August 17, 1898, at Omaha, Nebr., and received the degrees of bachelor of science in electrical engineering (1921), master of science in electrical engineering (1922), and doctor of philosophy (1926) at the University of Illinois. Following his graduation in 1921 he was appointed assistant in the physics department of the University of Illinois, where he taught electrical measurements until he had completed his graduate studies. In 1926 he was appointed to the faculty of the Texas Technologic College, Lubbock, as adjunct professor of general and engineering physics, but in the following year was transferred to the electrical engineering department as associate professor. Doctor Young became associate professor of electrical engineering at the University of Iowa in 1930; however, he remained there only one year before leaving the teaching



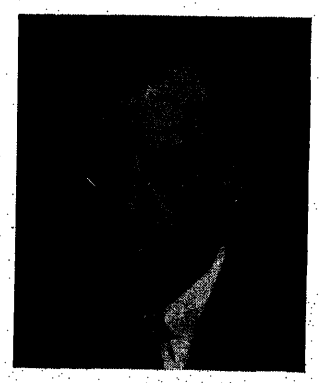
E. E. DREESE



WILLS MACLACHLAN



A. M. MacCUTCHEON



W. M. YOUNG



Stein, Milwaukee

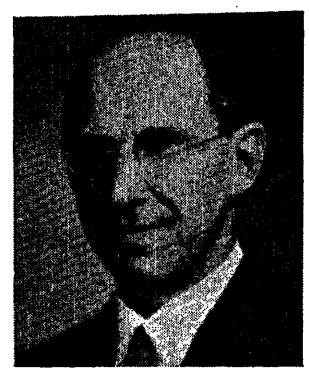
W. E. CRAWFORD



E. S. LEE



E. L. PHILLIPS



ROBIN BEACH

profession to become a research engineer for the Taylor Instrument Companies, in which capacity he has been engaged in the derivation of electrical control instruments for application to industrial processes. He has made numerous contributions of articles and papers to technical and professional journals, and is a member of the American Physical Society, Society for the Promotion of Engineering Education, Tau Beta Pi, Sigma Xi, and Eta Kappa Nu.

ROBIN BEACH (A'15, F'35) professor and head of the department of electrical engineering, Polytechnic Institute of Brooklyn, Brooklyn, N. Y., has been appointed chairman of the Institute's committee on production and application of light for the year 1937–38. Professor Beach was born at Robin's Island, N. Y., August 30, 1889, and received the degrees of bachelor of science in electrical engineering (1913) and electrical engineer (1922) at New Hampshire University. In 1922 he received also the degree of master of science at New York University. Following his graduation in 1913 he served briefly as an instructor in engineering drawing and descriptive geometry at the University of Illinois, but in 1914 became assistant professor of electrical engineering at the Texas Agricultural and Mechanical College and was placed in charge of the development of an electrical measurements laboratory at that school. In 1917 Professor Beach was appointed head of the department of electrical engineering at Norwich University, Norwich, Vt., but remained there for only one year before being appointed to the electrical engineering faculty of the Brooklyn Polytechnic Institute as associate professor. In 1927 he received his full professorship, and in 1930 was appointed head of the department. He has been a member of the Institute's committees on education and production and application of light since 1935 and previously served on the latter committee during 1933–34. He is Institute representative on the United States National Committee of the International Commission on Illumination. Professor Beach is a member of the Society for the Promotion of Engineering Education.

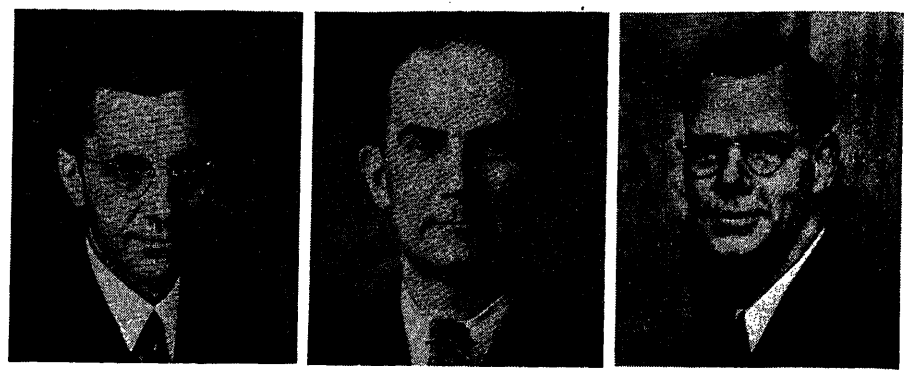
E. L. PHILLIPS (A'26) has retired from the presidency of the Long Island Lighting Company, New York, N. Y., to become chairman of the board of the company. Mr. Phillips was born at Naples, N. Y., March 1, 1873, and was graduated from Cornell University in 1895 with the degree of mechanical engineer, following which he entered the employ of the DeLaval Separator Company as a draftsman. In the following year he transferred his affiliation to the Sprague Electric Company, where he served in a similar capacity as draftsman and designer. Mr. Phillips became associated with Westinghouse, Church, Kerr, and Company, a consulting engineering firm in New York, as engineer in charge in 1897. He remained with that organization for 8 years until he established his own consulting engineering firm in 1905 under the name of E. L. Phillips and Company, with headquarters in New York. For many years he conducted a consulting and contracting business in New York and devoted much of his activity to the construction, expansion, and operation of public utility companies. Mr. Phillips was one of the founders of the Long Island Lighting Company in 1911 and held the position of president of that company for more than 25 years; however, at various times he served as president of the Empire Power Corporation and the Kings County Lighting Company and as chairman of the board of Queens Borough Gas and Electric Company, United Gas and Electric Corporation, and United Gas Engineering Company. He is a member of The American Society of Mechanical Engineers.

E. S. LEE (A'20, F'30, past director) engineer in charge of the general engineering laboratory, General Electric Company, Schenectady, N. Y., has been appointed chairman of the Institute's committee on transfers for the year 1937–38. Mr. Lee, who was born at Chicago, Ill., November 19, 1891, was graduated from the University of Illinois in 1913. He then became an instructor in electrical engineering at Union College and there earned the degree of master of science in electrical engineering, which he received in 1915. Since 1918 he has been affiliated continuously with the General Electric Company, becoming assistant engineer of the general engineering laboratory in 1928 and being appointed to his present position in 1931. Mr. Lee, a past chairman of the AIEE Schenectady Section, has served on many of the Institute's committees: finance, 1933–37 (chairman 1936–37); co-ordination of Institute activities, 1930–33, 1936–37; headquarters, 1936–37; and executive, 1933–37. He has been a member of the committee on instruments and measurements since 1927 (chairman 1927–30) and of the membership committee (chairman 1933–36) since 1933. He has served as Institute representative for the division of engineering and industrial research of the National Research Council, and was director of the Institute from 1933 until 1937. Mr. Lee is the author of numerous technical papers. He has been active in committee work of The American Society of Mechanical Engineers, American Society for Testing Materials, and American Standards Association.

W. E. CRAWFORD (M'28, F'36) consulting engineer, A. O. Smith Corporation, Milwaukee, Wis., has been appointed chairman of the Institute's committee on electric welding for the year 1937–38. Mr. Crawford was born August 21, 1889, at Big Rapids, Mich., and was graduated from the University of Michigan in 1914 with the degree of bachelor of science in electrical engineering. From 1911 until 1917 he taught physics in Michigan high schools, but in 1914 undertook electrical and power survey work for the German American Sugar Company, Bay City, Mich., concurrently with his teaching activities. After serving briefly as assistant chief engineer of the Republic Truck Company, Mr. Crawford became chief engineer of works of the Duplex Truck Company, Lansing, Mich., and remained in that capacity until 1919, when he became consulting engineer to the Mitchell Motors Company. One year later he became plant engineer for the A. O. Smith Corporation; in 1926 he was appointed consulting engineer to that organization and has been retained in that capacity continuously. He has been a member of the Institute's committee on electric welding since 1933. He is a member and past-president of the Milwaukee Welding Society and a member of the American Welding Society.

C. P. RANDOLPH (M'17) chief engineer of the Edison General Electric Appliance Company, Inc., Chicago, Ill., has been elected vice-president of the company. Mr. Randolph was born at Austin, Texas, December 30, 1888, and received the degrees of bachelor of arts (1908) and master of arts (1909) at the University of Texas. In 1909 he enrolled in the graduate school of Massachusetts Institute of Technology, and in the following year was appointed a research associate in chemical engineering. During 1911–12 he was an assistant to William Stanley

(A'87, M'98, F'13, Edison Medalist'12, past vice-president) in evolving electric heating apparatus for the General Electric Company, Pittsfield, Mass., following which he was placed in charge of experimental work on heating devices and later made managing engineer of the heating device department of that company. When the heating device department of the General Electric Company was consolidated with the Hughes Electric Heating Company and the Hotpoint Company to form the Edison General Electric Appliance Company, Inc., in 1928, Mr. Randolph went to Chicago to become chief engineer of the new company.



C. P. RANDOLPH J. B. THOMAS R. L. KINGSLAND

R. L. KINGSLAND (M'14) electrical engineer, Consolidation Coal Company, Inc., Fairmont, W. Va., has been appointed chairman of the Institute's committee on applications to mining work for the year 1937–38. Born May 15, 1882, at Nutley, N. J., Mr. Kingsland was graduated from Cornell University in 1905, and immediately after graduation entered the employ of the Westinghouse Electric & Manufacturing Company, East Pittsburgh, Pa., as an engineering apprentice. In 1907 he was transferred to the turbine testing department of the Westinghouse company, but later in the same year became superintendent of motive power of the Pittsburgh and Butler Street Railway Company. From 1908 until 1909 Mr. Kingsland again served the Westinghouse company in several positions, until he became electrical engineer for the Consolidation Coal Company. His affiliation with that company has been continuous since 1909, during which time he has been assistant superintendent of the power and mechanical department, superintendent of the power and mechanical department, and electrical engineer. Mr. Kingsland has been a member of the Institute's committee on applications to mining work since 1916, and served on the committee on protective devices from 1927 until 1929.

R. D. MCMANIGAL (A'18) assistant department manager of the Westinghouse Electric International Company, New York, N.Y., recently was appointed manager of the central station and transportation division of the company. Mr. McManigal joined the Westinghouse company in 1915 after graduation from Lafayette College with a degree in electrical engineering. After completing the company's student training course he was transferred to the general engineering department, where he remained for 7 years, with the exception of a period of service in the United States Navy during the World War. In 1922 he went to Japan as railway specialist for the Westinghouse Electric International Company, and later became managing director of the Westinghouse Electric Company of Japan. In 1931 he returned to the United States to become assistant department manager.

J. B. THOMAS (M'28) vice-president of the Texas Electric Service Company, Fort Worth, has been appointed chairman of the Institute's committee on legislation affecting the engineering profession for the term 1937–38. Mr. Thomas was born July 19, 1891, at San Marcos, Texas, and received the degree of bachelor of science in mechanical engineering at the Texas Agricultural and Mechanical College in 1911, following which he held various positions for brief periods before becoming affiliated with the Texas Power and Light Company, Dallas, first as a draftsman and later as an office engineer. During the World War he served in the United States Army Coast Artillery Corps, and at the end of the War returned to the Texas Power and Light Company as resident engineer in 1919; later he became office engineer and assistant chief engineer before being appointed chief engineer of that company in 1921. Mr. Thomas became vice-president of the Texas Electric Service Company in 1930. He has been a member of the Institute's committee on legislation affecting the engineering profession since 1931 and is at present a member of the committee on general power applications. He was a member of the special committee on the engineering profession during 1930–31. Mr. Thomas is a member of The American Society of Mechanical Engineers.

SIDNEY HOSMER (A'97, F'12, member for life) vice-president and general manager of the Edison Electric Illuminating Company of Boston (Mass.), has retired from active service. He was born July 13, 1871 in London, England, and after being graduated from Yale University in 1892 entered the employ of the Mather Electric Company, Manchester, Conn. In 1894 he was made superintendent of the underground cable department of the Boston Electric Light Company, and when that company was merged with the Edison Electric Illuminating Company of Boston, Mr. Hosmer was made superintendent of construction. He was elected a vice-president in 1926 and in 1932 became general manager and a director.

B. M. BRIGMAN (M'28) dean of the Speed Scientific School, University of Louisville (Ky.), recently was elected a vice-president of The American Society of Mechanical Engineers for the year 1937–38. Dean Brigman, born February 25, 1881, at Louisville, attended the University of Kentucky, received the degrees of bachelor of science (1908) and master of science (1912) at the University of Louisville, and studied in the graduate school of the University of Wisconsin. After teaching in Louisville high schools for several years, he joined the teaching staff of the University of Louisville in 1912, where he has remained since. In 1923 he organized the Speed Scientific School of that institution and was made its dean, a position he has held continuously.

A. A. ATKINSON (A'07, M'27) dean of the college of applied science and professor of electrical engineering and physics at Ohio University, Athens, since 1893, has retired. Dean Atkinson was born March 7, 1867, at Nelsonville, Ohio, and received the degree of bachelor of science at Ohio University in 1892. Following one year of graduate study (1892–93) at the University of Michigan he returned to Ohio University and received the degree of master of science in 1895 while serving on the faculty of that institution as associate professor of physics. He is a member of the American Association for the Advancement of Science and the American Physical Society.

E. W. KIMBARK (A'27, M'35) formerly an assistant in electrical engineering at Massachusetts Institute of Technology, Cambridge, now is assistant professor of electrical engineering at the Polytechnic Institute of Brooklyn, Brooklyn, N. Y. Professor Kimbark is a native (1902) of Chicago, Ill., and received the degrees of bachelor of science (1924) and electrical engineer (1925) at Northwestern University, following which he entered the graduate school of Massachusetts Institute of Technology and obtained the degree of master of science in electrical engineering in 1933. He was appointed to the staff of that institution in the following year.

W. H. GEIGER (A'12) assistant superintendent of the Bergen division, Public Service Electric and Gas Company, Hackensack, N. J., has been promoted to superintendent of that division. Mr. Geiger, a native (1881) of Brumfieldville, Pa., was graduated from the Keystone State Normal School of Pennsylvania in 1904 and from Lehigh University in 1908. Immediately after his graduation in 1908 he became affiliated with the Public Service Electric and Gas Company, where he has spent his entire professional career. He was assistant superintendent of the Bergen division for 18 years.

C. L. DUDLEY (A'23, M'29) assistant distribution engineer in the electrical distribution department of the Public Service Electric and Gas Company, Newark, N. J., has been made southern division superintendent of that company's electrical distribution department, with headquarters at Trenton, N. J. Mr. Dudley was born at North Branford, Conn., in 1899, and is an electrical engineering graduate of Yale University. He has served in the distribution department of the Public Service company for more than 17 years.

VICTOR SIEGFRIED (A'32) instructor in electrical engineering at Worcester Polytechnic Institute, Worcester, Mass., has been made assistant professor of electrical engineering. Professor Siegfried, a native (1909) of Seattle, Wash., and an electrical engineering graduate of Stanford University, has been on the teaching staff of Worcester Polytechnic Institute since 1933. He is author or co-author of several papers presented before the AIEE, the latest of which appeared in the October 1937 issue of ELECTRICAL ENGINEERING, pages 1285–9.

T. Y. MERRELL (Enrolled Student) has received the AIEE North West District prize for Branch paper with E. A. Rich (Enrolled Student) for their paper "Investigation of Losses in Single-phase Induction Motors," presented at a meeting of the University of Utah Branch, May 19, 1937. Mr. Merrell was born December 27, 1914, at Brigham City, Utah, and received the degree of bachelor of science at the University of Utah in 1937.

L. H. FOX (A'31, M'36) who has been associate professor of electrical engineering at Mississippi State College, State College, Miss., now is a member of the development department of Ward Leonard Electric Company, Mount Vernon, N. Y. A native of Fox, Miss., he is an electrical engineering graduate of Mississippi State College and Massachusetts Institute of Technology, and has been a member of the faculty of the former institution since 1930. He is a member of Tau Beta Pi and the Society for the Promotion of Engineering Education.

C. C. LONG (A'14, M'30) until recently mechanical and electrical construction engineer, Riegos y Fuerza del Ebro, Barcelona, Spain, now is senior electrical engineer of the Metropolitan Water District of Southern California, Los Angeles. Mr. Long previously was in Spain (1920–22), following which he was an electrical engineer in the department of engineering design of the Southern California Edison Company, Los Angeles, until 1930.

C. L. CHATHAM (A'25, M'32) electrical distribution department, Public Service Electric and Gas Company, Newark, N. J., has been made assistant distribution engineer. He is a graduate of Massachusetts Institute of Technology and has been with the Public Service company since 1922. Upon completion of a cadet engineering course he was assigned to the Passaic (N. J.) division and was transferred to the Newark offices in 1926.

E. A. RICH (Enrolled Student) has received the AIEE North West District prize for Branch paper with T. Y. Merrell (Enrolled Student) for their paper "Investigation of Losses in Single-Phase Induction Motors," presented at a meeting of the University of Utah Branch, May 19, 1937. Mr. Rich was born March 30, 1916, at Salt Lake City, Utah, and received the degree of bachelor of science at the University of Utah in 1937.

T. S. SLOAN (A'21, M'33) for the last 9 years manager of the Rome division of the Georgia Power Company, has been appointed to direct company operations in southwestern Georgia. Prior to his affiliation with the Georgia Power Company, Mr. Sloan was associated with the Central Georgia Power Company in various capacities for more than 12 years.

E. A. CHILDERHOSE (M'37, F'37) senior engineer, Federal Power Commission, New York, N. Y., has resigned to join the staff of Jackson and Moreland, consulting engineers, Boston, Mass. Mr. Childerhose will be in charge of electrical engineering on new projects coming under the supervision of that company.

W. F. JACOB (A'35) librarian of the General Electric Company, Schenectady, N. Y., and a former member of the Engineering Societies Library staff, recently was elected president of The Special Libraries Association. He served that organization previously as vice-president.

C. L. COLLENS (A'07) president of the Reliance Electric & Engineering Company, Cleveland, Ohio, has been elected to membership on the board of directors of the American Standards Association. Mr. Collens is active in the work of the National Electrical Manufacturers Association also.

J. S. JOHNSON (A'37) instructor in the department of theoretical and applied mechanics at Iowa State College, Ames, who received the degree of doctor of philosophy at that school recently, has become an instructor in electrical engineering at the Missouri School of Mines and Metallurgy, Rolla.

W. O. RAY (A'35) instructor in electrical engineering at the Texas Agricultural and Mechanical College, College Station, was appointed this fall to the electrical engineering department of the Michigan College of Mining and Technology, Houghton.

R. J. W. KOOPMAN (A'36) who has been an instructor in electrical engineering at Michigan College of Mining and Technology, Houghton, now is a member of the electrical engineering faculty of the University of Kansas, Lawrence.

H. T. KOHLHAAS (A'07, M'19) editor of *Electrical Communication*, a publication of the International Telephone and Telegraph Company, New York, N. Y., has been transferred to London, England, where that periodical now is being published.

R. E. THOMPSON (M'34) formerly mechanical engineer for the Federal Light and Traction Company, New York, N. Y., now holds a similar position with the Albuquerque (N. M.) Gas and Electric Company.

E. J. POITRAS (A'33) formerly director of research, Ford Instrument Company, Inc., Long Island City, N. Y., now is employed by the Lombard Governor Corporation, Ashland, Mass.

W. F. RAMSAY (A'30) recently was employed as a draftsman for Gibbs & Cox, Inc., marine architects and engineers, New York, N. Y.

E. J. WHEELER (A'35) asistant engineering aide, U.S. Biological Survey, San Antonio, Texas, has been made engineering aide and transferred to Denver, Colo.

W. R. UFFELMAN (A'34) sales engineer for the Clark Controller Company, Detroit, Mich., has been transferred to the Cleveland, Ohio, offices of that company.

H. F. TINCOMBE (A'36) has been appointed assistant electrical superintendent of the Canadian Johns-Manville Company, Ltd., Asbestos, Que.

J. H. ANDERSON (A'36) recently affiliated himself with the Electro-Motive Corporation, LaGrange, Ill., as a junior engineer.

F. P. WEISS (A'36) recently entered the employ of the Carnegie-Illinois Steel Corporation, Gary, Ind., as a test engineer.

W. B. RENTON (A'34) recently was appointed resident engineer for the H. J. Heinz Company, at Medina, N. Y.

G. N. BROWN (A'36) recently was employed by the Western Electric Company, Chicago, Ill., as an equipment engineer.

# Obituary

HENRY WRIGHT FISHER (A'95, M'01, F'12, member for life) retired consulting engineer for the General Cable Corporation, Perth Amboy, N. J., died near Asheville, N. C., October 7, 1937. Mr. Fisher was born January 31, 1861, at Youghal, Ireland, and was graduated from Cornell University with the degree of mechanical engineer in the class of 1888. After graduation he held one or 2 minor positions before joining the staff of the Standard Underground Cable Company, remaining with that firm until 1927, when it became a part of the General Cable Corporation and he was retained on the engineering staff of the new organization. He was chief electrical engineer of the Standard Underground Cable Company from 1889 to 1915, manager of the lead cable and rubber works from 1915 to 1923, technical director of electrical engineering from 1923 to 1927, and for one year thereafter with the General Cable Corporation, and consulting engineer from 1928 to 1930, when he retired. Mr. Fisher held patents on several improvements in cable construction and methods of locat-

ing faults in underground cables, and during the World War was one of a staff of engineers acting in an advisory capacity to the government. He served the Institute as a member of the committees on standards (1914–22) and power transmission and distribution (1915–19) and was a member of the United States National Committee of the International Electrotechnical Commission from 1919 until 1926. He was a member of the American Society for Testing Materials, American Electrochemical Society, and Sigma Xi.

KAY AXEL CHRISTIANSEN (F'37) chief engineer of the Administration of Danish Posts and Telegraphs, Copenhagen, Denmark, died July 13, 1937. Mr. Christiansen was born May 1, 1891, in Copenhagen, and received his technical education in that city, where he was graduated in 1917 as diploma engineer at the Polytechnic Institute. He entered the communications branch of electrical engineering almost immediately, and from 1919 until 1923 he worked for several telephone companies in the United States. During 1923 he entered the service of the Administration of Danish Posts and Telegraphs and became its chief engineer and head of the radio service in 1926. In that capacity he participated in the activities of the International Telephone Consultative Committee, International Consultative Committee on Radio, and the International Radio Union. In 1931 he was president of the second plenary meeting of the committee on radio at Copenhagen.

THEODORE BLACKWELL MORGAN (A'21, M'21) southern division superintendent of the Public Service Electric and Gas Company, Trenton, N. J., died September 25, 1937. Mr. Morgan was born at Morgan, N. J., in 1881, and attended Pratt Institute and the Polytechnic Institute of Brooklyn. In 1899 he entered the employ of the Electrical Testing Laboratories, Harrison, N. J., and in 1902 became a helper in the electrical laboratories of the New York Edison Company, Inc., New York, N. Y. He remained with the latter company until 1907, when he was placed in charge of the electrical laboratories of the Brooklyn (N. Y.) Rapid Transit Company. From 1909 until 1920 Mr. Morgan was associated with the Connecticut Electric Light and Power Company, and held various positions in that company until he was appointed assistant superintendent of the southern division of the Public Service Electric and Gas Company in 1920. He became division superintendent in 1928.

DAVID COBURN BACON (A'28) building and equipment engineer, Southwestern Bell Telephone Company, Dallas, Texas, died August 22, 1937. Mr. Bacon was born September 22, 1884, at Jaffrey, N. H., and was graduated from Worchester Polytechnic Institute with the degree of bachelor of science in electrical engineering. In 1909 he joined the plant department staff of the American Telephone and Telegraph Company, but 2 years later was transferred to the traffic department of the Southwestern Bell Telephone company. After 9 years in the traffic department he was made building and equipment engineer in the engineering department, a position he held continuously for 17 years.

LUCIUS FOY DEMING (A'11) district engineer for the General Electric Company, Philadelphia, Pa., died recently. Mr. Deming was born February 11, 1876, at Amboy, Ill., and was graduated from Yale University in the class of 1896. He became affiliated with the General Electric Company soon after his graduation and never relinquished his position with that company during more than 40 years of active professional service. His first position was in the testing department of the General Electric Company; later he became a d-c designer, a rotary converter designer, and in 1906 district engineer.

BANKA BEHARI ROY (A'31) power station superintendent, Ahmedabad (India) Electricity Company, Ltd., died several months ago, according to word just received at Institute headquarters. Mr. Roy was born September 14, 1889, at Dakshinpaiksha, India, and attended Calcutta University, following which he received practical training in electrical engineering as a general assistant for the British Engineering Company, Calcutta, and later was employed by several railway companies in India. He became power station superintendent of the Ahmedabad Electricity Company in 1929.

MILTON M. GESS (A'34) electrical engineer, Battery Equipment and Supply Company, Chicago, Ill., died August 25, 1937. Mr. Gess was born December 18, 1909, at Dolton, Ill., and was graduated from Armour Institute of Technology with the degree of bachelor of science in electrical engineering in 1929, following which he became a testman, and later electrical engineer for the Battery Equipment and Supply Company.

# Membership

## Recommended for Transfer

The board of examiners, at its meeting on October 14, 1937, recommended the following members for transfer to the grade of membership indicated. Any objection to these transfers should be filed at once with the national secretary.

**To Grade of Member**

Conlon, F. B., development engineer, Airtemp Inc., Dayton, Ohio.
Endicott, William, general assistant, General Electric Company, Minneapolis, Minn.
Gaskins, Richard W., electrical engineer, Union Electric Company of Illinois, St. Louis, Mo.
Meyerand, R. G., electrical engineer, Union Electric Company of Missouri, St. Louis.
O'Neill, O., assistant engineer, Consolidated Edison Company of New York, Inc., New York, N. Y.
Parker, L. H., electrical engineer, Turlock Irrigation District, Turlock, Calif.
Polster, M. A., assistant to superintendent, electrical distribution department, Consolidated Gas, Electric Light and Power Company of Baltimore, Baltimore, Md.
Shoffner, J. R., electrical and chief engineer, Allegheny River Mining Company; Reid Coal Company; Ringgold Coal Company; Ringgold Corporation, Timblin, Pa.
Spencer, T. A., member technical staff, Bell Telephone Laboratories, Incorporated, New York, N. Y.
Wolf, H. B., maintenance foreman, Duke Power Company, Charlotte, N. C.

**10 to Grade of Member**

## Applications for Election

Applications have been received at headquarters from the following candidates for election to membership in the Institute. If the applicant has applied for direct admission to a grade higher than Associate, the grade follows immediately after the name. Any member objecting to the election of any of these candidates should so inform the national secretary before November 30, 1937 or January 31, 1938, if the applicant resides outside of the United States or Canada.

Abramson, L. Z., Gibbs & Hill, New York, N. Y.
Bailey, R. E., Utah Power & Light Co., Park City, Utah.
Belkin, E. I., 1166 Manor Avenue, New York, N. Y.
Brandenstein, E. W. (Member), General Electric Co., Erie, Pa.
Burnham, R. F., Connecticut Power Company, Stamford, Conn.
Carter, H. E. (Member), Duke Power Co., Charlotte, N. C.
Carter, L. T. (Member), General Electric Company, New York, N. Y.
Cohen, LeR. D., Tennessee Valley Authority, Wilson Dam, Ala.
Dayton, C. S., Jr., Safety Car Heating and Lighting Company, New Haven, Conn.
Deardorff, H. E., Dayton Power and Light Company, Dayton, Ohio.
Dellamano, F. J., Consolidated Edison Company of New York, Inc., New York, N. Y.
Douglass, W. E. (Member), Monongahela West Penn Public Service Company, Wellsburg, W. Va.
Doyle, A. M., Canadian General Electric Company, Toronto, Ont., Canada.
Durbeck, E. F., Jr., Louisville Gas and Electric Company, Louisville, Ky.
Dyer, W. L., Southern California Edison Company, Ltd., Long Beach, Calif.
Enschede, M. H., Pacific Tel. & Tel. Co., Seattle, Washington.
Festner, R. H., New York Telephone Company, New York, N. Y.
Fulmer, J. L., Southern Bell Telephone and Telegraph Company, New Orleans, La.
Funderburg, C. H., Tennessee Valley Authority, Pickwick, Tenn.
Genthner, H. J., Rochester Gas and Electric Corporation, Rochester, N. Y.
Giba, J. J., Arma Engineering Company, Inc., Brooklyn, N. Y.
Giegerich, B. V., General Electric Company, Pittsfield, Mass.
Hagadorn, F. G., General Electric Company, San Francisco, Calif.
Hamilton, H. L., Keystone Pipe Line Company, Philadelphia, Pa.
Havens, M. LeR., 40 Arneys Mount Road, Pemberton, N. J.
Hellmann, R. K., Transatlantic Research and Information Service, Inc., New York, N. Y.
Hickey, W. J., Consolidated Edison Company of New York, Inc., New York, N. Y.
Hollifield, R., Ohio Edison Company, Akron.
Holt, C. B., Jr., Pennsylvania State College, State College, Pa.
Jewett, LeR. R., Gamewell Company, Sacramento, Calif.
Johnson, W. R., Tennessee Valley Authority, Chattanooga, Tenn.
Joyce, T., Union Electric Company of Missouri, St. Louis, Mo.
Kado, Y., Westinghouse Electric & Manufacturing Company, East Pittsburgh, Pa.
Koch, C. A., Cleveland Railway Company, Cleveland, Ohio.
Kyne, S. B., Connecticut Light and Power Company, Norwich.
Leitch, J. D. (Member), Electric Controller and Manufacturing Company, Cleveland, Ohio.
Lincoln, G. E., Western Union Telegraph Company, New York, N. Y.
Loehr, J. E., Consolidated Edison Company of New York, Inc., New York, N. Y.
Marshall, M. G., Commonwealth and Southern Corporation, New York, Jackson, Mich.
Masters, L., Eisemann Magneto Corporation, Brooklyn, N. Y.
McDonald, D. B., Texas Electric Service Co., Fort Worth, Texas.
McDonald, J. P., Scranton Electric Company, Harding, Pa.
McNamara, F. T., Yale University, New Haven, Conn.
Merwin, G. W., American Telephone and Telegraph Company, New York, N. Y.
Miller, M. C. (Member), Ebasco Services, Inc., New York, N. Y.
Neal, C. W., Oklahoma Gas and Electric Co., Oklahoma City, Okla.
Norberg, H. A., Phillips Petroleum Company, Bartlesville, Okla.

Owen, L. E., Tennessee Valley Authority, Wilson Dam, Ala.
Parks, W. K., Westinghouse Electric & Manufacturing Company, Buffalo, N. Y.
Peabody, A. W., Phoenix Engineering Corporation, New York, N. Y.
Pepperberg, L. E., Republic Steel Corporation, Cleveland, Ohio.
Peterson, J. A., Commonwealth and Southern Corporation, Jackson, Mich.
Putnam, T. R., New York Telephone Company, New York, N. Y.
Raab, C. F., Tennessee Valley Authority, Chattanooga, Tenn.
Rue, F. H., Norma-Hoffmann Bearings Corporation, Stamford, Conn.
Relfe, D. H., Port of Oakland, Oakland, Calif.
Rexroth, B. A., Southwestern Bell Telephone Company, Oklahoma City, Okla.
Rice, J. B., Allis-Chalmers Manufacturing Company, Pittsburgh, Pa.
Salisbury, A. M., Westfield Gas and Electric Department, Westfield, Mass.
Scheffer, S. L., Phoenix Engineering Corporation, New York, N. Y.
Shelton, S. P., Bureau of Power and Light, City of Los Angeles, Calif.
Sherry, R. P., Long Island Lighting Company, Glenwood Landing, N. Y.
Slater, E. A. (Member), Westinghouse Electric & Manufacturing Company, San Francisco, Calif.
Spencer, H. H., Bell Telephone Laboratories, Incorporated, New York, N. Y.
Stanley, W. McC., Tennessee Valley Authority, Wilson Dam, Ala.
Starr, F. C., General Electric Company, Rochester, N. Y.
Stein, G. M. L. (Member), General Electric Company, Pittsfield, Mass.
Stemler, D. R., Pennsylvania Power & Light Company, Allentown, Pa.
Toth, A., International Printing Ink Company, New York, N. Y.
Tratt, F. H., Stromberg-Carlson Telephone Manufacturing Company, Rochester, N. Y.
Vallin, G. L., General Electric Company, Pittsfield, Mass.
Walsh, P. H., Jr., Paul H. Jaehnig, Inc., Newark, N. J.
Watkins, J. H., Jr., General Electric Company, Pittsfield, Mass.
Weaver, C. E., Eastman Kodak Company, Rochester, N. Y.
Woods, C. A., Jr., Westinghouse Electric & Manufacturing Company, East Pittsburgh, Pa.
Wright, N. G., Ohio Brass Company, Barberton, Ohio.
Wyatt, C. H., Oklahoma Gas & Electric Co., Oklahoma City, Okla.
Young, C. F., Federal Shipbuilding & Dry Dock Company, Kearny, N. J.
Youngs, F. L., General Electric Company, Pittsfield, Mass.
Zeiner, G. E. (Member), American Telephone and Telegraph Company, New York, N. Y.

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**Foreign**

Hill, H., in care of Roan Antelope Copper Mines, Luanshya, Northern Rhodesia, Africa.
Laroza, E. E. (Fellow), Escuela de Ingenieros de Lima, Lima, Peru.
Narayan, B., Poona Electric Supply Company, Ltd., Poona, India.
Nethersole, H. J. H. (Member), Trinidad Leaseholds, Ltd., Pointe-a-Pierre, Trinidad, B. W. I.
Preston, W. F., Pernambuco Tramways and Power Company, Ltd., Brazil.

5 Foreign

## Addresses Wanted

A list of members whose mail has been returned by the postal authorities is given below, with the addresses as they now appear on the Institute record. Any member knowing of corrections to these addresses will kindly communicate them at once to the office of the secretary at 33 West 39th St., New York, N. Y.

Bodine, Ralph B., 14 N. Ferry, Schenectady, N. Y.
Boissonnault, F. L., 928 W. 8th Place, Los Angeles, Calif.
Charlton, H. C., 4827 Wilson Avenue, Montreal, Que., Canada.
Cooper, Peter G., 50 Stanton St., Schuykill Haven, Pa.
Dadashev, Musa, 32 Zamkovaja, Ulitsa, Baku, U.S.S.R.
Eakins, William V. G., 45 W. Mohawk St., Buffalo, N. Y.
Fassett, Frank C., 100 Seward Ave., Detroit, Mich.
Gregory, G. A., 1217 Jefferson Street, Olympia, Wash.
Hall, John R., 1464 S. 74th St., West Allis, Wis.
Herr, Melvin D., South 228 Lincoln St., Spokane, Wash.
Kirk, W. C., 216 E. 22nd St., Owensboro, Ky.
Koziol, Roman Joseph, 174 Farmington Ave., Hartford, Conn.
Macomber, George S., Federal Power Commission, Washington, D. C.
Matthews, Robert W., 42 St. Stephen St., Boston, Mass.
McLean, Lee Vance, 1926 North Blvd., Baton Rouge, La.
Rizk, Kaleel S., Co. 418, C.C.C., Olustee, Fla.
Roberts, William N., 4175 Springle, Detroit, Mich.
Tribble, William Harry, 303 Park Place, Brooklyn, N. Y.
Williams, Thomas J. C., 325 Seward Place, Schenectady, N. Y.

19 Addresses Wanted

# Engineering Literature

## New Books in the Societies Library

Among the new books received at the Engineering Societies Library, New York, recently are the following which have been selected because of their possible interest to the electrical engineer. Unless otherwise specified, books listed have been presented gratis by the publishers. The Institute assumes no responsibility for statements made in the following outlines, information for which is taken from the preface of the book in question.

MODERN ELECTRIC and GAS REFRIGERATION. By A. D. Althouse and C. H. Turnquist. Chicago, Goodheart-Willcox Company, 1936. 858 pages, illustrated, 8x5 in., leather, $5.00. A practical textbook for school use and home study.

PHYSICS of ELECTRON TUBES. By L. R. Koller. 2nd edition. New York and London, McGraw-Hill Book Company, 1937. 284 pages, illustrated, 9x6 in., cloth, $3.00. Considers the fundamental physical phenomena of electron tubes, disregarding external circuit conditions. The revision consists of corrections, added topics, and some expansion. Designed to interest technical men having no special training in electronics.

RECOLLECTIONS and REFLECTIONS. By J. J. Thomson. New York, Macmillan Company, 1937. 451 pages, illustrated, 10x6 in., cloth, $4.00. Mainly autobiographical, covering school and college days, first experimental work, visits to various countries, and psychical research. Later chapters contain sketches of contemporaries and lucid descriptions of certain important developments in the field of physics in which Thompson had a part, or which came within his time.

REPORTS on PROGRESS in PHYSICS, volume 3, edited by A. Ferguson. Published by the Physical Society, London, at University Press, Cambridge, 1937. 394 pages, illustrated, 10x7 in., cloth, 20s. Provides a review of the advances in physics during 1935. Among the subjects covered are: general physics, atomic physics, the measurement of noise, magnetism, experimental electricity and magnetism, electrical methods of counting, superconductivity, and the theory of metals, photoelectricity, optics, X rays, and spectroscopy.

SCIENCE MUSEUM. Board of Education. ELECTRIC ILLUMINATION, by W. T. O'Dea. London, His Majesty's Stationery Office, 1936. 40 pages, illustrated, 10x6 in., paper (obtainable from British Library of Information, 270 Madison Ave., New York, $0.20). A brief sketch of the principles, application, and development of electric lighting, prepared for general use by the Science Museum.

TROUBLES of ELECTRICAL EQUIPMENT. By H. E. Stafford. New York and London, McGraw-Hill Book Company, 1937. 330 pages, illustrated, 9x6 in., cloth, $3.00. A treatment of the ills of electrical equipment from the diagnostic viewpoint. For the practical man.

UNIFORM SYSTEM of ACCOUNTS for ELECTRIC UTILITIES. Edited by National Association of Railroad and Utilities Commissioners. New York, State Law Reporting Company, 1937. 213 pages, tables, 9x6 in., paper, $2.00. Prepared by the committee on statistics and accounts of public utilities, and recommended to the commissions represented in the membership of the Association at the 1936 convention.

WIRELESS SERVICING MANUAL. By W. T. Cocking. 2nd edition. London, Wireless World, Iliffe and Sons, 1936. 231 pages, illustrated, 5s. Devoted entirely to servicing problems; the reader is assumed to have a knowledge of basic principles.

APPLIED GEOPHYSICS, by H. Shaw. London, Science Museum. Publ. by His Majesty's Stationery Office, 1936. 102 p., illus., 10x6 in., paper, 2s. (Obtainable from British Library of Information, 270 Madison Ave., New York, $.65.) Intended as a guide to the exhibit of geophysical apparatus in the Science Museum, London; in addition contains an explanation of the various methods of geophysical surveying.

ELECTROLYTIC CONDENSERS. By P. R. Coursey. London, Chapman & Hall, 1937. 172 p. illus., 9x6 in., cloth, 10s. 6d. A summary of recent developments in the design of electrolytic condensers, together with an account of their properties and uses.

ELEKTROTECHNISCHE ISOLIERSTOFFE, Entwicklung, Gestaltung, Verwendung; Vorträge von H. Burmeister, W. Eitel, W. Estorff, W. Fischer, K. Franz, G. Pfestorf, R. Vieweg, W. Weicker. Ed. by R. Vieweg. Berlin, Julius Springer, 1937. 295 p., illus., 10x6 in., cloth, 19.80 rm. A series of lectures which aimed to give a review of the present development of insulating materials, both scientifically and technically.

INTRODUCTION to FERROMAGNETISM. By F. Bitter. New York and London, McGraw-Hill Book Co., 1937. 314 p., illus., 9x6 in., cloth, $4.00. Defines the problems whose solution may be expected to reveal the fundamental processes which constitute ferromagnetism, and discusses magnetic, mechanical, and electrical phenomena.

ORIGINS of CLERK MAXWELL'S ELECTRIC IDEAS as described in familiar letters to William Thomson. Ed. by Sir Joseph Larmor. Cambridge (England) The University Press; New York, Macmillan Co., 1937. 56 p., illus., 10x7 in., cloth, $1.00. Contains a series of letters written between 1854 and 1879 that present an account of the genesis and rapid progress of Maxwell's ideas.

THEORY of ALTERNATING-CURRENT MACHINERY. By A. S. Langsdorf. New York and London, McGraw-Hill Book Co., 1937. 788 p., illus., 9x6 in., cloth, $6.00. A text for advanced electrical engineering students, giving a comprehensive discussion of all types of electromagnetic machines as well as of the basic principles which influence their design and operating characteristics; quantitative relations are approached through the medium of geometrical representation.

VERSUCHE zur ELEKTRISCHEN RESONANZ mit HOCHFREQUENTEN und NIEDERFREQUENTEN WECHSELSTRÖMEN (Versuche mit kleinen Röhrengeneratoren). (Abhandlungen zur Didaktik und Philosophie der Naturwissenschaft, Heft 16). By F. Moeller. Berlin, Julius Springer, 1937, 1937. 82 p., illus., 11x8 in., paper, 4.80 rm. A guide to numerous experiments in the field of resonance with small vacuum-tube generators.

VORSCHRIFTENBUCH des VERBANDES DEUTSCHER ELEKTROTECHNIKER. Ed. by die Geschäftsstelle des VDE. 21 ed. Berlin, Verband Deutscher Elektrotechniker, 1937. 1414 p., illus., 8x6 in., cloth, 16.20 rm. Contains a complete set of the specifications, rules, and practices for electrical work adopted by the Society of German Electrical Engineers and in force on January 1, 1937.

WHO'S WHO in ENGINEERING, a Biographical Dictionary of the Engineering Profession. Ed. 4, 1937. Ed. by W. S. Downs. New York, Lewis Historical Publishing Co., 1937. 1638 p., 10x6 in., cloth, $10.00. Contains brief professional biographies of 12,000 American engineers.


**Engineering Societies Library**
29 West 39th Street, New York, N. Y.

MAINTAINED as a public reference library of engineering and the allied sciences, this library is a co-operative activity of the national societies of civil, electrical, mechanical, and mining engineers.

Resources of the library are available also to those unable to visit it in person. Lists of references, copies or translation of articles, and similar assistance may be obtained upon written application, subject only to charges sufficient to cover the cost of the work required.

A collection of modern technical books is available to any member residing in North America at a rental rate of five cents per day per volume, plus transportation charges.

Many other services are obtainable and an inquiry to the director of the library will bring information concerning them.

# Industrial Notes

**Federal Power Commission Hearing.**—The Federal Power Commission will hold a public hearing on November 15, in Washington, D. C., on the application of the Pacific Gas & Electric Co., San Francisco, for a preliminary permit to construct six major hydroelectric developments on the North Fork of the Feather River, having an aggregate proposed installed capacity of 368,000 kva. The company at present owns and operates the only three hydroelectric plants on the North Fork of the Feather River. These are known as Big Bend, Bucks Creek, and Caribou plants. The six proposed plants are planned to be built between the Caribou plant and the Big Bend plant. The difference in elevation between these two points is 2,072 feet and it is this difference in elevation or head of the river which is to be developed through the proposed construction. On the date of the application, the company is shown as operating 39 hydroelectric plants, two operated under lease, with a total installed capacity of 1,011,285 horsepower and 8 steam plants with a total installed capacity of 426,608 horsepower.

**Westinghouse Expands Elevator Plant.**—One of the largest and most complete elevator and electric stairway plants in the world is now located in Jersey City, as a consequence of the recent acquisition by the Westinghouse Elevator Co. of the assets of the A. B. See Elevator Co., Inc. With the removal of the Westinghouse company's headquarters from Chicago to Jersey City, plans have gone forward for increasing the manufacturing aisle space at the plant at 150 Pacific Ave., Jersey City, by approximately 50 per cent, and for doubling office space there. The A. B. See Company, third largest in the industry, was founded in 1883 by Alonzo Bertram See, and specialized in apartment house and industrial elevators.

**General Electric Orders Rise.**—Orders received by the General Electric Co., during the first nine months of this year amounted to $305,276,556, an increase of 44 per cent over the $211,891,038 received during the same time last year. Sales billed during this period amounted to $260,773,533 compared to $189,263,156 during the corresponding period of 1936, an increase of 38 per cent. Orders received during the third quarter this year amounted to $88,010,937 compared with $74,922,441 during the corresponding period last year, an increase of 17 per cent. The third quarter and the first nine months during 1937 were the largest of any similar periods since 1929.

**Roller-Smith Appointment.**—C. F. Cate, 234 N. Davis St., El Paso, Texas, has been appointed sales agent for the Roller-Smith Co., of New York City, for the southwestern portion of Texas and the southern portion of New Mexico.

**U. S. Rubber Appointment.**—The mechanical goods division of U. S. Rubber Products, Inc., has announced the appointment of Frederick D. Benz, formerly manager of wire sales, Chicago branch, as district manager of wire sales, Pacific division, with headquarters at San Francisco.

**Cutler-Hammer Appointments.**—A. R. Johnson has been appointed manager of the merchandising sales division of Cutler-Hammer, Inc., Milwaukee; Elmer F. Weiss is now manager of the Detroit office, succeeding Mr. Johnson; E. T. Rees has been appointed branch sales manager of the office in Indianapolis, and a new branch sales office at Portland, Oregon, has been opened with F. J. Woldrich in charge.

**New Thread-Cutting Screw.**—The Shakeproof Lock Washer Co., 2501 N. Keeler Ave., Chicago, Ill., has announced the development of a screw that cuts its own thread in metals and plastics of practically any thickness. Its patented, thread-cutting slot, plus a special hardening process, eliminates the separate tapping operation normally required in the use of standard machine screws. Important production savings in both labor costs and time are claimed for use of this new fastening method.

**Improved Solenoid Relay.**—An improved Durakool mercury switch is now used on type A solenoid relays manufactured by G-M Laboratories, Inc., Chicago. The Durakool switch is of unbreakable construction; the steel shell enclosing the chamber contains mercury and a liquid fill. The liquid fill is a new development which insures maximum initial contact, prevents oxidation, quenches the arc and washes away impurities. The steel enclosure is covered with a Bakelite housing. This type relay has proved particularly suited to operations where an enclosed switch contact is desirable or necessary, such as a refrigerator fan control.

# Trade Literature

**Millivoltmeters.**—Bulletin 480. Describes recording millivoltmeters for electrolysis surveys. Scales and ranges are included. The Bristol Co., Waterbury, Conn.

**Oscillograph.**—Bulletin, 4 pp. Describes new, type 168, Du Mont all purpose 5-inch cathode-ray oscillograph. Portable, for laboratory or field. Allen B. Du Mont Laboratories, Inc., Upper Montclair, N. J.

**Industrial Lighting Equipment.**—"Handbook of Localized Lighting," ML6, 16 pp. Describes flexible arm lighting units with various types of reflectors, including indirect canopy types. The Fostoria Pressed Steel Corp., Fostoria, O.

**Transformers.**—Bulletin (broadside). Illustrates 14 of the various types of transformers of this manufacturer, principally distribution and power equipment. R. E. Uptegraff Manufacturing Co., 300 N. Lexington Ave., Pittsburgh, Pa.

**Tree Wire.**—Bulletin C-36, 8 pp. Describes Anaconda Duracord tree wire. Includes interesting illustrated tests indicating the reliability of such wires under extreme operating conditions. Insulation thickness tables are also included. Anaconda Wire & Cable Co., 25 Broadway, New York City.

**Pin Type Insulators.**—Bulletin 39-1918, 4 pp. Describes radio interference proof, high voltage, pin type insulators—the method of applying copper oxide glaze, application of insulators, and methods of testing for radio interference. Westinghouse Electric & Mfg. Co., East Pittsburgh, Pa.

**Stiffness Testers.**—Bulletin 11, 12 pp. Describes various types of machines for testing stiffness of practically all materials, in every form, as well as many manufactured products used in industry. Methods of tests are outlined in full, and diagrams showing results of typical tests are included. Tinius Olsen Testing Machine Co., 500 N. 12th St., Philadelphia, Pa.

**Radio Noise Suppression.**—Folder, "Clear Reception," on the subject of background noise suppression. The several ways in which noises reach a receiver and how they may be stopped either at the set itself, or preferably at the noise source, are outlined. Also featured are the several types of noise eliminators or filters. Aerovox Corp., 70 Washington St., Brooklyn, N. Y.

**Conduit, Insulating Materials, Etc.**—Catalog G1-6A, 64 pp. Includes chapters on asbestos-cement conduit for electrical wires and cables; Asbestos Ebony, used for switchboard panels and other electrical mountings; Transcell for cell structures and doors. Among other products described are built-up and insulated roofs, industrial friction materials, pipe insulations, packings, gaskets, etc. Johns-Manville, 22 E. 40th St., New York City.

**Non-Metallic Underground Cable.**—Bulletin UC-2, 16 pp. Describes Trenchlay and Ruralay cables for direct earth installation on single phase systems. Summarizes the economic and other advantages of these types of cables for rural application, and illustrates installation and splicing methods. A comparative voltage drop chart for a specific overhead and underground line is included in the bulletin. General Cable Corp., 420 Lexington Ave., New York City.

**New Photoelectric Potentiometer.**—Bulletin 501-A, 4 pp. Describes Model 721 photoelectric potentiometer and its related equipment. The unique electronic balancing method of the new instrument is outlined, whereby widened application of potentiometric sensitivity to continuous measurement and control of rapidly varying electrical quantities, or other quantities (temperature, light, etc.) may be translated into electrical units. Among the fields of application for the unit, suggested in the bulletin, are pyrometry, electrochemical measurement and control, standardization and regulation of currents, voltages, light values, etc. Weston Electrical Instrument Corp., Newark, N. J.

# Electrical Engineering

Registered U. S. Patent Office

## for December 1937—


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### The Cover

**Not a lobster, but electric breakdown progressing through a rock-salt crystal, as seen by a visual method which gives a new insight into the breakdown mechanism of solid and liquid insulation**

Photo courtesy A. von Hippel (M'37)



# High Lights

**Earnings of Engineers.** Statistics based upon monthly earnings of engineers suggest conclusions different from those deduced by an analysis of the annual earnings. A continuation of a comprehensive survey of employment in the engineering profession shows marked differences in earnings within each professional class, and within each group classified on the basis of educational background (*pages 1450–60*).

**Winter Convention.** An enlarged program will feature the AIEE 1938 winter convention to be held January 24–28 in New York, N. Y. Tentatively, 66 papers have been scheduled to be discussed in 16 technical sessions. The program will include also several addresses and technical conferences, and a post-convention cruise to Bermuda (*pages 1516–17*).

**Co-operation Among Societies.** Two years of successful operation attest to the effectiveness of the co-operative action that resulted in the organization of the Technical and Scientific Societies Council of Cincinnati, Ohio, which brings together ten organizations comprising some 1,500 members (*pages 1525–6*).

**Trolley-Coach Operation.** The so-called "trackless trolley" has been adopted for public transportation in more than 30 cities in the United States, and in Europe. Some operating experiences with trackless trolleys on systems situated on opposite sides of the United States have been summarized and are presented in two papers in this issue (*pages 1461–3 and 1483–6*).

**Oil Oxidation.** Separate studies of the effect of equal amounts of air and of nitrogen in cable paper impregnated with oil, of the oxidation behavior of the oil alone and as affected by paper and metal, produce new information regarding the progressive changes of electrical characteristics of oil-impregnated cables (*pages 1492–1501*).

**American Engineering Council.** Recommendations for a public works department, and discussions of mapping by government agencies and of scientific research legislation now under consideration by Congress were included in the current "News Letter" of American Engineering Council (*pages 1526–7*).

**The Dielectric Circuit.** Electrostatics and the theory of the dielectric circuit frequently are confusing to students of electrical engineering. A teacher, who is renowned among his own students for his ability to make abstruse subjects lucid, has presented the fundamentals of dielectric-circuit theory in graphic style (*pages 1454–40*).

**Institute Directors Meet.** At the October 28 meeting of the AIEE board of directors, the budget for the year 1937–38 was adopted, representatives on joint organizations and committees were appointed, a revised publication policy was adopted, and other questions of importance to the membership discussed (*page 1518*).

**1937 Index . . . . . 1537**

On the 20 pages beginning with page 1537 of this issue is published the annual reference index, listing some 2,200 entries, covering all text material published in ELECTRICAL ENGINEERING during 1937. Special information regarding the index is given on page 1537.

**Insulation Committee Meets.** The tenth annual meeting of the committee on electrical insulation of National Research Council was characterized by the usual spontaneous and informal discussion, and reflected the continuing advance of research in dielectrics (*pages 1520–2*).

**United Engineering Trustees.** Officers were elected and annual reports presented at the annual meetings of United Engineering Trustees, Inc., and the Engineering Foundation; the annual report of the Engineering Societies' Library also was presented (*pages 1527–30*).

**Stray-Load Losses.** A method of measuring the stray-load losses of d-c machines, which is described in a paper in this issue, is adaptable to the testing departments of manufacturers, and requires no special equipment (*pages 1487–91*).

**Switching Surges.** The magnitude and characteristics of abnormal voltage transients accompanying operation of load-ratio control cotractors on power transformers have been studied both experimentally and theoretically (*pages 1464–75*).

**Telephone Research.** Transmitters and receivers have been developed to their present high quality by research which includes an extensive analysis of the composition of speech sounds and the study of hearing (*pages 1441–8*).

**Exposition Lighting.** Plans for the illumination of the Golden Gate Exposition in 1939 reveal the large part that lighting will play in novel forms at this $50,000,000 fair (*page 1449*).

**Institute Budget.** The AIEE budget, as adopted by the board of directors for the year 1937–38, provides for a broadening of several essential services to the membership (*pages 1433; 1522–4*).

**Noble Prize Awarded.** For the third time since its establishment in 1931, the Alfred Noble prize has been awarded to an AIEE member (*page 1519*).

**Multiple Unbalances.** The solution of a network containing a multiple unbalance may be simplified by the use of a network analyzer (*pages 1476–82*).

**Letters to the Editor.** A rotor-flux-locus concept of single-phase induction-motor operation is discussed in this month's "Letters" section (*page 1531*).

**New AIEE Section.** The Institute's 64th Section recently was organized at Tulsa, Okla. (*page 1518*).

# DISCUSSIONS

Appearing in this issue are discussions of the following papers:

## Electrical Machinery


The Saturated Synchronous Machine—Robertson, Rogers, and Dalziel 1502


## Electric Ranges


Heat Transfer Efficiency of Range Units—Walsh . 1512


## Protective Devices


Surge Protection of Distribution Systems—Hodnette and Ludwig 1503
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Expulsion Protective Gaps—Rudge and Wade . . 1508
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Relay Operation During System Oscillations—Mason 1513
Capacitance Control of Voltage Distribution in Multibreak Breakers—Van Sickle 1514
The Ultrahigh-Speed Reclosing Expulsion Oil Circuit Breaker—Schwager 1514
A Comprehensive Method of Determining the Performance of Distance Relays—Neher 1515


## Transmission and Distribution


Lightning Currents in 132-Kv Lines—Sporn and Gross 1511
Probable Outages of Shielded Transmission Lines—Waldorf 1511



Statements and opinions given in articles and papers appearing in ELECTRICAL ENGINEERING are the expressions of contributors, for which the Institute assumes no responsibility. Correspondence is invited on all controversial matters. ¶ Subscriptions—$12 per year to United States, Mexico, Cuba, Porto Rico, Hawaii, Philippine Islands, Central and South America, Haiti, Spain, Spanish Colonies; $13 to Canada; $14 elsewhere. Single copy $1.50. ¶ Address changes must be received by the fifteenth of the month to be effective with the succeeding issue. Copies undelivered because of incorrect address cannot be replaced without charge. ¶ ELECTRICAL ENGINEERING is indexed annually by the Institute, weekly and monthly by *Engineering Index*, and monthly by *Industrial Arts Index*; abstracted monthly by *Science Abstracts* (London).


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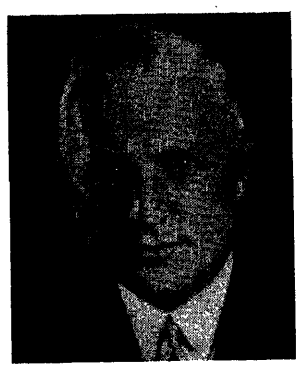

Number of copies this issue—21,800.

# The AIEE 1937-38 Budget

## *To the Membership:*

AT ITS MEETING on October 28 your board of directors adopted the budget for the year ending September 30, 1938, the details of which are covered on pages 1522–4. There are some phases of the board's consideration of the budget which seem of special interest.

The broad operations of the Institute have been conducted in an excellent manner and the modest surplus accumulated over a period of years shows an encouraging trend—a commendable showing especially as the essential services to the membership have been maintained at a satisfactory level. A few years back, here and there some curtailment of expenditures was necessary; but through constructive co-operation and sympathetic understanding of the membership at large, interest in the affairs of the Institute was sustained and activities broadened, even during these years.



President Harrison

The budget for the current year assumes that revenues will increase $10,000 as contrasted with last year and that expenditures will increase $30,000 over the same period. Total revenues are expected to be $299,500 and expenses $299,000—practically nothing to be carried over to surplus.

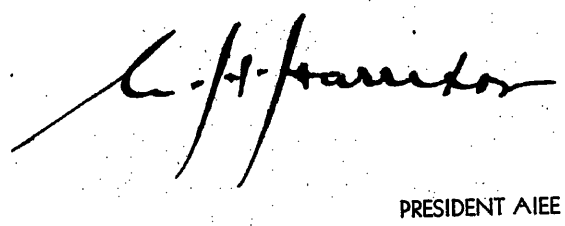
Some in the membership may question the wisdom at this time of planning expenditures on such a liberal basis and so close to the estimated income. The board recognized this but thought it proper, all things considered, to broaden several of the essential services. With the interest of the membership so great, and with so much voluntary effort being expended in behalf of the work of the Institute, it seemed clear that increased appropriations for some activities would produce substantial benefits.

In considering the expenditures it will be realized how well they are directed toward the fulfillment of the two objectives for which the Institute was created and exists: ". . . the advancement of the theory and practice of electrical engineering and of the allied arts and sciences and the maintenance of a high professional standard among its members." A considerable part of our activity centers about our publications and meetings. These activities not only satisfy the first objective but, in addition, the free interchange of information and the personal contacts which they provide are an important contribution toward the second objective. More money will be spent this year than last on publications and on national, District, Section, and Branch meetings. It is interesting to note that what we pay for is the machinery by means of which we receive a continuous flow of invaluable information and, in turn, impart to our fellow members information of value which we possess. We pay nothing for the information—we pay only for the paper, the printing, the meeting places, and the other means through which we obtain and discuss the information conveniently. A new publication policy which is to be put into practice next month and which is expected to make the publications of even greater value, already has been described in the November issue of ELECTRICAL ENGINEERING.

The Institute's objectives are also advanced through the contributions made for the support of the American Engineering Council, the Engineers' Council for Professional Development, the American Standards Association, the Engineering Societies' Library, and similar organizations through which the Institute co-operates with other national engineering societies in considering and acting on matters of common concern to the engineering and allied technical professions.

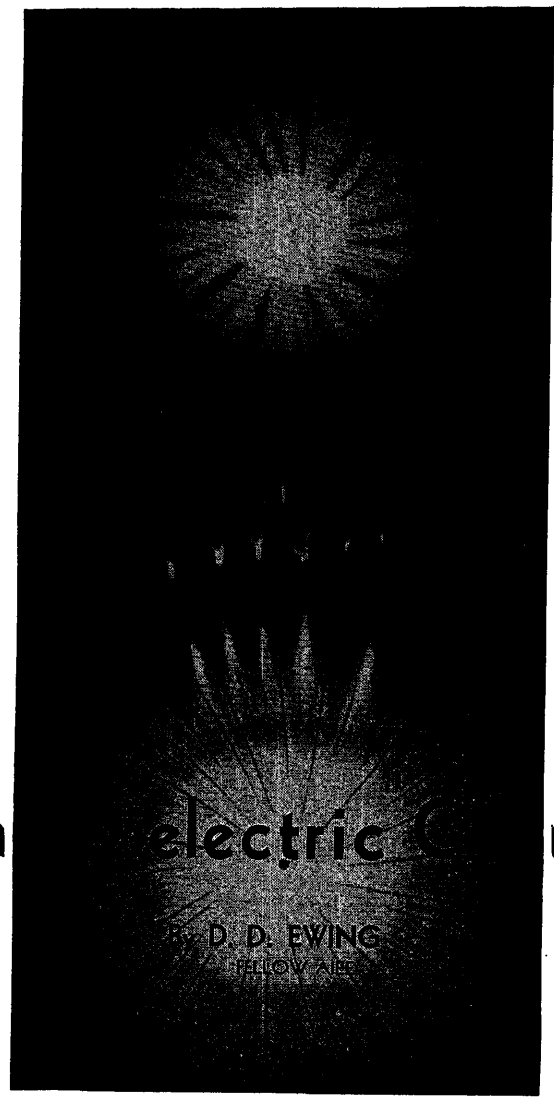
Every member of the Institute will get something of value from the sum total of expenditure no matter where he may be located. However, it is those who actively take part in the Branch, Section, and other Institute affairs who will get the greatest value. Let each of us read the publications, go more often to meetings, enter more actively into the discussions of talks and papers, and participate in the business of the committees to which we may belong. We will find that there is hardly an activity of any kind within the scope of the professional interests of an electrical engineer in which the Institute is not engaged through its committees and relations with other bodies.

We have undertaken an ambitious budget of expenditures. Your board is mindful too that still further expenditures could be made to advantage. Our principal source of income is from members in the form of dues. To assure the carrying out of this year's program and to make possible an ever broadening range of desirable activities, an increase in membership rolls is essential. Consideration of the budget makes this evident. I earnestly ask your continuing support toward this end.



PRESIDENT AIEE

# The Dielectric Circuit




**The dielectric circuit is a baffling enigma to many undergraduate students of electrical engineering; indeed, to many engineers whose work is not intimately concerned with it. This outline of some of the elementary notions regarding electrostatics and the dielectric circuit is presented here because of its possible interest and value to students and others wishing to review the subject with the aim of attaining a working knowledge of it.**

THERE IS AN ancient proverb that says in part: "he who is first shall be last." This phrase seems to have some application to the subject of electrostatics. Until Galvani and Volta made the discoveries that "galvanized" the subject of electrodynamics into life, at about the same time the present form of constitutional government was being born in the United States, the world's knowledge of electricity, and its effects, was confined pretty much to the subject of electrostatics. The versatile and questioning Franklin made many forays into this field of thought and his feat of flying a kite during a thunderstorm is known to every school boy. But with the discovery of the voltaic cell in the passing days of the eighteenth century came the great developments in the field of electrodynamics, which for a century completely overshadowed almost everything pertaining to the subject of electrostatics. True, lightning remained as a manifestation of natural electrostatic activity, and some use was found for capacitors and similar electrostatic apparatus, but a general interest in electrostatics and the dielectric circuit was quickened only when such interest was demanded by the more complex problems in telephony and radio, and by the insulation and other electrostatic problems associated with high-voltage apparatus.

Few indeed were the electrical-engineering curricula that contained any but the most meager courses of instruction in electrostatics 25 years ago; but today this neglect is not so general. As students in physics and in beginning courses in electrical engineering most of the readers of this article devoted some little time to studies of the dielectric circuit. Unfortunately it seems to be a subject about which the average seniors in electrical engineering—yes, even most of the engineers engaged in the ordinary routine work of the electrical engineer—have almost unlimited powers of forgetfulness. In the hope of paving the way, as it were, for a flying start in further studies of transmission lines and problems concerning high voltages this brief review of some of the elements of electrostatics and the dielectric circuit has been prepared.

In the space available it is not possible to give credit to all those deserving it. Also, from a strictly rigorous point of view, some readers may wish to question the methods and the accuracy of some of the illustrations used in this review. Be that as it may, the immediate object is to arrive at a reasonable working knowledge of the dielectric circuit, and the finer distinctions may well be left for argument at some other time.

For convenience, and for the purpose of securing a bird's eye view of the realm of electrostatics, the accompanying "tabloid" presentation of the subject has been arranged.

As a foundation for this discussion, almost all knowledge of the dielectric circuit may be said to be based upon the 5 fundamental laws contained in the first "box" of the tabloid presentation. Now these "laws," as most readers well know, are not written on the statute books of this or any other country. They are compilations of bits of fundamental truth refined from the elementary discoveries of many investigators. They are all based on knowledge experimentally determined. Whether or not they may be determined by rational processes instead of experimentation is a subject that is left to the physicists. For the present these laws will be considered "constitutional," at least until thrown aside by the high court of rigorous scientific research.

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Written especially for ELECTRICAL ENGINEERING, this article presents the essence of a review lecture delivered by the author to a group of senior electrical-engineering students at Purdue University.

D. D. EWING is professor of electrical engineering at Purdue University, Lafayette, Ind. A native (1883) of Vanlue, Ohio, he was graduated in electrical and mechanical engineering from Ohio Northern University in 1906, following which he spent a year in telephone and railway work. In 1907 he was appointed to the faculty of Ohio Northern University as professor of electrical and mechanical engineering, and remained in that position until 1913, when he became assistant professor of electrical engineering at Purdue University. Subsequently he became associate professor, and received his full professorship in 1918. Besides his regular teaching duties, Professor Ewing has devoted much time to consulting engineering work. He is co-author of a textbook and author of many papers on electric railway engineering. He has been a member of the Institute's committee on electric welding since 1932, and is a member of the committees on power transmission and distribution, and transportation.

These basic principles are, or should be, well known to everyone who has studied even an elementary course in physics. Misunderstanding comes when one desires to make use of this basic knowledge in the solution of the practical problems with which the engineer is familiar as part of his daily routine of duties.

The first law, namely, the law of electrostatic attraction, or repulsion, has been known for many years. The language and symbolism used in describing this law are, of course, recent; but the basic idea has been known for ages. Probably some cave-man ancestor of ours discovered it on a frosty day long ago when he stroked the back of some member of the cat family, which he was trying to tame. Thales, the Greek, wrote of the effect of rubbing amber in 600 B.C. and possibly others had noticed the effect and even written about it long before the time of Thales.

Coulomb, a contemporary of Washington and Franklin, making use of the first law, discovered the second law, which bears his name. The third law is not as well known as Oersted's discovery of a similar principle in electromagnetics but is just as true. Many readers have witnessed its demonstration—the usual procedure being to energize at high voltage a wire projecting upward through a horizontal pane of glass. Mica chips or bits of cotton lint scattered over the glass promptly arrange themselves in radial lines as shown in figure 1. The arrowheads in these figures indicate the direction of force action.

That the forces of electrostatic attraction, or repulsion, are greater in some media than in others was known to several of the earlier investigators in electrical science. In some dielectrics a given charge of electricity may produce from one to 10 times the force action that is produced in air (see the fourth law).

Like the law of attraction, or repulsion, the law of electrostatic induction (fifth law) has been known, in effect at least, for many years. Its scientific observation and formulation, however, belong to a more recent date. Other laws and effects of importance might be enumerated, but at the moment and for the present purpose, the groups of discoveries formulated in the "box" of basic laws seem most important. From these experimental laws several concepts and definitions have been set up by the physicists. These are necessary in order that the engineer may be able to formulate his problems in electrostatics. By way of illustration the basic laws might be likened to the primary roots of a great tree as shown in figure 2. Growing out of these roots comes the "trunk" of definitions and concepts, and out of the trunk grow the ideas and formulas needed in the specific fields of practical application. The most useful of these concepts are placed in the second "box."

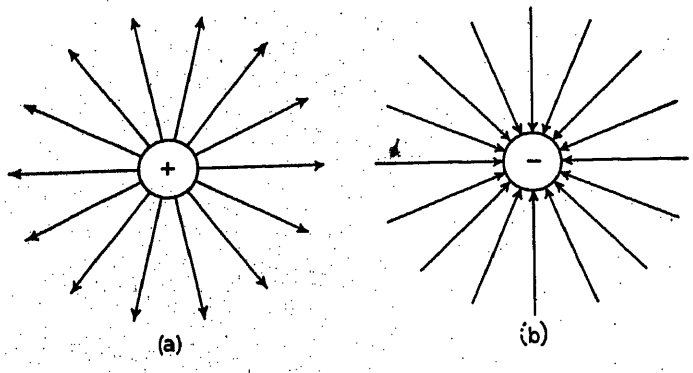



**Figure 1. Sketch of the dielectric flux lines around conductors carrying current**

(*a*)—Electrically positive conductor
(*b*)—Electrically negative conductor

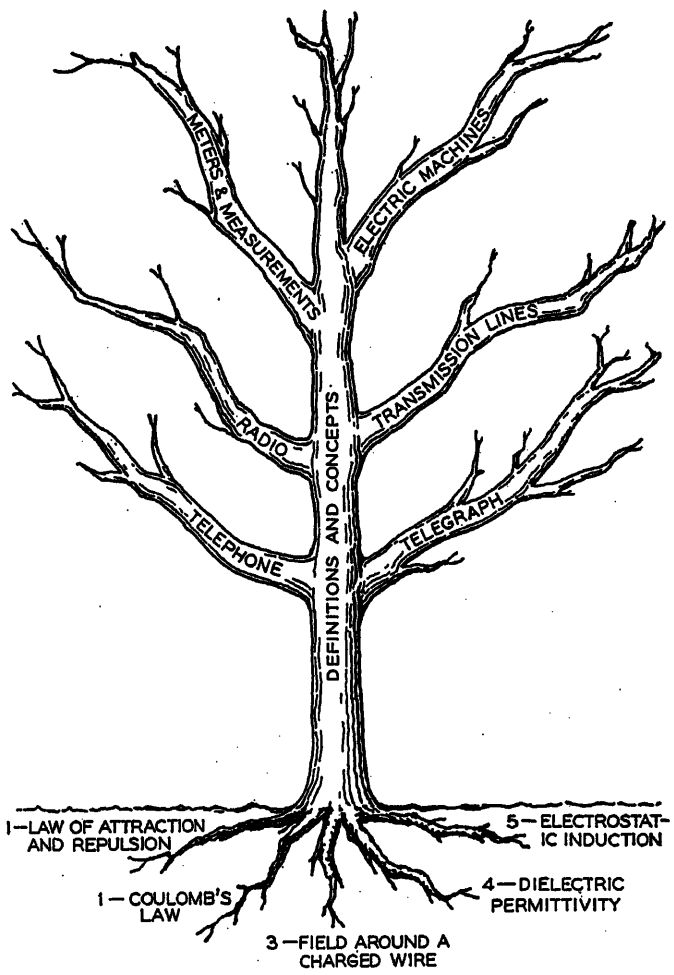



**Figure 2. The "tree" of dielectric laws and concepts**

The unit-charge concept comes directly from the first 2 laws, a unit charge of electricity being assumed to be of such magnitude that 2 similar unit charges placed one centimeter apart would repel each other with a force of one dyne. Here everything, it will be noted, is on a "unit" basis.

In order to determine the "strength" $g$ of a given field at a specified point, someone had the happy thought of placing a unit charge at that point and measuring the resulting force action. This concept of *field intensity* is based on the second law and is most useful in the formulation of problems, although no one ever attempts in a practical way to measure a unit charge, place it in an electrostatic field, and then with some sort of spring scale or balance measure the resulting force action.

# Electrostatics and the Dielectric Circuit

## 5 Basic Laws

1. Unlike charges attract; like charges repel.
2. The force of attraction (or repulsion) varies directly as the product of the charges and inversely as the square of the distance between them (Coulomb's Law: $F = q_1q_2/r^2$).
3. A charged wire is surrounded by an electrostatic field.
4. Some substances are more susceptible to electrostatic forces than are others.
5. A conducting body placed in an electrostatic field undergoes a change in potential (law of electrostatic induction).

## Definitions and Concepts

1. Unit charge.
2. Field intensity: $g = \frac{q \times 1}{r^2} = \frac{q}{r^2}$
3. Line of flux.
4. Flux per unit charge $= 4\pi$ lines

## Physicist

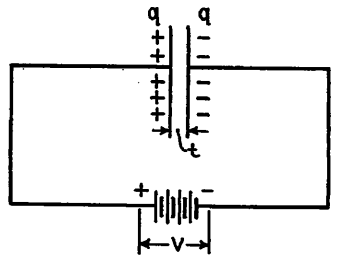
**Tools**

$g = D/K$ $\quad g = \frac{dE}{dr}$ or $\frac{dV}{dr}$

$q = VC$ $\quad D = \Psi/A$ $\quad \Psi = 4\pi q$

EXAMPLE 1—PLATE CAPACITOR

$A$ = total area of one plate
$t$ = thickness of dielectric




Assume $q$ units of charge on each plate; then $D = 4\pi q$, but $g = D/K = 4\pi q/KA$. Also $V = gt$ (see eighth concept); therefore, $g = V/t$ and

$$\frac{V}{t} = \frac{4\pi q}{KA} \quad \text{or} \quad V = \frac{4\pi qt}{KA}$$

But $V = q/C$ and $C = q/V$; therefore,

$$C = \frac{KA}{4\pi t} \text{ statfarads}$$

EXAMPLE 2—FIELD AROUND A CONDUCTOR

This method may be used for computing the potential difference between 2 concentric surfaces of radii $r_1$ and $r_2$ about the conductor. Let $q$ be the charge per centimeter of length of conductor. Then $\Psi = 4\pi q$ (fifth concept). At a radius of $x$ centimeters

$D = \frac{4\pi q}{2\pi x}$ (sixth concept); then $D = 2q/x$.

But $g = D/K$; therefore,

$$V_{r_2-r_1} = \int_{r_1}^{r_1} g\,dx = \int_{r_1}^{r_2} \frac{2q\,dx}{xK}$$

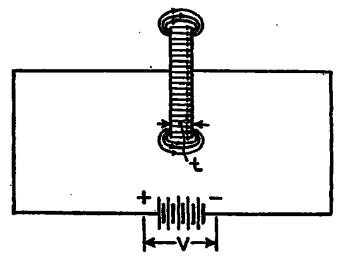
## Engineer

**Tools**

$\Psi = V/S$ or $E/S$ $\quad S = l/KA$ $\quad C = \frac{1}{4\pi S}$

EXAMPLE 1—PLATE CAPACITOR

$A$ = total area of one plate
$t$ = thickness of dielectric




First determine the elastance. This can be written at once, as

$$S = \frac{l}{KA} \text{ and } C = \frac{1}{4\pi S}$$

therefore

$$S = \frac{t}{KA}$$

because $t$ is the length of flux path, and

$$C = \frac{1}{4\pi \frac{t}{KA}} = \frac{KA}{4\pi t} \text{ statfarads}$$

EXAMPLE 2—FIELD AROUND A CONDUCTOR

This method may be used for computing the potential difference between 2 concentric surfaces of radii $r_1$ and $r_2$ about the conductor.

If $S = l/KA$, in this case $dS$ is

$dS = \frac{dx}{2\pi Kx}$ per centimeter length of conductor.

$$S = r_2 - r_1 \int_{r_1}^{r_2} dS = \int_{r_1}^{r_2} \frac{dx}{2\pi Kx} = \frac{1}{2\pi K} \log_e \frac{r_2}{r_1}$$

5. Dielectric flux per charge: $q = 4\pi q = \Psi$

6. Flux density: $D = Kg$; $D = \frac{\Psi}{A}$

7. Electrostatic potential:

$$E = \int_r^\infty g\,dr$$

where $g = f(r)$; that is, if $= g\,q/r^2$, then

$$E = \int_r^\infty \frac{q}{r^2}\,dr = \frac{q}{r}$$

8. Voltage = difference of potential $= V = \int_{r_1}^{r_2} g\,dr$

and $g = \frac{dV}{dr}$ or $dV = g\,dr$

For a flux path of uniform area $V = gl$, where $l$ = length of path. Since $V = gl$ and $g = D/K$,

$$V = \frac{Dl}{K} = \frac{ADl}{KA}$$

therefore

$$V = \Psi\frac{l}{KA} = \Psi S$$

where $S = \frac{l}{KA}$

$$\frac{V}{S} = \Psi$$

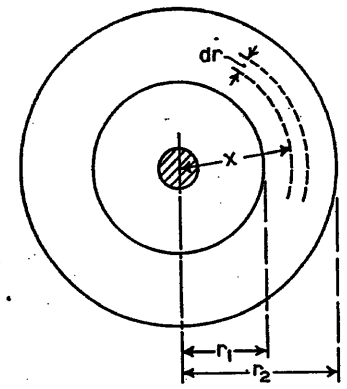
9. Unit capacitance: $V = q/C$; $C = q/V$; $q = VC$, where $V$ is the voltage impressed on capacitance $C$. Since $\Psi = 4\pi q$, $\Psi = 4\pi CE$ or $4\pi CV$; therefore,

$$\frac{V}{S} = 4\pi CV \quad \text{or} \quad S = \frac{1}{4\pi C}$$

and

$$C = \frac{1}{4\pi S}$$

where $C$ is the capacitance in farads

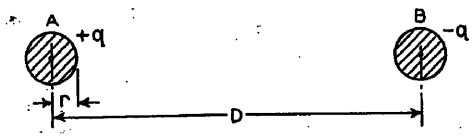



Integrating,

$$V_{r_2-r_1} = \frac{2q}{K}\log_e\frac{r_2}{r_1}\ \text{statvolts}$$

which is the voltage between the 2 surfaces.

EXAMPLE 3—LINE-TO-NEUTRAL CAPACITANCE IN A SINGLE-PHASE CIRCUIT




$V_{AB}$ = voltage between lines. Using the relations from the 2 previous examples,

$$V_{AB} = \int_r^D 2q\frac{dx}{x} - \int_r^D -2q\frac{dx}{x} = 4q\log_e(D/r)$$

remembering that in air $K = 1$. But

$$C = \frac{q}{V} = \frac{q}{4q\log_e(D/r)} \quad \frac{1}{4\log_e\frac{D}{r}}\ \text{statfarads}$$

which is the line-to-line capacitance. Since the line-to-neutral capacitance is twice the line-to-line capacitance, the line-to-neutral capacitance is

$$C_A = \frac{1}{2\log_e(D/r)}$$

statfarads per centimeter of length of the conductor.

But $V = \Psi S$; therefore (eight concept),

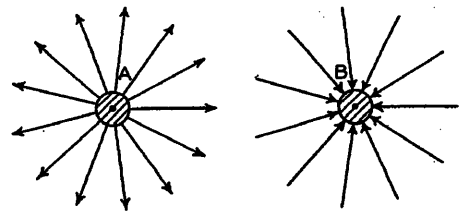
$$V_{r_2-r_1} = \frac{\Psi}{2\pi K}\log_e\frac{r_2}{r_1}$$

Since $\Psi = 4\pi q$,

$$V_{r_2-r_1} = \frac{4\pi q}{2\pi K}\log_e\frac{r_2}{r_1} = \frac{2q}{K}\log_e\frac{r_2}{r_1}\ \text{statvolt}$$

which is the voltage between the 2 conductors.

EXAMPLE 3—LINE-TO-NEUTRAL CAPACITANCE IN A SINGLE-PHASE CIRCUIT




Let $r$ = radius of conductor. Using the relations for the 2 previous examples,

$$V_{r_2-r_1} = \frac{\Psi}{2\pi K}\log_e\frac{r_2}{r_1}$$

Then the absolute potential of conductor $A$ is (that is, when $r_2 = \infty$ and $r_1 = r$, $V_{r_2-r_1}$ becomes equal to this value)

$$E_A = \frac{\Psi_A}{2\pi}\log_e\frac{\infty}{r} + \frac{\Psi_B}{2\pi}\log_e\frac{\infty}{D}$$

But $\Psi_A + \Psi_B = 0$ and also $\Psi_A\log_e\infty + \Psi_B\log_e\infty = 0$; therefore

$$E_A = \frac{\Psi}{2\pi}\left(\log_e\frac{1}{r} - \log_e\frac{1}{D}\right) = \frac{\Psi}{2\pi}\log_e\frac{D}{r}$$

But $E_A = \Psi S_A$; therefore,

$$\frac{1}{2\pi}\log_e(D/r) = S_A$$

$$C_A = \frac{1}{4\pi S_A} = \frac{1}{2\log_e(D/r)}\ \text{statfarads}$$

the line-to-neutral capacitance per centimeter length of conductor. $E_A$ is the absolute potential of conductor $A$ (line-to-neutral volts), and $S_A$ is the line-to-neutral elastance.

Whatever the invisible and mysterious thing is that surrounds a charged wire produces force action on electric charges. To assist in the visualization of this phenomenon Faraday's concept of lines of flux may be used, drawing a line per square centimeter for each dyne of force action (third concept). Since at any point distant one centimeter from a unit charge concentrated in a point the force is one dyne, and since a sphere of unit radius has an area of $4\pi$ square centimeters, it follows that the field around a unit charge may be represented by $4\pi$

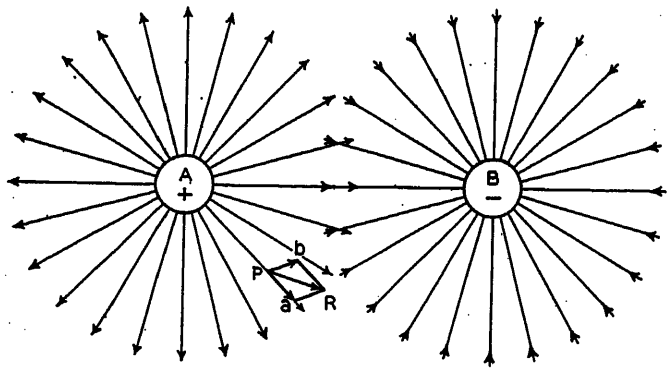



**Figure 3. Sketch of the component fields surrounding the conductors of a single-phase circuit**

lines of flux, the lines radiating from the charge like the spines of a sand bur (concept number 4). If, instead of a unit charge, the charge be of $q$ units, the total flux will be $4\pi q$ lines and the flux density (concept number 6) will be the total flux $\Psi$ divided by the area, or $D = \Psi/A$ lines per square centimeter. $D$, it will be noted from the previous discussion is equal numerically to the number of dynes of force acting on a unit charge in air and in this case is also numerically equal to $g$.

In certain media a given charge of electricity produces more force action than does the same charge in air. To illustrate, the charge that will produce a field intensity of $g$ and a flux density of $D$ in air will produce $K$ times this flux density in a specific medium. This, of course, is an exemplification of the fourth basic law. The factor $K$ is called the dielectric constant and corresponds to specific conductivity in the electric circuit and to permeability in the magnetic circuit (as $B = \mu H$). It is apparent from this discussion that the dielectric constant of air is unity. Someone who wishes to attain fame might achieve his wish if he were to discover some natural or synthetic material of which the dielectric constant is as much greater than the dielectric constant of air as the permeability of even a low grade of steel is greater than the permeability of air.

When a one-pound weight has been lifted through an elevation of 10 feet, 10 foot-pounds of work has been done. That is, the work done is equal, *numerically* in this case, *to the elevation.* This simple deduction produces an idea: The height of a mountain could be measured by determining the amount of work done in elevating a given mass from the datum plane to the summit of the mountain. Not a very good idea, the reader may say, because no good instrument for measuring the work is available. The idea is all right but the trouble is in the instrumentation. Now this idea may be used in both magnetics and electrostatics in measuring "elevation." The "elevation" (electric potential) of a charge is measured as *numerically* equal to the work done in carrying a unit charge from infinity (the "sea level" or absolute datum plane of electric potential) to the point at which the potential is to be determined. Expressing this mathematically,

$$E = \int_r^\infty g\, dr$$

where $g$ is the field intensity (force action on a unit charge) and $E$ is the potential at a point distant $r$ centimeters from the point where the inducing charge is located. In the general case $g$ is some function of $r$. To illustrate, if an electric charge of $q$ units is concentrated at a point $P$, the field intensity of another point $r$ centimeters distant from $P$ is, by the second concept, $g = q/r^2$. Therefore the electric potential at the point $r$ centimeters distant from $P$ is

$$E = \int_r^\infty \left(\frac{q}{r^2}\, dr\right) = \frac{q}{r}$$

Thus the seventh concept, the concept of electric potential has been derived. The fact that the field intensity $g$ usually is some function of the distance $r$ adds complications in the practical applications of the concept.

The eighth concept grows out of the previous one. It is more important practically, because ordinarily one is interested not in absolute potential (elevation above the absolute zero of elevation) but in difference of potential

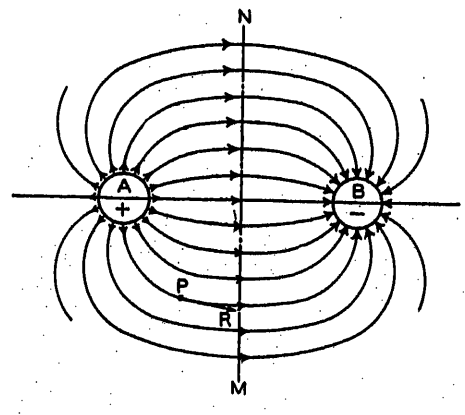



**Figure 4. Sketch showing the resultant dielectric field between the 2 conductors of a single-phase circuit**

(difference in elevation). By way of illustration, the voltage between 2 points, distant $r_1$ and $r_2$ centimeters, respectively, from the point $P$ at which is concentrated a charge of $q$ units is

$$V = \int_{r_1}^{r_2} g\, dr$$

Before integrating this expression, substitute for $g$ its value in terms of $q$ and $r$ as indicated in the previous illustration.

If this equation be differentiated, 2 useful relations result:

$$dV = g\,dr \quad \text{and} \quad g = \frac{dV}{dr}$$

If the field intensity along a path is uniform, then $g$ will be a constant and not dependent on the distance $r$. The voltage between 2 points on this path, located $l$ centimeters apart is

$$V = \int_0^l g\,dr = gl$$

But from the sixth concept, $g = D/K$; therefore,

$$V = \frac{Dl}{K} = \frac{ADl}{AK}$$

where $A$ equals the cross section of the flux path in square centimeters. But $AD = \Psi$ and so

$$V = \Psi \frac{l}{AK} = \Psi S$$

where

$$S = \frac{l}{KA}$$

It will be noted from these algebraic formulations that out of this concept grows the important relation, $V = \Psi S$, where $V$ has the significance of voltage or difference in elevation or pressure, $\Psi$ the significance of flux and $S$ that of resistance. ($S$ sometimes is called elastance and is measured in units known as darafs.) Thus this relation is similar to $E = IR$ in the electric circuit and to $\mathfrak{F} = \Phi\mathfrak{R}$ in the magnetic circuit.

Also the reader will see that elastance $S = l/KA$ is similar to reluctance in the magnetic circuit, where $\mathfrak{R} = l/\mu A$, and to resistance in the electric circuit, where $R = l/\rho A$ (the factor $\rho$ is the reciprocal of resistivity).

Another idea of importance is that the term $g$ is equal to $dV/dR$, that is, to the rate of change of voltage with distance, or to the so-called potential gradient. The quantity $g$, therefore, can be measured in volts per centimeter, volts per inch, or other suitable units. Also since $g = D/K$ it is apparent that $g$ varies directly with the dielectric flux density. This idea is of great value to the engineer in designing insulation because points at which the flux density is high are the danger points as far as insulation breakdown is concerned.

The ninth concept is well known, but the relations between $S$ and $C$ may not be so well remembered. From the relation $q = VC$ a capacitor seems to be a sort of electrical tank into which electrons can be pushed and the more electrons that are crowded into the tank, the greater the pressure $V$ will be. From another point of view the relation $C = 1/4\pi S$ indicates that from the dielectric circuit standpoint capacitance is akin to permeance, or the reciprocal of reluctance in the magnetic circuit.

The first 2 "boxes" contain about all that is needed to solve most of the problems in electrostatics. The difficulty comes in the application of this basic knowledge. Ordinarily 2 somewhat different procedures are followed, either separately or in combination, in the solution of such

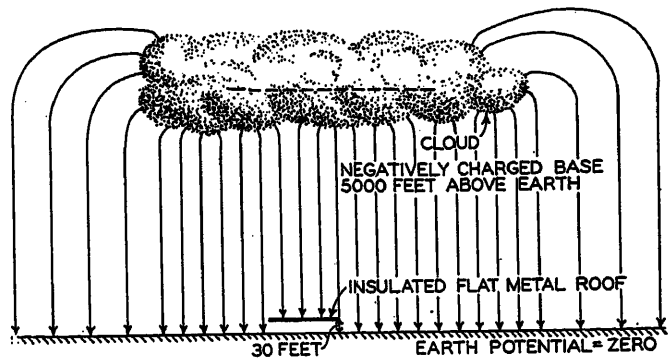



**Figure 5. Sketch showing how an insulated object close to earth may have a potential introduced in it by a charged cloud**

problems. Rather arbitrarily, and with no offense intended to either group, for the present one method may be called the method of the physicist and the other the method of the engineer. One method consists of placing imaginary charges at desired points and computing their effects. The other method accomplishes the same end by visualizing of lines of flux and determining the desired results from formulas applicable to this visualization.

In the twin boxes headed "Physicist" and "Engineer" a few typical examples have been worked out illustrating the application of the 2 procedures. The reader will notice that under the procedure headed "Physicist" a charge is assumed on the capacitor plate or wire, the gradient is then determined at some point, as at $x$ distance, and then the gradient is integrated to obtain the voltage between plates or wires, the capacitance being later determined if desired by the $q = VC$ relation. Under the other procedure the elastance $S$ is determined from the physical dimensions and then the capacitance from the relation $C = 1/4\pi S$. As elastance depends only on physical dimensions and quality of insulation, this method, as far as technique is concerned, is similar to the determination of resistance in the electric circuit and reluctance in the magnetic circuit. This is of practical importance where the design involves forms not reducible to simple geometric figures and where, therefore, mapping of the field is necessary. In general, with this procedure the engineer may use the same methods for solving dielectric-circuit problems that he uses in solving electric- and magnetic-circuit problems. This does not condemn the first procedure, however, for these procedures are but tools in the engineer's tool kit. No one would think much of a man's ability as a carpenter if he used the same saw to rip rough work and to cut off pieces of finishing lumber. Each tool has its advantages and the one used should be the one that will do the job most efficiently.

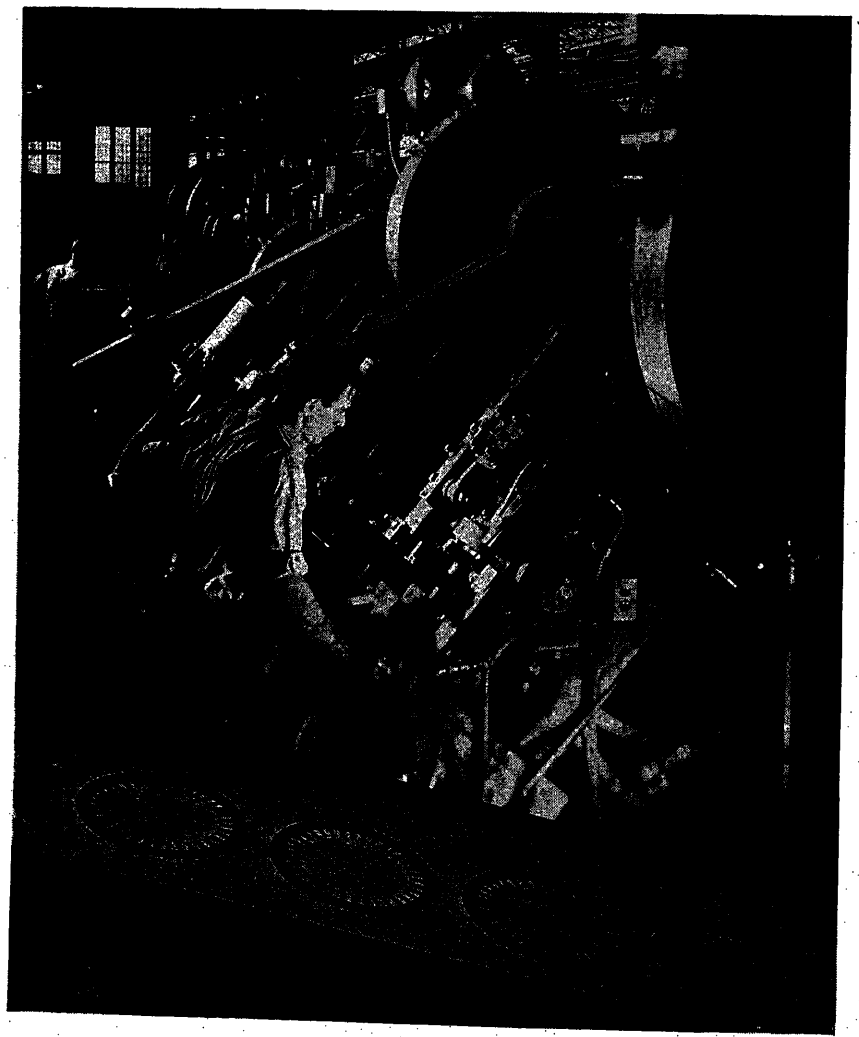
In the third example, using the second procedure, an equation for the absolute potential $E_A$ of wire $A$ has been set up in terms of fluxes and elastances. In this case there were 2 energized wires and therefore wire $A$ is in 2 component fields: its own field and that set up by wire $B$. There are 2 terms in the equation, therefore. Had it been a 3-phase circuit with 3 wires there would have been 3 terms, and so on. In this example, as in many problems in mechanics, the computer has the choice of using either

the components or the resultant of the components. The component fields, that is the field set up by each wire acting separately are shown in figure 3, the resultant force at a given point $P$ being shown together with the 2 components at this point. The resultant field between the 2 wires is shown in figure 4. It is quite apparent that the component fields, because of their simple geometry, are much easier to work with than the resultant field. In the example under discussion each term in the absolute-potential equation represents the effect of a component field.

As another example of the second procedure, assume that the potential to ground induced by a charged cloud as in figure 5 on a perfectly insulated metal roof must be determined. If the field under the cloud is reasonably uniform the potential of the roof can be estimated with some accuracy, because here, as with other series circuits, the potential of the roof has the same ratio to the potential of the cloud as the elastance from the roof to the earth has to the elastance from the cloud to the earth. Assuming the earth's surface to be at zero potential (which is not often correct) the roof potential is 30/5,000 of the potential of the cloud. In practice the potential never would be indicated by this calculation, because the roof would not be perfectly insulated from the ground.

Finally, there is one other idea that may be of some use in clarifying the reader's thinking relative to the dielectric circuits involved in transmission lines. Assume that water must be circulated through a large block of concrete, such as the Boulder Dam, for example. How could it be done? Someone might suggest that pipes or ducts should be placed in the concrete while the concrete was being poured. Quite true. Pumps then could be connected to these pipes and the water could be circulated without any difficulty except that offered by the resistance of the pipes to the flow of water. Now electrons travel through the air about as freely as water travels through concrete. If electrons are to be transmitted through the air, suitable holes or tunnels must be provided for them to travel in, just as holes through the concrete are provided to permit the circulation of water. When a line gang is sent out to build transmission lines, then, they really are being sent out to string electron holes through the air.

If too much pressure is put on the water in the hole in the concrete, radial cracks or failure of the concrete around the circumference of the hole might be expected. Similarly, if too much voltage (pressure) is placed on the electrons traveling in the holes in the air (wires), failure of the air around the circumference of the hole (wire) will result and the phenomenon known as corona will appear.



Recently placed in operation at the East Pittsburgh (Pa.) works of the Westinghouse Electric & Manufacturing Company, the battery of automatic inclined punch presses shown at the left is part of a new straight-line-production system of manufacturing a-c motors of the standard industrial type, ranging in size from 1 to 50 horsepower. Rotor and stator laminations fall from these presses upon endless belts, which convey them to other conveyors and thence to automatic assembly jigs. Although the new "motor aisle" is intended to specialize in the production of "standard" motors it is said to have facilities for turning out special items without impeding regular production

# Scientific Research Applied to the Telephone Transmitter and Receiver

By EDWIN H. COLPITTS
FELLOW AIEE

**Improvements in the transmitter and receiver, instruments basic to the telephone art, continually have led to a higher grade of service and further economies. Research work has made possible predetermination of performance by calculation, the effect of studies of speech sounds, hearing, materials, and testing methods on the development of instruments giving high quality for conversation is shown by this article, which is based on one of three Iwadare lectures* delivered in 1937.**

LET US recall a scene at the Centennial Exhibition in Philadelphia in 1876. Across a room had been strung wires connecting crude instruments, at one end of the room a transmitter and at the other end of the room a receiver. Dom Pedro, Emperor of Brazil, takes up the receiver and listens while Alexander Graham Bell speaks into the transmitter. The Emperor, astonished at hearing Mr. Bell's voice in the receiver, exclaims in amazement, "My God, it talks."

When at the same place, Sir William Thomson (later Lord Kelvin) took up the receiver and listened to Mr. Bell, the words of this distinguished scientist were, "It does speak," and continuing, "it is the most wonderful thing I have seen in America."

Sixty years have passed and, as a result of continued effort, the use of the telephone has become such an everyday matter that even the ability to talk from one continent to another scarcely excites comment or wonder. It is not surprising that, to the layman, the element of distance seems the most striking factor in the technical development of the telephone art. As a matter of fact, while the conquest of distance has involved much scientific effort, and very ingenious and highly developed methods for the transmission of speech currents, the magic of the telephone still resides in the instruments which provide for the conversion of mechanical energy, namely speech sounds of highly complex wave form, into electrical currents of corresponding wave form, and the reverse process of converting these electrical currents into speech sounds. These instruments, the transmitter and the receiver, are basic to the whole telephone art. As they have been improved by development and design, it has become possible not only to render a higher grade of service but to effect economies in other portions of the plant. For example, the very extensive use of fine-gauge cables was, to a large extent, made possible by the development of more efficient transmitters and receivers. Further perfecting of these instruments promises additional improvements in service and some further economies.

Telephony, restricting the term to ordinary 2-way talking between individuals, involves an element not present in any other service. It does not greatly concern one customer of an electric light or power company whether another customer chooses to use inadequate or inefficient or poorly located lamps or other equipment. That is, each user of the service is, under any ordinary conditions, independent of all other users. In the case of telephony, however, the problem is entirely different; for one user of the telephone is greatly concerned with not only the apparatus furnished to any one with whom he has occasion to talk but also with other factors affecting the use of this apparatus, such as the amount of noise in the room where the apparatus is located, the user's habits of speech, and whether his ability to hear is normal. Telephone instrumentalities must therefore be so designed and the plant so engineered as to meet reasonably wide variations from what may be termed normal conditions, and ratings of performance should be similarly established.

No single factor is more important to a sound development of this art than the subscriber apparatus. The research program basic to the development and design of transmission instruments has itself been a matter of development as a better understanding of the problems unfolded and as the need for research in this or that direction became apparent. The research problem basic to the development and design of transmission instruments may be described as having the following very broad scope: an understanding of their physical operation viewed as electromechanical structures; an understanding of speech mechanism and an accurate physical definition of speech air waves; an understanding of the hearing processes and a determination of how hearing is affected by factors present in telephony. Also, the research program may be said to have included research upon certain materials, the results of which have an important bearing either upon an understanding of the operation of these instruments or upon their practical design. In addition to the development of many methods of measurement and testing applicable to laboratory research and development, of very

* Essential substance of a lecture delivered in the spring of 1937 in Japan under the sponsorship of the Iwadare Foundation. This foundation was established in the Denki-Gakkwai (Institution of Electrical Engineers of Japan) for the following purposes: (1) to send one or two Japanese electrical engineers to the United States each year to study for about one year, and (2) to invite distinguished electrical engineers from the United States to deliver several lectures in Japan once or twice a year. The Japanese society asked the assistance of the AIEE in the guidance of the engineers sent to the United States for study, and also in the selection of distinguished electrical engineers to lecture in Japan. The AIEE board of directors authorized a committee for this purpose in 1931.

EDWIN H. COLPITTS retired early in 1937 as a vice-president of the Bell Telephone Laboratories, Inc., New York, N. Y., after having been engaged in telephone work since the beginning of the century. He has been granted many patents, and has written numerous technical papers. Recently he was awarded the Japanese Fourth Order of Merit of the Sacred Treasure in recognition of his promotion of electrical engineering in Japan.

great importance has been a development of the testing methods which permit of a better final evaluation of the developments based upon the results of this activity.

## Instruments as Electromechanical Structures

The telephone transmitter itself is a complex mechanical and electrical structure. Its general method of operation can be described qualitatively in relatively simple terms, but the operation of few structures is more difficult to define in definite quantitative terms and relationships. For example, there are acoustical problems such as those involved in the air connection between the lips of the speaker and the diaphragm of the instrument. This air connection may involve a short column of air as in those instruments which have a telephone mouthpiece. Connection between the column of air and the working parts of the transmitter may be partially closed by a perforated section. When the operation of the instrument itself is considered, there is involved the mechanical vibration of the diaphragm as it operates on the carbon, and further, the whole question of electric conduction in the small mass of granular carbon itself.

In the receiver which converts telephonic currents into speech sounds, there are very similar acoustical, mechanical, and electrical problems with the exception, of course, of the mechanical and electrical problems introduced by the carbon of the transmitter.

A large amount of research work has been carried on relating broadly to the transmitter and the receiver as electro-mechanical physical structures. The theory of these devices as vibrating systems has been developed so that their over-all performance can be related to the various structural features. Consequently, development and design engineers are now enabled to predetermine by calculation how certain modifications in structure will affect the physical performance of the instrument. In other words, the design process has become very much less "cut and try."

Research has been undertaken and substantial progress has been made on a study of microphonic action in carbon.

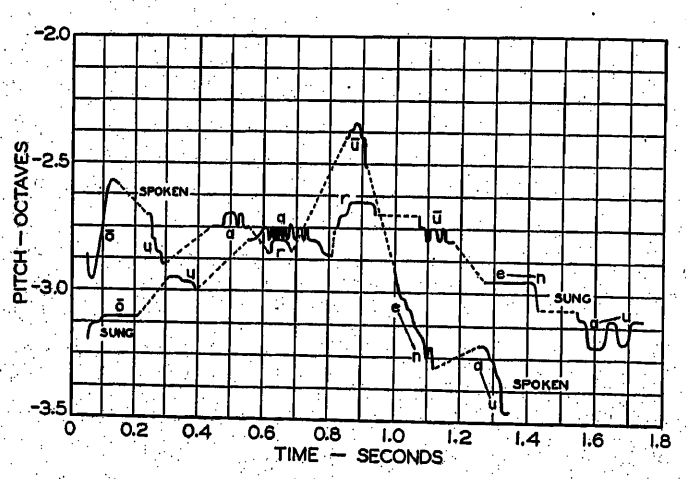



**Figure 1. Melodic curves showing the variation of pitch with time as the sentence "Joe took father's shoe bench out" is spoken and sung**

In order to develop a complete theory of the operation of the transmitter, it is necessary to understand fully what takes place between each carbon granule in the carbon chamber.

## Speech Sounds

The source of any voiced sound is in the larynx. On both sides of this larynx there are 2 muscular ledges called the vocal cords. During breathing these ledges are widely separated, but when a voiced sound is produced, they come close together, forming a long narrow slit. As they come close together, the air passing through the resulting slit is set into vibration producing a sound. It has been generally supposed that the pitch of the tone thus produced was determined by the natural frequency of vibration of the 2 vocal cords, and that by changing the tension of these cords, the pitch of the tone can be raised or lowered at will. The studies revealed that the natural pitch of these cords while a tone is being produced is considerably below that of the pitch of the tone. It is true that the pitch of the tone produced is affected, somewhat, by the elasticity of the vocal cords, but it is principally controlled by the size of the air opening between them. The little plug of air between the 2 vocal cords vibrates through a very much larger amplitude than the amplitude of the cords themselves and is the real source of the sound. The mass of this small plug is controlled by the size of the opening and by the elastic forces pushing it to and fro—namely, the air pressures on either side of it. It is evident that these oscillating pressures will be influenced by the size and shape of the trachea leading into the lungs on one side and by the size and shape of the tongue, mouth, and nasal cavities on the other. The mechanical action involved is analogous to the electrical action in a vacuum-tube oscillator. The sound which is generated at the vocal cords is modified as it passes through the throat, mouth, and nasal passages. The real character of the sound which enables identification of words is wholly dependent upon the manner in which this cord tone is modified by the changing sizes, shapes, and characters of these passages and the outlet to the outside air.

After the various speech sounds leave the mouth, they are transmitted to the ear of the listener by means of air vibration. As an example of the type of disturbance created in the air, consider the sentence, "Joe took father's shoe bench out." This silly-sounding sentence is chosen because it is used for making tests on the efficiency of telephone systems. The sentence, together with its mate, "She was waiting at my lawn," contains all the fundamental sounds in the English language that contribute appreciably toward the loudness of speech. As the sound wave produced by speaking this sentence travels along, each particle of air over which it passes executes a vibration through its original or undisturbed position. The successive positions occupied by the particle as it moves in the complicated series of vibrations corresponding to a spoken sound can be visualized in laboratory investigations from oscillographic records of the corresponding telephone currents.

Each successive particle of air along the line in which the sound is traveling executes a similar complicated series of vibrations but any particular oscillation is performed at a later instant by the particle which is farther away from the source of the sound. The disturbance in the air which represents a spoken sound may then be pictured either, as was first described, in terms of the successive positions of a single particle or in terms of the displacements at any instant of each of the particles along the line of travel of the sound wave. For example, for the sentence "Joe took father's shoe bench out," the disturbance carrying the sound *j* in the word "Joe" is about 1,500 feet from the mouth by the time the sentence is finished.

If an analysis is made of the wave when the sentence "Joe took father's shoe bench out" is spoken, the variations in pitch of the speech sounds can be determined from the vibration rate. Such an analysis is shown in figure 1. The variations in pitch are represented on the vertical axis, zero being taken at 1,000 cycles per second. The duration of the sounds in fractions of a second is represented on the horizontal axis. It may be seen that the pitch rises and falls as the various sounds are spoken. This representation of the pitch variation is called the fundamental melodic stream. It is the melody in the same sense as this term is used in music, although it is evident that the pitch changes do not take place in musical intervals as would be the case if the sentence were sung.

To show the contrast, a graph was made when the sentence was intoned on the musical intervals *do, re, mi, fa, mi, re, do.* An analysis of the graph gave the result shown in figure 1. In the case of the sung sentence the pitch changes are in definite intervals on the musical scale, while for the spoken sentence the pitch varies irregularly, depending upon the emphasis given. The pitch of the fricative and stop consonants is ignored in the musical score, and since these consonants form no part of the music, they are generally slid over, making it difficult for a listener to understand the meaning of the words. A singer's principal aim is to produce beautiful vowel quality and to manipulate the melodic stream so as to produce emotional effects. To do this, it is necessary in singing to lengthen the vowels and to shorten and give less emphasis to the stop and fricative consonants. It is for this reason that it is more difficult to understand song than speech.

There are 2 secondary melodic streams of speech represented by the second and third curves from the bottom of figure 2, which are due to the resonances imposed upon the speech sound by the throat and mouth cavities. The numbers on these curves give the number of the harmonic which is reinforced. These 2 secondary melodic streams are not sensed as changes in pitch, but rather as changes in the vowel quality. Then there is a fourth stream, or, it would probably be better to say, a fourth series of interrupted sounds which are very high in pitch and are the sounds which enable us to identify the fricative consonants. The secondary melodic streams produced while speaking the same sentence are approximately the same for different persons, even for a man and a woman, while the fundamental melodic stream is usually quite different. This latter stream is not used in identifying words, but it is

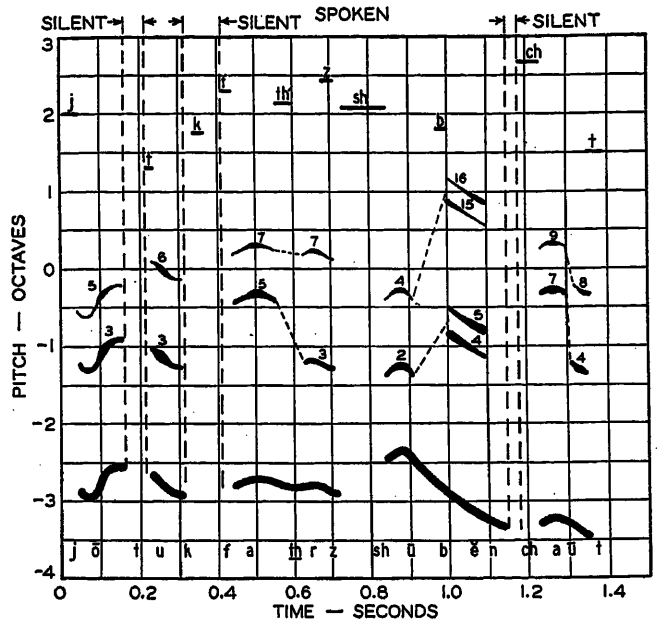



**Figure 2. Melodic curves showing the variation of pitch with time as the sentence "Joe took father's shoe bench out" is intoned on the musical intervals do, re, mi, fa, mi, re, do. The pitch changes in regular intervals rather than in irregular intervals as shown in figure 1**

used sometimes to give different meanings to the same words.

As one listens to this sentence he hears the variations in loudness as well as in pitch. Loudness is related to the amplitudes and frequencies of the components of the tone, but this relationship is very complicated. It is dependent upon the action of the ear, including the nerve mechanism carrying the message to the brain. This relationship has been under study for several years so that it is now possible to calculate from physical measurements the loudness for a typical ear and also to devise instruments for measuring approximately the loudness of any sound. The result of using such a device for recording the variations of loudness in the spoken sentence which has been discussed is shown in figure 3. For comparison, the variations in pitch are also shown in this figure.

It is not possible here to describe the devices by which the energies and frequencies involved in speech are measured accurately, but the results of this research work are interesting. When this sentence is spoken fairly rapidly, it will contain about 200 ergs of energy. About 500,000,000 ergs of energy pass through the filament of an ordinary incandescent lamp each second. This shows that the acoustic energy in this sentence is very small. An examination of the wave produced by this sentence shows that the vowels contain considerably more energy than the consonants. Exact measurements have indicated that in ordinary conversation the ratio of the intensity of the faintest speech sound, which is *th* as in "thin," to the loudest sound, which is *aw* as in "awl," is about one to 500. The actual power used in producing the various sounds depends, of course, upon the speaker and the emphasis with which he pronounces the sound. The

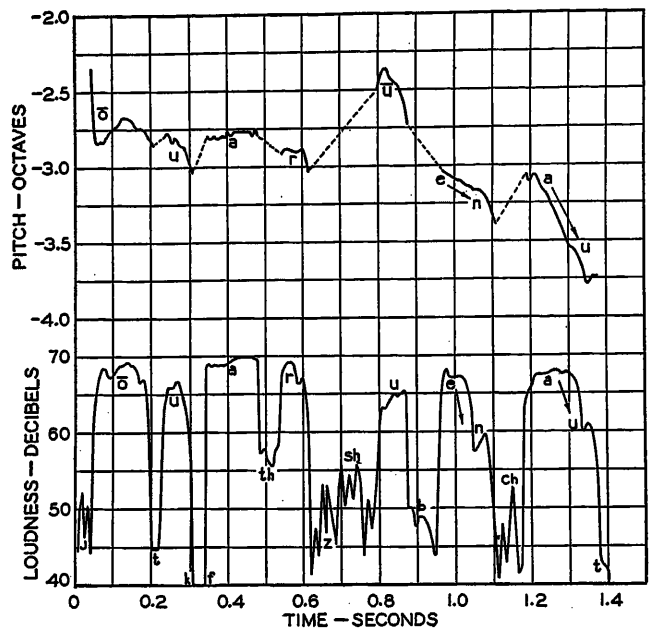



**Figure 3. Graph of the loudness of the various sound elements when the sentence "Joe took father's shoe bench out" is spoken**

power in an accented syllable is 3 or 4 times that in a similar unaccented syllable. Measurements upon voices during a conversation have indicated that the average power in the speech produced is 10 microwatts. Some speak with more and others with less than this power. Tests on a sample group show that 7 per cent speak with less than one sixteenth the average power, 18 per cent use powers lying between one quarter and one half the average, and 4 per cent between 4 and 8 times the average. No speakers were found to use more than 8 times the average for conversational purposes.

As a conversation proceeds, the speech power varies from zero during the silent intervals to peak values which frequently are 100 times the average power. Examination of one-eighth-second-intervals throughout a typical conversation shows that for 17 per cent of them the peak power lies between 8 to 16 times the average over a long interval. It is found that the most frequently occurring value of the peak power is about 10 times the average.

Although a typical voice of a man and a typical voice of a woman are alike in that they use the same average power and variations of power from this average, they are different in other respects. It is well known that the pitch of the voice of a woman is about one octave higher than that of a man. It was not known, however, until laboratory experiments revealed it, that the intensity of the components having vibration rates above 3,000 cycles per second was definitely greater for voices from women than from men. For some reason which is not very evident, women use higher pitch sounds for producing the fricative consonants, and this results in greater power in the regions of higher pitch. Every one who is familiar with transmission systems knows well that these high-frequency components are nearly always eliminated. While these sounds are not of controlling importance in properly understanding speech, it is evident that the women's voices are somewhat handicapped as compared with men in systems which eliminate them.

## Hearing

Paralleling research on speech sounds, hearing has been investigated. Broadly speaking, the aim has been to arrive at an accurate physical description and a measure of the mechanical operation of human ears in such terms that they may be related directly to the electrical and acoustical instruments. The keenness of the sound-discriminating sense has been measured, and the smallest distortion which the mind can perceive, and how it reacts to somewhat larger distortions, has been determined. This information is utilized in determining a reasonable basis of design both for separate instruments and for transmission systems as a whole, to give a proper balance between cost and performance.

One of the first steps was to determine in a quantitative way the performance of ears as machines. It was obviously important to know how faint a sound the ear can hear, and also how loud a sound the ear can tolerate. With the advent of the vacuum tube, it was possible to develop methods of accurately measuring the intensity of faint sounds and of readily producing such sounds. Figure 4 gives the results of measurements made to determine the limits of hearing. This graph is called the auditory sensation area. The lower solid curve represents the minimum sound that an average young person can hear. The abscissa gives the frequency of the pure tone, and the ordinate the sound pressure in dynes per square centimeter. The top solid curve represents the maximum intensity of sound that the ear is capable of handling. This curve was determined by noting that intensity which produced a feeling sensation. Intensities slightly higher than this result in pain and in some instances serious injury to the ear. The dotted lines on either side complete the enclosure and represent the upper and lower limits of pitch that can be heard. From this figure, the upper or lower limit of pitch obviously is greatly dependent upon the intensity at which the sound is produced. It may be seen that near the middle range of frequencies, the pressure range is one million to one. The pitch range of pure tones is from about 16 to 25,000 cycles per second.

These results are for young adults, and it may be of interest to note that as one becomes older the hearing acuity, at the higher frequencies particularly, becomes less. In table I are shown some measurements to determine what the effect of age would be upon the hearing acuity; these are average values obtained from measurements on a large number of persons.

Another important measurement of average hearing is that concerned with minimum perceptible differences in pitch and in intensity. Careful measurements on large groups of people have given reliable data. Near the threshold changes in intensity of about 4 decibels are necessary to be perceptible, while at fairly high intensities about $1/4$ decibel is all that is necessary for the change to be perceived. Minimum perceptible differences in pitch

vary from about 0.0025 octave to 0.19 octave, depending on the frequency and the intensity. The results of this line of investigation have an important bearing on the physiological theory of hearing, and another important result has been the development of methods of determining the degree of impairment of hearing.

In telephony we are, of course, not directly concerned with simple sounds, but with the highly complex sounds of speech, and these are on actual telephone circuits generally associated with extraneous sounds which may be grouped under the broad term of noise. Further, telephone instruments are not perfect, and could be made to approach perfection only at a great expense. In order to arrive at a quantitative understanding of the importance of departures from perfection in telephone transmission elements and conditions of use, the general procedure in very general terms has been as follows: Transmission systems so nearly perfect that even the keenest ear could not find a flaw in their transmission performance are set up, and then measured imperfections or variations are introduced.

By this general process, the effect of noise of chosen intensities either as noise present in the telephone receiver or as noise in the room was determined. Similarly, the effect of a line or other characteristic such that voice frequencies above a certain value or below a certain value were not transmitted, was determined. The effect of introducing a highly resonant element or of a nonlinear element was studied. The range in loudness of speech necessary for best reception was likewise measured.

As noise became recognized as a very real factor, a standard basis for noise measurements was established. Consequently it is now possible to measure noise on a telephone circuit or in a room, and to state the result in terms of a standard unit.

## Materials

In the practical design of modern telephone instruments we owe a large debt to the chemist and the metallurgist. Modern molding materials and processes are utilized in order to secure forms of apparatus satisfactory from the standpoint of appearance and of mechanical strength. The newer types of permanent magnet steel provide possibilities of light-weight and very efficient magnetic structures.

It is a most striking circumstance that commercial telephony is dependent upon the performance of a small mass of carbon granules in the transmitter. No single material entering into the construction of telephone apparatus has therefore greater importance. In America at least, transmitter carbons are largely derived from a certain specially selected anthracite coal. In its natural state, this coal exhibits none of the characteristics required for its use in a transmitter. These characteristics or properties are secured by heat treatment. These heat-treatment processes were for many years the result of empirical development and were not well understood nor, as is now recognized, adequately controlled. This resulted in a product of uncertain quality. An important task of the Bell Laboratories was therefore to study each step in the process of producing carbon and to develop a process definitely specified at each step, which would be capable of giving the desired uniform quality. The results so far obtained have had very important reactions upon transmitter performance. The Laboratories have also set themselves the more elementary task of understanding the fundamental properties of carbon contacts. One important element of this research is to determine the causes of resistance changes produced when the compressive force on a mass of carbon granules is changed. It is too early to report results from this research, but it seems clear that granular carbon will be an important element in the design of transmitters for many years to come, and we should seek to obtain complete fundamental knowledge of its operation.

**Table I. Decibel Loss in Hearing With Age**

| Frequency | 60 to 1,024 Cycles | 2,048 Cycles | 4,096 Cycles | 8,192 Cycles |
|---|---|---|---|---|
| Ages 20–29 (96 ears) | 0 | 0 | 6 | 6 |
| Ages 30–39 (162 ears) | 0 | 0 | 16 | 11 |
| Ages 40–49 (84 ears) | 0 | 2 | 18 | 16 |
| Ages 50–59 (28 ears) | 0 | 5 | 30 | 32 |

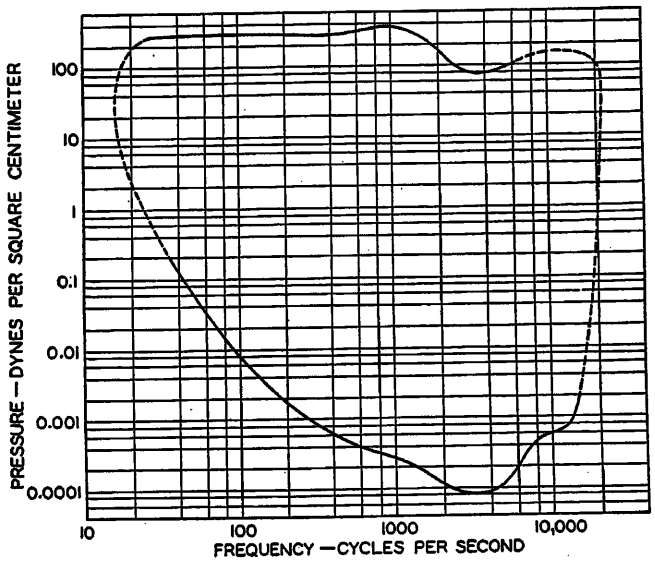



**Figure 4. Auditory sensation area for the typical ear of a young adult**

## Testing Methods

Broadly speaking, methods of testing have been developed, first, to enable the development and design engineer to determine quantitatively the various performance factors of the apparatus under development, and second, to determine how well the apparatus which has been developed performs under service conditions. In the Bell Laboratories, methods have been developed during the last 20 years for measuring the physical constants of the apparatus involved so that this apparatus may be an-

alyzed as electromechanical structures. Further, in the design of telephone transmission apparatus we are concerned with a power transmission system in which the design engineer has no control over the power source, the human voice, nor over the receiving agency, the human ear. His control is limited to the conveyance of power from speaker to listener. In the Laboratories, therefore, we have recognized that it is necessary, at least with our present knowledge, to supplement physical measurements by measurements involving speech sounds and the human ear. Some years ago, these tests consisted of comparisons between different instruments or transmission elements made by the process of talking first over a circuit containing, for example, one instrument, and then over the same circuit containing a different instrument. Dependence was placed wholly upon the listener's skill to detect differences in volume, quality, and intelligibility. It was recognized that this method of testing left much to be desired. Owing to the limitations of the human ear, small volume differences could not be detected, but even more important, this simple test furnished no very accurate measure of speech distortion affecting intelligibility, and obviously no definite information as to the relation between volume, various types of distortion, and over-all effectiveness.

Doctor George A. Campbell, in 1910, proposed a method of testing which has been highly developed in the Laboratories. This method, termed "articulation testing," measures the relation between the reproduced and impressed sounds from the standpoint of effects on intelligibility of different kinds of distortion. This method has been described in several publications. Briefly, in this method, lists of syllables chosen at random and usually meaningless monosyllables are called over the circuits to be rated, and the percentage of syllables correctly understood gives a measure of the circuit performance. Further, the method has been extended to give quantitative measures in terms of the recognizability of reproduced speech sounds, of the effects of loudness of these sounds, and of the noise which may be present.

While various physical tests and the articulation test method are exceedingly useful tools in the hands of the research and development engineer, they do not give a direct measure of the transmission service performance of a circuit in terms of the ability of the user to carry on a conversation under actual commercial conditions. This ability of the user to carry on what may be termed a successful telephone conversation depends not only upon the performance of the telephone instruments and circuits but also, to a substantial extent, upon the users' own performances—the subject material of conversation, how they talk into the transmitters, and how they hold the receivers —and upon the room noise conditions. In other words, there are a number of factors random in nature which, while beyond the control of those who design and engineer the telephone plant, must be taken account of in rating the service performance.

Much thought and effort have been given to the problem of how best to determine transmission service performance. Very briefly stated, we have been led to the following steps: In order to take suitably weighted account of all the factors involved, service performance ratings should be based on service results, that is, transmission service performance should be measured by the success which users of the telephone circuit have in carrying on conversations over the circuit. With the various factors in mind, we have fixed upon what we have termed "effective transmission" ratings for transmission plant design. These ratings are based on a determination of the *repetition rate* in normal telephone conversations.

As the effect of a change in a circuit depends upon its initial characteristics, it is necessary in order to be able to compare numerical results to have a basic circuit for reference. By suitable choice of basic circuit, it is possible to express the effects of changes in any one transmission characteristic in terms of the attenuation of the trunk. For example, the effect of changes in sidetone level in the subscriber's set can be expressed as so many decibels change in trunk attenuation.

## Association of Transmitter and Receiver

In order to furnish a convenient 2-way talking circuit over a single pair of wires, the transmitter and the receiver at each end of the circuit must be continuously associated in the circuit. This has been accomplished by various circuit arrangements since the early days of the telephone, and as every user of the telephone knows, leads to the condition that when speaking into the transmitter one hears his own voice in the receiver. Local speech so heard is designated as sidetone. The Laboratories have carried on research in order to determine the effect of sidetone on the over-all efficiency of the circuit. Sidetone above a certain volume has been found to decrease the conversational efficiency of the circuit. Parallel with the study of the effects of sidetone, research has been carried on on methods which could be applied to limit sidetone in amount to more nearly its optimum value. This has led to the development of what are known as anti-sidetone circuits, which do not eliminate sidetone but reduce it to an amount which is more nearly that found to be desirable.

An important step in the association of the transmitter and the receiver is represented by the handset which provides a rigid mechanical connection between the 2 units. This rigid mechanical connection introduces mechanical coupling between the receiver and the transmitter, which had to be given very serious consideration in order to avoid speech distortion.

## Trends in Instrument Development

I have broadly indicated fields of research which underlie the development and design of the telephone transmitter and receiver. It will now be of interest to note what application is likely to be made of the results of what has amounted to an enormous total of scientific effort. In this connection, it may be well again to emphasize that station apparatus is intimately associated with the user, and has therefore to be designed to fit him, his habits of using the telephone, and the conditions attending such

use. The handset has to be designed to fit his head, the holes in the dial to fit the size of his finger, the bell to be loud enough, and so on. Our effective transmission rating system has been set up in an attempt to rate the performance of the telephone when employed by the customer in

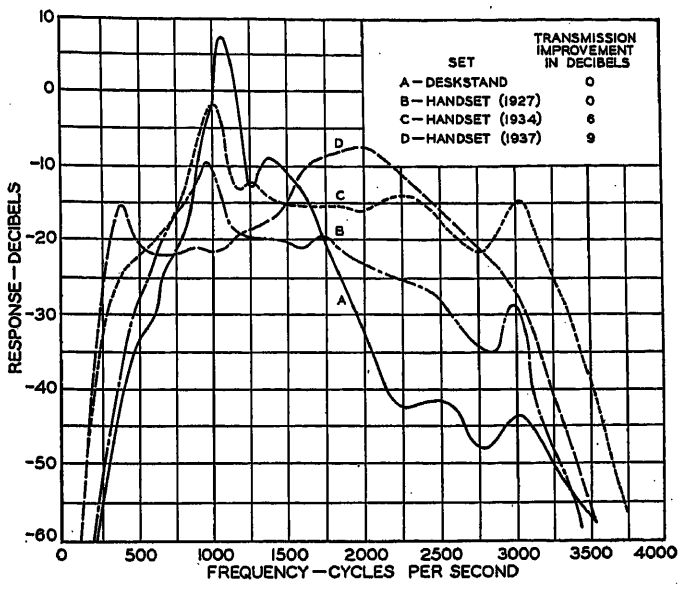



**Figure 5. Comparison of the response-frequency characteristics of telephone instruments**

the way he wants to use it, under the conditions surrounding him. For this reason, this method of rating has been found particularly valuable in the development work on instruments.

Because of the wide range of customer usage and conditions, a number of factors have to be taken into account in the design of the apparatus. Also, because this apparatus is located on the customer's premises, where it is relatively inaccessible to the telephone personnel, it must be capable of standing up without undue trouble under this wide range of usage and conditions. To strike a proper balance in meeting all these factors requires an intimate knowledge of the field conditions as well as of the development and manufacturing possibilities. A continuing close contact with field experience is employed to modify the designs toward securing the proper balance to meet these factors.

In order to indicate more clearly the present trends in design, I shall refer briefly to the earlier art. In the early development of transmitters and receivers, the matter of getting efficiency was of primary importance since this could be evaluated directly in terms of the amount of copper required in the connecting line. The early transmitters, which were of the same construction as the receiver, depended on the generator action of a diaphragm and coil and developed sufficient power to be heard over only a few miles of heavy-gauge wire. Some amplification was necessary before telephone communication could begin to assume the proportions of a widespread service. This amplification was obtained at a reasonable cost in the carbon-contact transmitter. Transmitters of this type are in the order of 60 decibels more efficient as transducers of acoustic to electric energy than the earlier type.

Both the transmitter and the receiver operate by means of diaphragms which have natural periods of vibration. These resonances and the resonances of the air spaces on each side of the diaphragm were used to obtain as efficient a transfer of energy as possible. In the early design, a great deal of attention was also given to locating these resonances at the portion of the frequency range where they would tend to increase the intelligibility of the reproduced sound. As a result, both instruments were made very efficient in the region of 1,000 cycles, which lies within the range where the ear and the sensation of loudness are most sensitive.

It was recognized that these resonances caused undesirable distortion, but under the conditions the resulting increase in efficiency more than compensated for this disadvantage. As time went on, the diaphragm resonances came to be looked upon as practically inherent in commercial transmitters and receivers, because no way was known of eliminating them without making a very material sacrifice in the efficiency of the instrument.

About 20 years ago, the development of the vacuum-tube amplifier and the high-quality condenser transmitter made it possible to demonstrate and measure quantitatively the advantages of reducing distortion. These high-quality instruments, the improvement in measuring technique, and the development of improved methods of de signing vibratory systems offered the promise of providing instruments in which the resonance effect could be reduced without unduly affecting efficiency.

The first commercial instrument for station use, which demonstrated the possibility of carrying out this promise, was the transmitter employed in the handset first supplied by the Bell System in 1927. This transmitter had to meet the requirement of giving the same transmission service as transmitters of the deskstand type, and at the same time meet the very exacting requirements imposed by the handset to make it free from howling and capable of performing over a wide range of positions. The diaphragm resonance was damped to a large extent by the use of paper rings and, by lightening the structure, the point of maximum response was moved up in frequency so that it no longer coincided with the peak of the receiver. The effect of this was not only to broaden the response characteristic and improve intelligibility, but also to reduce the gain in the local howling circuit which is, of course, a maximum when both transmitter and receiver have their greatest efficiency at the same frequency. The same separation of peaks resulted in the received speech being less loud, but in spite of this the over-all performance was equivalent to that of the best deskstand type of instrument then available.

With this accomplishment, further work was directed toward maintaining the lower distortion and increasing the efficiency. The transmitter introduced in 1934 represented a marked improvement along this line. This instrument still further broadens the transmitted frequency range and is used with about the same efficiency in deskstands, handsets, wall sets, and coin-collect sets.

A new type of handset is being introduced in the Bell System in 1937 which, in addition to having a more pleasing and simplified design, will incorporate the new transmitter mounted in such a way as to make fullest use of its ability to transmit efficiently over a wide-frequency band.

During this evolution of the transmitter, the knowledge which had been gained as to the importance of transmitting different widths of frequency band over commercial telephone circuits led to the establishment of the range from 250 to 2,750 cycles for designs of new circuits. It was not the intention in the establishment of this range that circuits should not do better than this where it is possible without materially increasing cost, but that all circuits should be at least as good as this. The establishment of this frequency range took into account a number of factors of which a very important one is that the over-all utilization of this range from the sound entering the transmitter to the sound output of the receiver provides a grade of transmission which is highly satisfactory for the reproduction of conversational material.

The establishment of this frequency range played a part not only in the design of circuits, but also in guiding the evolution of the transmitter and receiver. The transmitter last referred to meets this requirement very well. In fact, its efficiency is fairly uniform for a frequency range extending beyond 4,000 cycles.

The next step in the process was to improve the performance of the receiver. A pronounced resonance at 1,000 cycles was no longer necessary since means had been found to improve the efficiency of instruments in other ways than by concentrating all the resonances at one frequency. The importance of the higher frequencies in transmitting and reproducing the transient sounds characteristic of the consonants in speech led to placing more emphasis on these frequencies and attempting to produce more uniformly the band of frequencies which was set as a limit for circuits. This has now been accomplished in a practical fashion in the receiver which is being introduced in 1937.

The effect of this evolution in the design of station instruments may be brought out by a comparison of the over-all response characteristic—that is, the relation of the sound delivered to the ear to the sound available at the transmitter—for a typical telephone connection having in one case, both terminal instruments of the 1920 type and, in the other case, the terminal instruments of the new 1937 type (figure 5). In this typical circuit, the trunk has been taken as free from distortion so that its effect will not influence the indicated performance of the instruments, although the circuit does include 2 22-gauge loops each 3 miles long.

At the resonance point of the old instruments, just over 1,000 cycles, the over-all response in going to the new instruments is reduced by almost 30 decibels while the response in the range from 2,000 to 3,000 cycles is increased by over 20 decibels. In the frequency range from 500 to 2,000 cycles, the circuit employing the older instruments shows a variation of over-all response of over 30 decibels. For the new type, the variation for this same frequency range is reduced to 15 decibels, and, furthermore, this variation of 15 decibels applies approximately for the range of from 250 to 2,750 cycles which was mentioned as the transmission range requirement for the design of new circuits. In regard to the variation of 15 decibels in this frequency range, there is good indication that this response is more desirable than one of no variation, from the standpoint of having the telephone performance approach that of direct air transmission.

In addition to these improvements in frequency response and efficiency, the intensive development program on these instruments has improved materially the stability of the carbon transmitter under service conditions. This is an important factor in extending the useful life of these instruments and in reducing the cost of maintaining the desired transmission performance.

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## Proposed Recommendations for Measurement of Surge Voltages and Currents

IN THE July 1936 issue of ELECTRICAL ENGINEERING the subcommittee of the AIEE committee on instruments and measurements presented a report giving the revised values for 60-cycle sphere-gap calibrations. The values for impulse voltages, however, were held pending development of instructions for their use. A new report by the same committee now has been made available containing the proposals defining the applications and use of sphere spark gaps for both 60-cycle and impulse measurements. This report also corrects certain errors made in the statement of 60-cycle values as published in July 1936.

The recommendations included in the report were formulated in recognition of a general need for a surge measurement standard from which could be derived necessary measurement technique for the surge-testing codes for apparatus and materials. Particular code requirements will necessitate varying measurement technique, and it is expected that this proposed standard will serve as a source from which can be drawn all the necessary measurement recommendations required. Accordingly, it is urged that it be viewed and used in this way. For specific measurement recommendations applying to a particular apparatus, the test code for that apparatus should be consulted.

When approved by the AIEE standards committee, all of the material contained in the subcommittee report will become a part of the proposed complete revision, now under way, of the present AIEE Standard No. 4, "Measurement of Test Voltage in Dielectric Tests."

Those interested in the subcommittee report on the "Proposed Recommendations for Measurement of Surge Voltages and Currents and the Sphere Gap Calibration Standards" may obtain a complete mimeographed copy, without charge, by writing to H. E. Farrer, secretary AIEE standards committee, 33 West 39th Street, New York, N. Y.

# Forty Million Kilowatt-Hours for a Fair

ILLUMINATION PLANS for the 1939 Golden Gate International Exposition on San Francisco Bay call for consumption of an estimated 40 million kilowatt-hours of energy during the 288 days of the fair, from February 18 to December 2, 1939.

The Exposition's site is a 400-acre island, created by dredging in the center of the harbor near the mid-point of the San Francisco–Oakland Bay Bridge. Power will be delivered at a 16,000-kva substation on this "Treasure Island" through 3 submarine cables, each 9,000 feet long, from the mainland. Distribution will be made by 10 miles of 4,000-volt underground 3-phase feeders, approximately 25 miles of streetlighting cable, and an undetermined length of secondary.

Approximately $1,000,000 is budgeted for illumination and electrical installation, and intensive field work will be started in the spring of 1938 after underlying water and sewer lines have been laid. Installation is divided into permanent and temporary classifications, for 3 buildings will remain after the close of the Exposition as air terminal building and hangars for the municipal airport that will take over the island. Other buildings will be razed. Decorative installations will use knob-and-tube work, but all interior wiring will be in conduits.

Exterior lighting, expected to set new standards of beauty, has been worked out by a committee of illumination engineers. The plan calls for extensive use of the new "fluorescent tube," a development not yet on the market. These 15-watt gas-filled tubes, mounted in trough reflectors and used for floodlighting, give spectacular effects particularly in pink, blue, green, and white.

Searchlight scintillators, marching cylindrical lanterns, moonlighting, flush lights, steam urns, and water effects have their necessary place in the night picture, and unusual methods of their use are being worked out. At some points, as in the Court of Reflections, lighting will be restrained to encourage a placid mood for greater enjoyment of the scene; at other points, such as the 40-acre Midway, the only restrictions will be against excessively bright exposed lamps that would violate the harmony of the whole.

"Stunts" will be few in number, for the intention is to create a pastel picture of mystery and fantasy, aiding in the interpretation of the basic creation of architects, landscape artists, sculptors, and colorists. Utilitarian roadway lighting will be so designed that it will not detract from the illusion of a white "jeweled city" floating upon the water, and the $50,000,000 fair will be blended into an artistic architectural unit by day or night, rather than a disconnected assemblage of exhibit buildings.

Architecturally, the Exposition will be a series of masses carried toward the skyline by stepped setbacks. These setbacks will be flooded in varying intensities or graduated colors to preserve their positions, with the monotony of normal floodlighting broken by highlights or color changes based upon flags, niches, and architectural elements. Flatness will be relieved also by large circles of color, by the shadows of palm trees, and by ultra-violet radiation playing from concealed projectors on fluorescent paint.

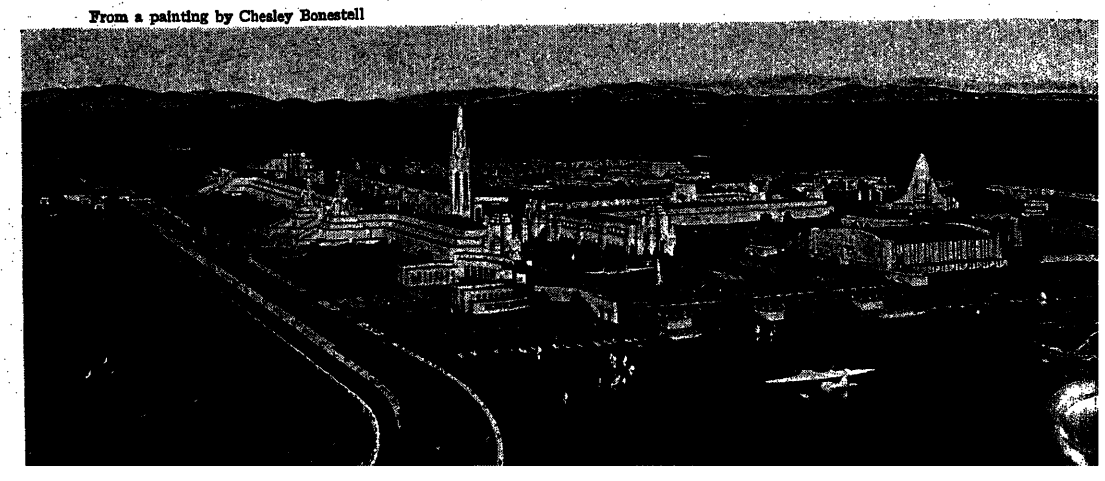
Trees generally will be treated as dark masses, or as silhouettes against glowing backgrounds. Lip lighting and jets will mark the rims of pools, and a feature will be a reproduction in the Port of the Trade Winds of Old Faithful geyser, playing to its full height of 150 feet at brief intervals and lighted by searchlights in changes. At the opposite end of the mile-long island will be an aurora of scintillator beams, created by 24 arc searchlights of 36-inch diameter.

Supplemental to standard lighting will be a power system for stage and spot lighting which can be adapted to special pageants as required. Interiors of exhibit buildings will be illuminated uniformly by day and night, with no windows to mar the planned effectiveness of displays. A spectacular feature in several courts will be cylindrical lanterns, from 60 to 75 feet high and 6 feet in diameter, lighted by concealed tubes within.

Colors will be restricted to harmonious groups of 2 or 3 in each court; chiefly employed will be amber, green, red, apricot, blue, peach, gold, pink, and magenta. The 400-foot central tower, an opportunity to the illuminator, will be a light amber at the base, shading into white of increasing intensity toward the spire. It will be topped by a searchlighted phoenix, rising from a bright red illumination at its base. The interior of the tower, viewed through tall arches, will be amber at the base and blend into a rose red at the upper level.

More than $10,000,000 worth of buildings for this 1939 World's Fair are under construction in the fall of 1937, and the programs of governmental and industrial participation are equally advanced. Except for firms planning to erect their own buildings, electrical displays will be concentrated in a hall of electricity and communication. Central co-ordinating displays planned for this phase of the exhibit program include great relief maps of the Pacific area, painted by "black light" on fluorescent paint to develop existing communication and power lines from virgin country in a twinkling.

From a painting by Chesley Bonestell



# Monthly Earnings of Engineers, 1929–34

**In this, the seventh article[1] of a series reporting a survey of employment in the engineering profession by the United States Bureau of Labor Statistics, data relative to the monthly rate of compensation received by engineers solely for engineering services in which they were engaged at the end of 1929, 1932, and 1934, are presented. Comparisons may be drawn among professional classes, ages, and educational background.**

IN 1929, the range in monthly engineering earnings of professional engineers was very great. Some 79 engineers reported earnings of less than $60 per month, while 168 earned more than $1,880 a month. The median monthly earnings of the 28,511 reporting engineers was $289. One-quarter earned more than $415, while only 10 per cent had earnings greater than $609 a month.

Between 1929 and 1934 there were progressive declines in monthly engineering earnings. While the sharpest absolute decreases occurred at the higher levels of earnings, the greatest percentage decreases took place at the lower earnings levels. Almost two-thirds of the decreases occurred between 1929 and 1932.

Comparison of earnings by professional class, without regard to age, and the consequent effect of the varying age distributions shows that in 1929 the upper 10 per cent of mining and metallurgical engineers, highest at this level, reported earnings of not less than $792 per month as against $515 a month for civil engineers, who were lowest at this level. Second in order came chemical and ceramic engineers, followed by mechanical and industrial, and electrical engineers. For the upper 25 per cent of the reporting engineers the order of the professional classes was the same, monthly engineering earnings ranging from not less than $372 for civil engineers to not less than $503 a month for mining and metallurgical engineers. At the middle and lower earnings levels, the differences in earning capacities of the 5 professional classes were less marked, although in each instance mining and metallurgical engineers and electrical engineers occupied the upper and lower extremes, respectively.

In 1932 and 1934 the order of the professional classes at the 2 higher earning levels was essentially the same as that noted for 1929. At the 3 lower earning levels shifts occurred in this order in 1929, and there were further shifts in 1932 and 1934.

On an age basis the 1929 monthly compensation for engineering services of the lowest tenth of reporting engineers was more than twice as high for those in the age group 48 to 55 as for those of 23 years. At the upper 10 per cent earnings level, maximum earnings of $1,050 a month were reached in the sixties. Similarly, at the average and at the upper and lower quarters of earning levels age 60 was the turning point.

For men of identical ages in 1929, 1932, and 1934 the data reveal that the greatest impact of the depression, as far as engineering earnings were concerned, fell upon men with from 2 to 5 years' experience.

Although the 1929 data on engineering earnings evidence an advantage in favor of men who have engineering degrees, this advantage was less clearly defined than was the case with earned annual incomes. However, the extra years of experience which the "other" engineers had while the graduates were in school permitted of their obtaining higher earnings than graduates only up to a point corresponding to 5 years after graduation. Even at 2 years after graduation the differentials in earnings between the 2 groups were slight. Similarly, at 4 years after graduation, while at the median level graduate earnings ranged from $225 for first-degree electrical engineers to $250 a month for first-degree chemical and ceramic engineers, among the "other" engineers they ranged from $200 for engineers with secondary school education to $229 a month for mechanical and industrial engineers with incomplete college courses.

With advancing age there was a considerable advantage in engineering earnings in favor of the graduates. There was also a distinct variation in the earning capacities among both graduate and "other" engineers.

The monthly engineering earnings of graduates continued to increase several years beyond the point of maximum earnings of "other" engineers. The earnings of the latter either remained stable or declined at 30 years after graduation.

While graduates who were 23½ in 1929 and 28½ in 1934 reported increased earnings for all kinds of engineering, except mining and metallurgical, no increases were reported by any of the "other" engineers of corresponding ages. For older engineers, however, the decreases apparently affected both graduates and "other" engineers in almost equal measure.

For men of identical years of experience, the earnings received in 1934 by both graduates and "other" engineers were all less than those obtained in 1929. The decreases reported by men with 5 years' experience were, in general, greater than those of men with 2 or with from 10 to 37 years' experience.

## Scope and Method

The earned annual incomes of any professional group are made up of earnings from professional work plus, in

1. An article prepared by Andrew Fraser, Jr., of the Division of Hours, Wages, and Working Conditions, Bureau of Labor Statistics, United States Department of Labor, which article was published in the November 1937 issue of *Monthly Labor Review*. Articles reporting other phases of this survey were published in ELECTRICAL ENGINEERING as follows: "Professional Aspects of Engineering Education," August 1936, pages 863–7; "Unemployment in the Engineering Profession," February 1937, pages 216–23; "Employment in the Engineering Profession," May 1937, pages 524–31; "Security of Engineering Employment," June 1937, pages 655–61; "Engineering Income and Earnings," September 1937, pages 1089–1104; "Sources of Engineering Income, 1929–34," November 1937, pages 1353–58. A detailed report of the survey will be published later in bulletin form by the Bureau of Labor Statistics.

some cases, those received for other services. They are affected, moreover, by periods of partial or complete unemployment during the year. In this article an analysis[2] is made of the compensation engineers received solely for professional services during periods of employment, based on the monthly rates of earnings reported for all kinds of engineering work combined.

As in the previous analyses of earned annual incomes, it has been necessary to assume that the kind of engineering employment reported for the end of the year was the source of the income for that year.

**Table I. Comparison of 5 Levels of Monthly Engineering Earnings for All Professional Engineers Reporting in 1929, 1932, and 1934**

Figures derived from adjusted data as explained on this page, and without regard to kind of engineering employment reported or type of education

| Per Cent at Specific Earning Level | Monthly Engineering Earnings of More Than Specified Amount | | | Amount of Decrease | | | Per Cent of Decrease | | |
|---|---|---|---|---|---|---|---|---|---|
| | 1929 | 1932 | 1934 | 1929–34 | 1929–32 | 1932–34 | 1929–34 | 1929–32 | 1932–34 |
| 10 per cent | $609 | $484 | $435 | $174 | $125 | $49 | 28.6 | 20.5 | 10.1 |
| 25 per cent | 415 | 334 | 304 | 111 | 81 | 30 | 26.7 | 19.5 | 9.0 |
| 50 per cent | 289 | 235 | 210 | 79 | 54 | 25 | 27.3 | 18.7 | 10.6 |
| 75 per cent | 215 | 167 | 148 | 67 | 48 | 19 | 31.2 | 22.3 | 11.4 |
| 90 per cent | 162 | 123 | 112 | 50 | 39 | 11 | 30.9 | 24.1 | 8.9 |

## Monthly Engineering Earnings

Of the 33,852 engineers who reported as of December 31, 1929, that they were professionally active prior to 1930, 28,511, or 84 per cent, stated their average monthly rates for the engineering work in which they were engaged. These 1929 data, together with the adjusted[3] figures for 1932 and 1934, are shown in table I, without regard to age or kind of engineering employment reported.

As in the case of earned annual incomes, the range in the 1929 monthly engineering earnings of professional engineers was very great. While some 79 engineers reported earnings of less than $60 per month, 168 earned more than $1,880 a month. The median monthly earnings of the 28,511 reporting engineers was $289; one-quarter earned more than $415; and only 10 per cent had earnings greater than $609 a month. The lowest 25 per cent of the reporting engineers earned less than $215 a month while the lowest 10 per cent earned less than $162 a month.

Over the period 1929–34 the changes which occurred in monthly engineering earnings were similar to those previously noted in the discussion of earned annual incomes: (1) Earnings progressively declined from 1929 to 1934; (2) the sharpest absolute decreases occurred at the higher levels of earnings, but the greatest percentage decreases took place at the 2 lower income levels; (3) of the respective total decreases, almost two-thirds occurred between 1929 and 1932.

At all levels, however, the changes in monthly engineering earnings were very much less than those for earned annual incomes. This was due to the fact that annual earnings reflect the combined effects of several factors which were operative in the depression years: (1) The decline in engineering earnings; (2) the acute unemployment; (3) the deterioration in the nature of the available nonengineering work; and (4) the large influx of young engineers in the years 1930–34.

Clearly, earned annual income data cannot be used as a measure of the rates at which engineering services were purchased. Illustrative of this is the fact that in 1929 only at the 2 higher earnings levels did earned annual income exceed 12 times the monthly earnings reported solely from engineering services. In the years 1932 and 1934, the estimated annual earnings from engineering work only were greater at all 5 income levels. But while the lowest 10 per cent of the reporting engineers had earned annual incomes of not less than $872 in 1934, the monthly rate of earnings at this level shows a possible income of not less than $1,344 a year from engineering work.

More particularly, however, while the lowest 10 per cent of the reporting engineers engaged in engineering work in 1929 had earned not less than $162 per month, by 1934 the monthly earnings at this level were not less than $112. This was a decline of 30.9 per cent. By contrast, the earned annual incomes of a similar proportion of engineers had declined by 53.6 per cent. At the next highest income level, engineering earnings decreased by 31.2 per cent, as against 41.3 per cent in the case of earned annual incomes. Similarly, average monthly engineering earnings dropped by 27.3 per cent, whereas annual incomes declined by 33.0 per cent. This decline in the average earnings differed but little from those which occurred at the upper 10 and 25 per cent of the reporting engineers, namely, 28.6 and 26.7 per cent, respectively. The corresponding decreases in annual incomes of similar proportions of engineers were 31.2 and 31.6 per cent. In other words, while the range in the decline in engineering earnings was from 26.7 to 31.2 per cent, it was from 31.2 to 53.6 per cent for annual incomes.

The findings and comments of the preceding analysis

2. See "Engineering Income and Earnings, 1929–34," ELECTRICAL ENGINEERING for September 1937, pages 1089–1104, for details of the scope and methods of analysis.

3. The procedure of adjustment adopted was similar to that outlined in the "Employment in the Engineering Profession," 1929 to 1934, ELECTRICAL ENGINEERING, May 1937, pages 524–31. The numbers of younger engineers reporting in each income class for 1932 and 1934 were reduced in the ratio of 15 to 32 and added to the corresponding figures reported by the older engineers in 1932 and 1934.

also apply to the engineering earnings reported by the 5 professional classes. These are shown, also without regard to age[4] or kind of engineering employment, in table II.

In 1929, the upper 10 per cent of mining and metallurgical engineers, highest at this level, had earnings of not less than $792 per month as against $515 for civil engineers, who were lowest at this level. Second in order came chemical and ceramic engineers, of whom the upper 10 per cent had monthly earnings of not less than $732, followed by mechanical and industrial engineers, and electrical engineers, respectively, with not less than $674 and $587 a month. For the upper 25 per cent of the reporting engineers the order of the professional classes was the same, monthly earnings ranging from not less than $372 for civil engineers to not less than $503 a month for mining and metallurgical engineers. At the middle and 2 lower earnings levels, the differences in earning capacity were less marked. However, in each instance mining and metallurgical engineers and electrical engineers occupied the upper and lower extremes, respectively. Civil engineers shifted from fourth place at the average earnings level to second at the lowest earnings level, while chemical and ceramic engineers shifted from second to fourth place. The ranges in monthly earnings over these 3 levels were, respectively, from not less than $275 to $334, $201 to $241, and $148 to $186.

Despite the progressive declines in engineering earnings between 1929 and 1934, the orders of the professional classes at the 2 higher levels were essentially the same as those noted for 1929. However, at the middle earnings level, chemical and ceramic engineers had dropped from second place in 1929 and 1932 to fifth by 1934; but even in 1934 their monthly engineering earnings were practically the same as those of the civil engineers, who were fourth in order. Mining and metallurgical engineers were highest both in 1932 and 1934. Thus in the latter year, while their median earnings were $241 a month, those of both mechanical and industrial engineers and electrical engineers were $215 a month.

At the lowest 25 per cent earnings level of the reporting engineers, the lowest and highest figures for 1932 and 1934 were again reported, respectively, by chemical and ceramic engineers and mining and metallurgical engineers. At the same level in 1934 the range was from not less than $131 for chemical and ceramic engineers to not less than $154 for mining and metallurgical engineers. This reduction in the range of earnings was more pronounced at the lowest earnings level both in 1932 and 1934, for while in the former year it was from not less than $116 to not less than $126, in the latter it was from not less than $101 to

**Table II. Comparison of 5 Levels of Monthly Engineering Earnings for All Engineers Reporting in Each Professional Class in 1929, 1932, and 1934**

Figures derived from adjusted data as explained on page 1451, and without regard to kind of engineering employment reported or type of education

| Per Cent of Professional Class at Specified Earning Level[1] | Monthly Engineering Earnings of More Than Specified Amount | | | Amount of Decrease | | | Per Cent of Decrease | | |
|---|---|---|---|---|---|---|---|---|---|
| | 1929 | 1932 | 1934 | 1929–34 | 1929–32 | 1932–34 | 1929–34 | 1929–32 | 1932–34 |
| 10 per cent: | | | | | | | | | |
| Mining and metallurgical | $792 | $585 | $524 | $268 | $207 | $61 | 33.8 | 26.1 | 10.4 |
| Chemical and ceramic | 732 | 579 | 509 | 223 | 153 | 70 | 30.5 | 20.9 | 12.1 |
| Mechanical and industrial | 674 | 512 | 441 | 233 | 162 | 71 | 34.6 | 24.0 | 13.9 |
| Electrical | 587 | 496 | 463 | 124 | 91 | 33 | 21.1 | 15.5 | 6.7 |
| Civil, agricultural, and architectural | 515 | 430 | 390 | 125 | 85 | 40 | 24.3 | 16.5 | 9.3 |
| 25 per cent: | | | | | | | | | |
| Mining and metallurgical | 503 | 409 | 371 | 132 | 94 | 38 | 26.2 | 18.7 | 9.3 |
| Chemical and ceramic | 490 | 400 | 339 | 151 | 90 | 61 | 30.8 | 18.4 | 15.2 |
| Mechanical and industrial | 455 | 356 | 313 | 142 | 99 | 43 | 31.2 | 21.8 | 12.1 |
| Electrical | 405 | 336 | 315 | 90 | 69 | 21 | 22.2 | 17.0 | 6.2 |
| Civil, agricultural, and architectural | 372 | 311 | 279 | 93 | 61 | 32 | 25.0 | 16.4 | 10.3 |
| 50 per cent: | | | | | | | | | |
| Mining and metallurgical | 334 | 274 | 241 | 93 | 60 | 33 | 27.8 | 18.0 | 12.0 |
| Chemical and ceramic | 326 | 251 | 203 | 123 | 75 | 48 | 37.7 | 23.0 | 19.1 |
| Mechanical and industrial | 311 | 246 | 215 | 96 | 65 | 31 | 30.9 | 20.9 | 12.6 |
| Civil, agricultural, and architectural | 277 | 229 | 205 | 72 | 48 | 24 | 26.0 | 17.3 | 10.5 |
| Electrical | 275 | 232 | 215 | 60 | 43 | 17 | 21.8 | 15.6 | 7.3 |
| 75 per cent: | | | | | | | | | |
| Mining and metallurgical | 241 | 183 | 154 | 87 | 58 | 29 | 36.1 | 24.1 | 15.8 |
| Mechanical and industrial | 225 | 166 | 145 | 80 | 59 | 21 | 35.6 | 26.2 | 12.7 |
| Chemical and ceramic | 221 | 157 | 131 | 90 | 64 | 26 | 40.7 | 29.0 | 16.6 |
| Civil, agricultural, and architectural | 213 | 169 | 150 | 63 | 44 | 19 | 29.6 | 20.7 | 11.2 |
| Electrical | 201 | 163 | 148 | 53 | 38 | 15 | 26.4 | 18.9 | 9.2 |
| 90 per cent: | | | | | | | | | |
| Mining and metallurgical | 186 | 125 | 115 | 71 | 61 | 10 | 38.2 | 32.8 | 8.0 |
| Civil, agricultural, and architectural | 167 | 126 | 120 | 47 | 41 | 6 | 28.1 | 24.6 | 4.8 |
| Mechanical and industrial | 167 | 122 | 107 | 60 | 45 | 15 | 35.9 | 26.9 | 12.3 |
| Chemical and ceramic | 156 | 116 | 101 | 55 | 40 | 15 | 35.3 | 25.6 | 12.9 |
| Electrical | 148 | 123 | 108 | 40 | 25 | 15 | 27.0 | 16.9 | 12.2 |

1. Arranged in ascension of monthly engineering earnings for 1929.

4. It is important to note that any data concerning the several professional classes as a whole without regard to age tend to obscure the effects of different age distributions within the classes. Those classes with a relatively high proportion of older men for this reason are likely to show relatively high earnings, and those with relatively more younger men to show smaller earnings.

## Table III. Comparison of 5 Levels of Monthly Engineering Earnings, on Age Basis, for All Engineers Reporting in 1929, 1932, and 1934

Without regard to kind of engineering employment reported or type of education

| Age | Year of Graduation | Years After Graduation | Proportion With Monthly Engineering Earnings of More Than Specified Amount | | | | |
|---|---|---|---|---|---|---|---|
| | | | 10 Per Cent | 25 Per Cent | 50 Per Cent | 75 Per Cent | 90 Per Cent |
| **1929** | | | | | | | |
| 64 years and over | Prior to 1889 | 40 and over | $820 | $601 | $388 | $263 | $194 |
| 56–63 years | 1889–96 | 33–40 | 1,050 | 628 | 425 | 296 | 210 |
| 48–55 years | 1897–1904 | 25–32 | 933 | 592 | 414 | 297 | 232 |
| 40–47 years | 1905–12 | 17–24 | 789 | 514 | 385 | 289 | 229 |
| 36–39 years | 1913–16 | 13–16 | 630 | 467 | 339 | 269 | 218 |
| 32–35 years | 1917–20 | 9–12 | 519 | 407 | 310 | 249 | 208 |
| 28–31 years | 1921–24 | 5–8 | 4 4 | 317 | 262 | 217 | 187 |
| 26–27 years | 1925–26 | 3–4 | 307 | 256 | 218 | 186 | 155 |
| 24–25 years | 1927–28 | 1–2 | 252 | 215 | 181 | 152 | 133 |
| 23 years | 1929 | 0 | 215 | 174 | 149 | 130 | 115 |
| **1932** | | | | | | | |
| 67 years and over | Prior to 1889 | 44 and over | $725 | $499 | $331 | $216 | $144 |
| 59–66 years | 1889–96 | 36–43 | 751 | 517 | 352 | 241 | 152 |
| 51–58 years | 1897–1904 | 28–35 | 707 | 486 | 340 | 241 | 164 |
| 43–50 years | 1905–12 | 20–27 | 624 | 433 | 315 | 234 | 168 |
| 39–42 years | 1913–16 | 16–19 | 517 | 396 | 295 | 223 | 170 |
| 35–38 years | 1917–20 | 12–15 | 458 | 349 | 272 | 211 | 157 |
| 31–34 years | 1921–24 | 8–11 | 358 | 293 | 234 | 189 | 143 |
| 29–30 years | 1925–26 | 6–7 | 299 | 244 | 205 | 166 | 135 |
| 27–28 years | 1927–28 | 4–5 | 250 | 215 | 181 | 147 | 119 |
| 26 years | 1929 | 3 | 221 | 185 | 156 | 134 | 110 |
| 25 years | 1930 | 2 | 190 | 161 | 143 | 122 | 101 |
| 24 years | 1931 | 1 | 173 | 149 | 126 | 104 | 84 |
| 23 years | 1932 | 0 | 165 | 137 | 111 | 89 | 66 |
| **1934** | | | | | | | |
| 69 years and over | Prior to 1889 | 46 and over | $620 | $430 | $284 | $173 | $108 |
| 61–68 years | 1889–96 | 38–45 | 711 | 480 | 321 | 205 | 126 |
| 53–60 years | 1897–1904 | 30–37 | 650 | 447 | 310 | 212 | 146 |
| 45–52 years | 1905–12 | 22–29 | 592 | 413 | 292 | 214 | 152 |
| 41–44 years | 1913–16 | 18–21 | 505 | 375 | 273 | 205 | 150 |
| 37–40 years | 1917–20 | 14–17 | 440 | 336 | 254 | 197 | 148 |
| 33–36 years | 1921–24 | 10–13 | 354 | 285 | 224 | 177 | 139 |
| 31–32 years | 1925–26 | 8–9 | 299 | 238 | 199 | 161 | 133 |
| 29–30 years | 1927–28 | 6–7 | 253 | 215 | 177 | 145 | 118 |
| 28 years | 1929 | 5 | 228 | 191 | 162 | 138 | 113 |
| 27 years | 1930 | 4 | 199 | 172 | 148 | 125 | 104 |
| 26 years | 1931 | 3 | 182 | 156 | 137 | 114 | 94 |
| 25 years | 1932 | 2 | 169 | 145 | 124 | 103 | 84 |
| 24 years | 1933 | 1 | 159 | 138 | 116 | 98 | 82 |
| 23 years | 1934 | 0 | 149 | 129 | 110 | 91 | 75 |

not less than $120, the upper and lower extremes being reported, respectively, by the civil engineers and the chemical and ceramic engineers.

The decline in engineering earnings of each professional class was very much less than that which occurred in earned annual incomes. The greatest percentage decreases took place at the 2 lower levels. For example, while engineering earnings of electrical engineers at these limits declined by 26.4 and 27.0 per cent, the corresponding annual incomes decreased by 42.6 and 56.0 per cent. In the case of chemical and ceramic engineers, the drops in earnings at these levels were 40.7 and 35.3 per cent as against 52.2 and 63.8 per cent in their annual incomes.

### Monthly Engineering Earnings Related to Age

In table III there are presented the monthly engineering earnings, by age,[5] of all engineers combined and without regard to kind of engineering employment.

As shown in table III there was, in general, a steady advance in monthly earnings at all levels up to the highest age groups. Except for the absence of the exceptionally rapid rise from 23 to 25 years, the changes with age in monthly engineering earnings at all 5 levels show no marked differences from those derived from the analysis of earned annual incomes by age. Thus, in 1929 the compensation for engineering services of the lowest tenth of the reporting engineers steadily increased from over $115 a month for those 23 years to a maximum of over $232 a month for those who were between 48 and 55 years. At each of the 4 higher earning levels maximum earnings were reached some 8 years later, or near to age 60. The respective maxima were not less than $297, $414, $592, and $1,050 per month. Even for engineers 23 years of age there was a considerable spread in earnings. This is evidenced by the fact that at the average level the earnings were not less than $149 a month, above this one-quarter earned over $174, and one-tenth over $215 per month, as against monthly engineering earnings of over $130 and $115 at the two lower levels.

The spread in engineering earnings with advancing age became quite marked at the age of 30; that is, some 8

5. Throughout the ensuing discussion age and years after graduation are used interchangeably. Of course in the case of nongraduates (that is "other engineers") age only applies. The relationship between these 2 factors can readily be derived from the fact that the median age of graduation of new graduates to the profession was found to be 23 years.

## Table IV. Comparison of 5 Levels of Monthly Engineering Earnings on Age Basis for All Graduate Engineers Reporting in 1929, 1932, and 1934

Without regard to kind of engineering employment reported or type of education

| Age | Year of Graduation | Years After Graduation | Proportion With Monthly Engineering Earnings of More Than Specified Amount | | | | |
|---|---|---|---|---|---|---|---|
| | | | 10 Per Cent | 25 Per Cent | 50 Per Cent | 75 Per Cent | 90 Per Cent |
| **1929** | | | | | | | |
| 64 years and over | Prior to 1889 | 41 and over | $880 | $624 | $417 | $302 | $215 |
| 56–63 years | 1889–96 | 33–40 | 1,152 | 661 | 472 | 326 | 243 |
| 48–55 years | 1897–1904 | 25–32 | 1,018 | 625 | 434 | 319 | 252 |
| 40–47 years | 1905–12 | 17–24 | 826 | 552 | 410 | 306 | 245 |
| 36–39 years | 1913–16 | 13–16 | 663 | 490 | 356 | 286 | 231 |
| 32–35 years | 1917–20 | 9–12 | 540 | 416 | 321 | 263 | 218 |
| 28–31 years | 1921–24 | 5–8 | 410 | 322 | 269 | 223 | 196 |
| 26–27 years | 1925–26 | 3–4 | 308 | 260 | 220 | 189 | 160 |
| 24–25 years | 1927–28 | 1–2 | 247 | 213 | 180 | 152 | 135 |
| 23 years | 1929 | 0 | 205 | 169 | 148 | 130 | 115 |
| **1932** | | | | | | | |
| 67 years and over | Prior to 1889 | 44 and over | $778 | $519 | $350 | $234 | $173 |
| 59–66 years | 1889–96 | 36–43 | 807 | 558 | 401 | 277 | 170 |
| 51–58 years | 1897–1904 | 28–35 | 739 | 505 | 374 | 265 | 185 |
| 43–50 years | 1905–12 | 20–27 | 653 | 458 | 334 | 248 | 178 |
| 39–42 years | 1913–16 | 16–19 | 557 | 419 | 312 | 240 | 187 |
| 35–38 years | 1917–20 | 12–15 | 480 | 365 | 288 | 223 | 171 |
| 31–34 years | 1921–24 | 8–11 | 368 | 301 | 241 | 198 | 149 |
| 29–30 years | 1925–26 | 6–7 | 302 | 251 | 210 | 172 | 141 |
| 27–28 years | 1927–28 | 4–5 | 253 | 217 | 183 | 149 | 122 |
| 26 years | 1929 | 3 | 219 | 184 | 156 | 135 | 113 |
| 25 years | 1930 | 2 | 187 | 160 | 143 | 122 | 101 |
| 24 years | 1931 | 1 | 171 | 148 | 125 | 104 | 84 |
| 23 years | 1932 | 0 | 159 | 134 | 110 | 88 | 64 |
| **1934** | | | | | | | |
| 69 years and over | Prior to 1889 | 46 and over | $636 | $480 | $307 | $205 | $110 |
| 61–68 years | 1889–96 | 38–45 | 770 | 517 | 360 | 232 | 132 |
| 53–60 years | 1897–1904 | 30–37 | 704 | 478 | 337 | 229 | 152 |
| 45–52 years | 1905–12 | 22–29 | 626 | 431 | 313 | 226 | 158 |
| 41–44 years | 1913–16 | 18–21 | 533 | 404 | 294 | 219 | 161 |
| 37–40 years | 1917–20 | 14–17 | 461 | 354 | 271 | 210 | 157 |
| 33–36 years | 1921–24 | 10–13 | 360 | 294 | 232 | 186 | 145 |
| 31–32 years | 1925–26 | 8–9 | 303 | 242 | 205 | 169 | 140 |
| 29–30 years | 1927–28 | 6–7 | 258 | 218 | 181 | 148 | 121 |
| 28 years | 1929 | 5 | 228 | 192 | 164 | 140 | 115 |
| 27 years | 1930 | 4 | 200 | 172 | 149 | 126 | 105 |
| 26 years | 1931 | 3 | 180 | 156 | 137 | 114 | 94 |
| 25 years | 1932 | 2 | 169 | 145 | 124 | 102 | 84 |
| 24 years | 1933 | 1 | 159 | 137 | 116 | 98 | 82 |
| 23 years | 1934 | 0 | 149 | 129 | 109 | 91 | 75 |

years earlier than was the case for earned annual incomes. (See figure 1.) Again the earnings of the upper 10 per cent of reporting engineers diverged sharply from those at corresponding ages in the lower levels. Thus, at age 44 the former were greater than the average by some 102 per cent, as against a corresponding difference at the upper 25 per cent level of only 33 per cent. At age 60, the respective differences were 144 and 48 per cent.

These general relationships of monthly engineering earnings by age of all engineers[6] reporting also held in the years 1932 and 1934, as well as for the monthly earnings of all graduates[7] shown in table IV.

Consideration will now be given to the extent to which monthly engineering earnings may have been affected by the depression. Reference, however, will be made only to the data reported by all graduate and "other" engineers combined.

For men of advancing years and experience, it appears from the data presented in table V that over the period 1929–34 only those engineers who were 23½ years in 1929 and 28½ in 1934 reported increased earnings. Earnings of the next higher age group showed practically no change. For succeeding age groups the declines in earnings were progressively greater. Thus, while there was a 15 per cent decrease between 1929 and 1934 at the middle level of earnings of engineers who were 30 in 1929 and 35 in 1934, the decrease was as high as 24 per cent for engineers who were 65 years of age in 1934. A similar situation existed at the other four earnings levels, for all engineers, and also for graduate engineers only, as shown in table VI.

One important aspect of these engineering earnings is that it is now possible to determine the compensation younger engineers received for their engineering services. This information could not be obtained from the data on earned annual incomes for reasons previously cited. The principal reason, however, was that most engineers 23 years of age could not have worked a full year.[8] Many of

6. That is, graduates and "other" engineers combined.

7. That is, postgraduates, nonengineering graduates, and first-degree engineering graduates combined.

8. This qualification applies only to graduate engineers, for in the case of "other" engineers many of them could have been working for a year or more.

the graduates estimated what their annual earnings would have been, based on what they had earned for the first 6 months after graduation. Obviously, this necessity for estimating does not apply to the monthly earnings for engineering work. Hence, the monthly earnings data are the most accurate indication of what the rates of compensation of younger engineers were for engineering work. This situation is best exemplified by considering the earnings reported by men who were of identical ages in 1929, 1932, and 1934, as presented in tables VII and VIII.

These data reveal the fact that the newcomers to the profession suffered less than those with from 2 to 5 years' experience in engineering. Thus, while median monthly earnings of the newcomers were 26 per cent less in 1934 than those of men of similar ages in 1929, they were 34 per cent less in the case of men with from 2 to 5 years' experience in each of these years. But it will also be noted that the declines in earnings of engineers between 1929 and 1934 with from 20 to 37 years of experience were practically the same as those reported by engineers $23^1/_2$ years of age. Furthermore, a similar relationship existed at the 4 other earnings levels, despite the fact that the declines in earnings were relatively greater in the case of engineers at the 2 lower earnings levels.

It will be recalled that in the discussion of employment status that as far as available engineering work was concerned, the tendency appeared to be to give preference to engineers who entered the profession in the period 1930–34. The analysis of the data in the table VII shows that it was not those engineers who entered the profession in 1934 who suffered relatively the greatest cuts but those who had entered during one or other of the depression years, 1930–33, inclusive. Similarly, data for earnings of graduates of identical ages are shown in table VIII.

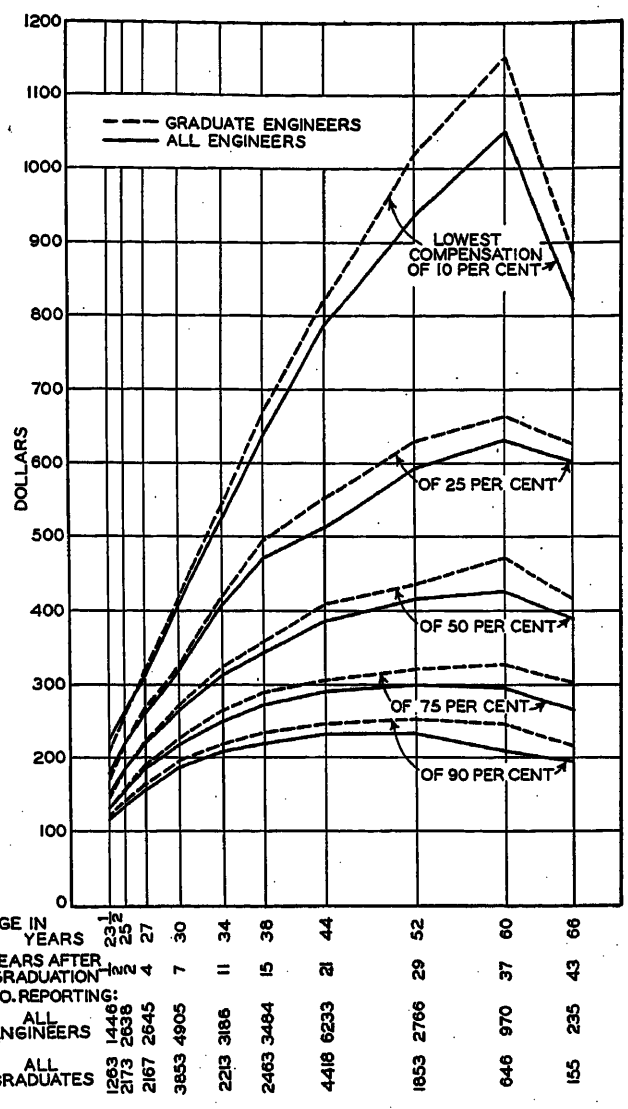



**Figure 1. Chart of monthly compensation of professional engineers in engineering work by age in 1929**

Includes compensation for all kinds of engineering services studied

## Engineering Earnings and Education

Of all engineers who furnished information on the monthly rates of compensation received by them for engi-

**Table V. Comparison of 5 Levels of Monthly Engineering Earnings for 5 Age Groups of Older[1] Engineers Reporting in 1929, 1932, and 1934**

Without regard to kind of engineering employment reported or type of education

| Per Cent at Specified Income Level | Monthly Engineering Earnings of More Than Specified Amount of Engineers Whose Age Was | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 60 in 1929 | 63 in 1932 | 65 in 1934 | 38 in 1929 | 41 in 1932 | 43 in 1934 | 30 in 1929 | 33 in 1932 | 35 in 1934 | 25 in 1929 | 28 in 1932 | 30 in 1934 | 23½ in 1929 | 26½ in 1932 | 28½ in 1934 |
| 10 per cent | $1,050 | $751 | $711 | $630 | $517 | $505 | $404 | $358 | $354 | $252 | $250 | $253 | $215 | $221 | $228 |
| 25 per cent | 628 | 517 | 480 | 467 | 396 | 375 | 317 | 293 | 285 | 215 | 215 | 215 | 174 | 185 | 191 |
| 50 per cent | 425 | 352 | 321 | 339 | 295 | 273 | 262 | 234 | 224 | 181 | 181 | 177 | 149 | 156 | 162 |
| 75 per cent | 296 | 241 | 205 | 269 | 223 | 205 | 217 | 189 | 177 | 152 | 147 | 145 | 130 | 134 | 138 |
| 90 per cent | 210 | 152 | 126 | 218 | 170 | 150 | 187 | 143 | 139 | 133 | 119 | 118 | 115 | 110 | 113 |

| | Per Cent of Increase or Decrease | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 1929–34 | 1929–32 | 1932–34 | 1929–34 | 1929–32 | 1932–34 | 1929–34 | 1929–32 | 1932–34 | 1929–34 | 1929–32 | 1932–34 | 1929–34 | 1929–32 | 1932–34 |
| 10 per cent | −32 | −28 | − 5 | −20 | −18 | − 2 | −12 | −11 | −1 | 0 | − 1 | +1 | + 6 | +8 | +3 |
| 25 per cent | −24 | −18 | − 7 | −20 | −15 | − 5 | −10 | − 8 | −3 | 0 | 0 | 0 | +10 | +6 | +3 |
| 50 per cent | −24 | −17 | − 9 | −19 | −13 | − 7 | −15 | −11 | −4 | − 2 | 0 | −2 | + 9 | +5 | +4 |
| 75 per cent | −31 | −19 | −15 | −24 | −17 | − 8 | −18 | −13 | −6 | − 5 | − 3 | −1 | + 6 | +3 | +3 |
| 90 per cent | −40 | −28 | −17 | −31 | −22 | −12 | −26 | −24 | −3 | −11 | −11 | −1 | − 2 | −4 | +3 |

1. Includes those engineers who were professionally active prior to 1930.

neering services in 1929, 21,205 were graduates and 7,305 were "other" engineers. The former number represented 86 per cent of the 24,837 graduates, and the latter covered 81 per cent of the 9,015 "other" engineers who reported that they were professionally active prior to 1930. A comparison of the engineering earnings of these 2 groups is shown, without regard to age and kind of engineering employment reported, in table IX.

Although the figures in the third from the last column in table IX indicate an advantage in favor of those men who have engineering degrees, this advantage is less clearly defined than was indicated in the similar analysis of earned annual incomes. This is evidenced by the fact that only at the highest earnings level did the earnings of graduates of all 5 professional classes exceed those of "other" engineers. Even at this level, the advantage did not accrue in equal measure for each of the 5 professional classes.

Thus, while the monthly earnings of the upper one-tenth of the mining and metallurgical graduates exceeded those of the upper tenth of the "other" engineers by $94 a month, the differences in monthly engineering earnings among the 4 remaining professional classes ranged from $31 for mechanical and industrial engineers to $61 for chemical and ceramic engineers. At the upper 25 per cent level, the engineering earnings of mechanical and industrial graduates and "other" engineers were practically the same. There was a difference of only $13 between the earnings of the 2 groups in the case of mining and metallurgical engineers, and for electrical engineers the difference was only

## Table VI. Comparison of 5 Levels of Monthly Engineering Earnings for 5 Age Groups of Older[1] Graduate Engineers Reporting in 1929, 1932, and 1934

Without regard to kind of engineering employment reported or type of education

| Per Cent at Specified Income Level | Monthly Engineering Earnings of More Than Specified Amount of Engineers Whose Age Was | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 60 in 1929 | 63 in 1932 | 65 in 1934 | 38 in 1929 | 41 in 1932 | 43 in 1934 | 30 in 1929 | 33 in 1932 | 35 in 1934 | 25 in 1929 | 28 in 1932 | 30 in 1934 | 23½ in 1929 | 26½ in 1932 | 28½ in 1934 |
| 10 per cent | $1,152 | $807 | $770 | $663 | $557 | $533 | $410 | $368 | $360 | $247 | $253 | $258 | $205 | $219 | $228 |
| 25 per cent | 661 | 558 | 517 | 490 | 419 | 404 | 322 | 301 | 294 | 213 | 217 | 218 | 169 | 184 | 192 |
| 50 per cent | 472 | 401 | 360 | 356 | 312 | 294 | 269 | 241 | 232 | 180 | 183 | 181 | 148 | 156 | 164 |
| 75 per cent | 326 | 277 | 232 | 286 | 240 | 219 | 223 | 198 | 186 | 152 | 149 | 148 | 130 | 135 | 140 |
| 90 per cent | 243 | 170 | 132 | 231 | 187 | 161 | 196 | 149 | 145 | 135 | 122 | 121 | 115 | 113 | 115 |

| | Per Cent of Increase or Decrease | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 1929–34 | 1929–32 | 1932–34 | 1929–34 | 1929–32 | 1932–34 | 1929–34 | 1929–32 | 1932–34 | 1929–34 | 1929–32 | 1932–34 | 1929–34 | 1929–32 | 1932–34 |
| 10 per cent | −33 | −30 | − 5 | −20 | −16 | − 4 | −12 | −10 | −2 | + 4 | + 2 | +2 | +11 | +7 | +4 |
| 25 per cent | −22 | −16 | − 7 | −18 | −14 | − 4 | − 9 | − 7 | −2 | + 2 | + 2 | 0 | +14 | +9 | +4 |
| 50 per cent | −24 | −15 | −10 | −17 | −12 | − 6 | −14 | −10 | −4 | + 1 | + 2 | −1 | +11 | +5 | +5 |
| 75 per cent | −29 | −15 | −16 | −23 | −16 | − 9 | −17 | −11 | −6 | − 3 | − 2 | −1 | + 8 | +4 | +4 |
| 90 per cent | −46 | −30 | −22 | −30 | −19 | −14 | −26 | −24 | −3 | −10 | −10 | −1 | 0 | −2 | +2 |

1. Includes those engineers who were professionally active prior to 1930.

## Table VII. Comparison of 5 Levels of Monthly Engineering Earnings of All Engineers for Corresponding Years After Graduation in 1929, 1932, and 1934

Without regard to kind of engineering employment reported or type of education

| Age of Engineers | Years After Graduation | Proportion With Monthly Engineering Earnings of More Than Specified Amount | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 10 Per Cent | | | 25 Per Cent | | | 50 Per Cent | | | 75 Per Cent | | | 90 Per Cent | | |
| | | 1929 | 1932 | 1934 | 1929 | 1932 | 1934 | 1929 | 1932 | 1934 | 1929 | 1932 | 1934 | 1929 | 1932 | 1934 |
| 23½ years | ½ | $215 | $165 | $149 | $174 | $137 | $129 | $149 | $111 | $110 | $130 | $ 89 | $ 91 | $115 | $ 66 | $ 75 |
| 25 years | 2 | 252 | 180 | 160 | 215 | 152 | 140 | 181 | 133 | 120 | 152 | 114 | 102 | 133 | 92 | 82 |
| 28 years | 5 | 339 | 250 | 210 | 276 | 215 | 187 | 231 | 181 | 153 | 196 | 147 | 130 | 167 | 119 | 109 |
| 33 years | 10 | 485 | 358 | 314 | 386 | 293 | 248 | 299 | 234 | 205 | 239 | 189 | 162 | 202 | 143 | 134 |
| 43 years | 20 | 741 | 559 | 505 | 501 | 405 | 375 | 375 | 301 | 273 | 283 | 227 | 205 | 229 | 169 | 150 |
| 53 years | 30 | 940 | 685 | 617 | 592 | 462 | 428 | 416 | 332 | 299 | 296 | 240 | 211 | 230 | 164 | 148 |
| 60 years | 37 | 1,050 | 733 | 670 | 628 | 497 | 459 | 425 | 349 | 313 | 296 | 242 | 209 | 210 | 157 | 137 |

| | | Per Cent of Increase or Decrease | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 1929–34 | 1929–32 | 1932–34 | 1929–34 | 1929–32 | 1932–34 | 1929–34 | 1929–32 | 1932–34 | 1929–34 | 1929–32 | 1932–34 | 1929–34 | 1929–32 | 1932–34 |
| 23½ years | ½ | −31 | −23 | −10 | −26 | −21 | − 6 | −26 | − 6 | − 1 | −30 | −32 | + 2 | −35 | −43 | +14 |
| 25 years | 2 | −37 | −29 | −11 | −35 | −29 | − 8 | −34 | −27 | −10 | −33 | −25 | −11 | −38 | −31 | −11 |
| 28 years | 5 | −38 | −26 | −16 | −32 | −22 | −13 | −34 | −22 | −15 | −34 | −25 | −12 | −35 | −29 | − 8 |
| 33 years | 10 | −35 | −26 | −12 | −36 | −24 | −15 | −31 | −22 | −12 | −32 | −21 | −14 | −34 | −29 | − 6 |
| 43 years | 20 | −32 | −25 | −10 | −25 | −19 | − 7 | −27 | −20 | − 9 | −28 | −20 | −10 | −34 | −26 | −11 |
| 53 years | 30 | −34 | −27 | −10 | −28 | −22 | − 7 | −28 | −20 | −10 | −29 | −19 | −12 | −36 | −29 | −10 |
| 60 years | 37 | −36 | −30 | − 9 | −27 | −21 | − 8 | −26 | −18 | −10 | −29 | −18 | −14 | −35 | −25 | −13 |

## Table VIII. Comparison of 5 Levels of Monthly Engineering Earnings of All Graduate Engineers for Corresponding Years After Graduation in 1929, 1932, and 1934

| Age of Engineers | Years After Graduation | Proportion With Monthly Engineering Earnings of More Than Specified Amount | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 10 Per Cent | | | 25 Per Cent | | | 50 Per Cent | | | 75 Per Cent | | | 90 Per Cent | | |
| | | 1929 | 1932 | 1934 | 1929 | 1932 | 1934 | 1929 | 1932 | 1934 | 1929 | 1932 | 1934 | 1929 | 1932 | 1934 |
| 23½ years | ½ | $205 | $159 | $149 | $169 | $134 | $129 | $148 | $110 | $109 | $130 | $ 88 | $ 91 | $115 | $ 64 | $ 75 |
| 25 years | 2 | 247 | 180 | 161 | 213 | 153 | 140 | 180 | 132 | 119 | 152 | 112 | 100 | 135 | 93 | 82 |
| 28 years | 5 | 339 | 253 | 210 | 280 | 217 | 184 | 238 | 183 | 155 | 199 | 149 | 132 | 170 | 122 | 110 |
| 33 years | 10 | 500 | 368 | 320 | 389 | 301 | 260 | 309 | 241 | 212 | 252 | 198 | 174 | 211 | 149 | 132 |
| 43 years | 20 | 797 | 583 | 533 | 539 | 428 | 404 | 400 | 320 | 294 | 301 | 241 | 219 | 243 | 181 | 161 |
| 53 years | 30 | 1,030 | 715 | 664 | 628 | 497 | 451 | 440 | 365 | 326 | 320 | 260 | 228 | 253 | 182 | 156 |
| 60 years | 37 | 1,152 | 780 | 729 | 661 | 539 | 489 | 472 | 394 | 348 | 326 | 271 | 230 | 243 | 175 | 146 |

| | Per Cent of Increase or Decrease | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 1929–34 | 1929–32 | 1932–34 | 1929–34 | 1929–32 | 1932–34 | 1929–34 | 1929–32 | 1932–34 | 1929–34 | 1929–32 | 1932–34 | 1929–34 | 1929–32 | 1932–34 |
| 23½ years | −27 | −22 | − 6 | −24 | −21 | − 4 | −26 | −26 | − 1 | −30 | −32 | + 3 | −35 | −44 | +17 |
| 25 years | −35 | −27 | −11 | −34 | −28 | − 8 | −34 | −27 | −10 | −34 | −26 | −11 | −39 | −31 | −12 |
| 28 years | −38 | −25 | −17 | −34 | −23 | −15 | −35 | −23 | −15 | −34 | −25 | −11 | −35 | −28 | −10 |
| 33 years | −36 | −26 | −13 | −33 | −23 | −14 | −31 | −22 | −12 | −31 | −21 | −12 | −37 | −29 | −11 |
| 43 years | −33 | −27 | − 9 | −25 | −21 | − 6 | −27 | −20 | − 8 | −27 | −20 | − 9 | −34 | −26 | −11 |
| 53 years | −36 | −31 | − 7 | −28 | −21 | − 9 | −26 | −17 | −11 | −29 | −19 | −12 | −38 | −28 | −14 |
| 60 years | −37 | −32 | − 7 | −26 | −18 | − 9 | −26 | −17 | −12 | −29 | −17 | −15 | −40 | −28 | −17 |

## Table IX. Comparison of 5 Levels of Monthly Engineering Earnings for Older[1] Graduate and "Other" Engineers Reporting in Each Professional Class in 1929, 1932, and 1934

Without regard to kind of engineering employment reported

| Per Cent of Professional Class at Specified Earnings Level[2] | Monthly Engineering Earnings of More Than Specified Amount | | | | | | Per Cent Earnings of "Other" Engineers Formed of Those of Graduate Engineers | | |
|---|---|---|---|---|---|---|---|---|---|
| | Graduate Engineers[3] | | | "Other" Engineers[4] | | | | | |
| | 1929 | 1932 | 1934 | 1929 | 1932 | 1934 | 1929 | 1932 | 1934 |
| **10 per cent:** | | | | | | | | | |
| Mining and metallurgical | $803 | $617 | $612 | $709 | $501 | $512 | 88 | 81 | 84 |
| Chemical and ceramic | 737 | 636 | 632 | 676 | 596 | 553 | 92 | 94 | 88 |
| Mechanical and industrial | 684 | 537 | 514 | 653 | 511 | 495 | 95 | 95 | 96 |
| Electrical | 594 | 516 | 505 | 557 | 504 | 482 | 94 | 98 | 95 |
| Civil, agricultural, and architectural | 544 | 463 | 427 | 478 | 385 | 352 | 88 | 83 | 82 |
| **25 per cent:** | | | | | | | | | |
| Mining and metallurgical | 506 | 423 | 413 | 493 | 408 | 392 | 97 | 95 | 95 |
| Chemical and ceramic | 494 | 433 | 426 | 433 | 408 | 365 | 88 | 94 | 86 |
| Mechanical and industrial | 454 | 385 | 362 | 455 | 364 | 341 | 100 | 95 | 94 |
| Electrical | 408 | 357 | 352 | 386 | 336 | 319 | 95 | 94 | 91 |
| Civil, agricultural, and architectural | 397 | 336 | 313 | 335 | 290 | 268 | 84 | 86 | 86 |
| **50 per cent:** | | | | | | | | | |
| Mining and metallurgical | 337 | 290 | 280 | 318 | 274 | 260 | 94 | 94 | 93 |
| Chemical and ceramic | 329 | 297 | 290 | 307 | 289 | 260 | 93 | 97 | 90 |
| Mechanical and industrial | 308 | 265 | 249 | 317 | 262 | 236 | 103 | 99 | 95 |
| Civil, agricultural, and architectural | 287 | 249 | 231 | 258 | 224 | 206 | 90 | 90 | 89 |
| Electrical | 276 | 252 | 246 | 272 | 238 | 229 | 99 | 94 | 93 |
| **75 per cent:** | | | | | | | | | |
| Mining and metallurgical | 240 | 202 | 197 | 246 | 197 | 186 | 103 | 98 | 94 |
| Chemical and ceramic | 222 | 206 | 203 | 216 | 206 | 185 | 97 | 100 | 91 |
| Mechanical and industrial | 219 | 188 | 180 | 243 | 188 | 171 | 111 | 100 | 95 |
| Civil, agricultural, and architectural | 217 | 190 | 177 | 207 | 174 | 156 | 95 | 92 | 88 |
| Electrical | 199 | 187 | 187 | 206 | 179 | 168 | 104 | 96 | 90 |
| **90 per cent:** | | | | | | | | | |
| Mining and metallurgical | 185 | 142 | 145 | 195 | 132 | 135 | 105 | 93 | 93 |
| Civil, agricultural, and architectural | 169 | 143 | 140 | 164 | 131 | 128 | 97 | 92 | 91 |
| Mechanical and industrial | 160 | 138 | 136 | 192 | 134 | 125 | 120 | 97 | 92 |
| Chemical and ceramic | 156 | 150 | 146 | 154 | 121 | 129 | 99 | 81 | 89 |
| Electrical | 145 | 145 | 144 | 159 | 128 | 126 | 110 | 89 | 88 |

1. Includes all engineers who reported they were professionally active prior to 1930.
2. Arranged in ascension of graduate monthly engineering earnings for 1929.
3. Graduate engineers embrace all postgraduates, nonengineering graduates, and final-degree engineering graduates.
4. "Other" engineers embrace all engineers with college course incomplete, noncollegiate technical school course, and secondary school education.

$22 a month. However, at this level, in the case of chemical and ceramic engineers and civil engineers the differences were much higher, being $61 and $62 per month, respectively.

At these 2 earnings levels, the relationships between the earnings of graduates and "other" engineers in 1932 and 1934 were similar to those just noted for 1929.

At the average and at the 2 lower levels of earnings, the ratios of engineering earnings of the 2 groups of engineers were practically the same as those noted for earned an-

nual incomes. That is, in 1929 there was a slight advantage in favor of the "other" engineers, which was maintained to a somewhat greater degree in 1932 and 1934 than was the case for earned annual incomes. In part, however, this advantage in earnings of "other" engineers was due primarily to a higher age among the nongraduates in the groups compared.

The advantages in increased earning capacity accruing from formal education are better seen in table X, which shows the engineering earnings by type of education and by age. Only the median earnings are given, as insufficient data were obtained for the 2 lower and the 2 higher earnings levels to enable a complete comparison for all age groups and types of education.

The extra years of experience which the "other" engineers had while the graduates were in school permitted of their obtaining higher earnings than graduates only up to a point corresponding to 5 years after graduation. Even at 2 years after graduation in 1929 the differentials in earnings between the 2 groups were slight. Thus, while the median monthly earnings of "other" engineers ranged from $183 for secondary-school engineers to $193 for mechanical engineers whose college course was incomplete, the earnings of graduates from engineering work ranged from $166 per month for those with a nonengineering education to $187 for first-degree civil engineers. At 4 years after graduation, as will be seen from figure 2, the graduates were beginning to pull ahead of the "other" engineers.

## Table X. Median Monthly Engineering Earnings in 1929, 1932, and 1934, for All Engineers Reporting by Age and Type of Education

Without regard to kind of engineering employment reported

| Age | Year of Graduation | Years After Graduation | Postgraduates | Nonengineering Graduates | First-Degree Engineering Graduates | | | | | Others With— | | | | Secondary-School Education |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | Chemical and Ceramic | Civil, Agricultural, and Architectural | Electrical | Mechanical and Industrial | Mining and Metallurgical | College Course Incomplete: Civil, Agricultural, and Architectural | College Course Incomplete: Mechanical and All Others | Noncollegiate Technical Course: Civil, Agricultural, and Architectural | Noncollegiate Technical Course: Mechanical and All Others | |
| **1929 Earnings (in Dollars)** | | | | | | | | | | | | | | |
| 64 and over | [1] | 41+ | [2] | 480 | [2] | 408 | [2] | 410 | 440 | 310 | 440 | [2] | [2] | 320 |
| 56–63 | 1889–96 | 33–40 | 484 | 493 | 510 | 424 | 484 | 506 | 493 | 315 | 420 | 347 | 380 | 360 |
| 48–55 | 1897–04 | 25–32 | 455 | 482 | 493 | 407 | 438 | 483 | 437 | 318 | 423 | 286 | 402 | 353 |
| 40–47 | 1905–12 | 17–24 | 421 | 414 | 523 | 358 | 428 | 440 | 458 | 302 | 401 | 203 | 354 | 308 |
| 36–39 | 1913–16 | 13–16 | 350 | 416 | 487 | 328 | 368 | 405 | 405 | 273 | 335 | 260 | 326 | 310 |
| 32–35 | 1917–20 | 9–12 | 307 | 335 | 395 | 305 | 338 | 337 | 370 | 257 | 319 | 254 | 290 | 275 |
| 28–31 | 1921–24 | 5–8 | 266 | 255 | 295 | 260 | 264 | 285 | 284 | 220 | 267 | 218 | 253 | 233 |
| 26–27 | 1925–26 | 3–4 | 220 | 224 | 236 | 220 | 213 | 224 | 235 | 204 | 215 | 210 | 211 | 192 |
| 24–25 | 1927–28 | 1–2 | 180 | 166 | 179 | 187 | 167 | 180 | 183 | 184 | 193 | 187 | 186 | 183 |
| 23 | 1929 | 0 | 145 | 152 | 150 | 155 | 137 | 141 | 156 | 166 | 178 | 160 | 150 | 160 |
| **1932 Earnings (in Dollars)** | | | | | | | | | | | | | | |
| 67 and over | [1] | 44+ | [2] | 260 | [2] | 336 | [2] | 420 | [2] | 247 | 380 | [2] | [2] | 295 |
| 59–66 | 1889–96 | 36–43 | 435 | 400 | [2] | 367 | 415 | 416 | 420 | 273 | 335 | 267 | 300 | 311 |
| 51–58 | 1897–04 | 28–35 | 421 | 427 | 420 | 334 | 420 | 390 | 356 | 262 | 333 | 247 | 311 | 311 |
| 43–50 | 1905–12 | 20–27 | 365 | 384 | 443 | 307 | 353 | 351 | 374 | 258 | 326 | 249 | 289 | 273 |
| 39–42 | 1913–16 | 16–19 | 318 | 353 | 418 | 289 | 330 | 327 | 314 | 235 | 284 | 232 | 270 | 265 |
| 35–38 | 1917–20 | 12–15 | 294 | 305 | 324 | 262 | 309 | 301 | 300 | 226 | 263 | 222 | 244 | 234 |
| 31–34 | 1921–24 | 8–11 | 249 | 245 | 273 | 232 | 243 | 250 | 239 | 206 | 228 | 193 | 209 | 212 |
| 29–30 | 1925–26 | 6–7 | 220 | 227 | 223 | 208 | 202 | 211 | 206 | 187 | 189 | 180 | 180 | 173 |
| 27–28 | 1927–28 | 4–5 | 188 | 190 | 185 | 187 | 178 | 175 | 162 | 168 | 174 | 154 | 156 | 168 |
| 26 | 1929 | 3 | 157 | 149 | 149 | 164 | 152 | 152 | 149 | 149 | 148 | 163 | 150 | 130 |
| 25 | 1930 | 2 | 142 | 149 | 144 | 149 | 136 | 137 | 143 | 156 | 133 | 167 | 140 | 150 |
| 24 | 1931 | 1 | 119 | 120 | 124 | 134 | 118 | 120 | 114 | 145 | 131 | [2] | 135 | 140 |
| 23 | 1932 | 0 | 110 | [2] | 108 | 116 | 103 | 106 | 97 | 143 | 127 | [2] | [2] | [2] |
| **1934 Earnings (in Dollars)** | | | | | | | | | | | | | | |
| 69 and over | [1] | 46+ | [2] | 250 | [2] | 306 | [2] | 330 | [2] | 210 | 310 | [2] | [2] | 280 |
| 61–68 | 1889–96 | 38–45 | 376 | 370 | [2] | 331 | 408 | 370 | 400 | 257 | 300 | 256 | 227 | 283 |
| 53–60 | 1897–1904 | 30–37 | 386 | 387 | 426 | 296 | 379 | 346 | 340 | 240 | 320 | 220 | 207 | 208 |
| 45–52 | 1905–12 | 22–29 | 339 | 353 | 425 | 285 | 349 | 333 | 347 | 236 | 301 | 227 | 261 | 252 |
| 41–44 | 1913–16 | 18–21 | 299 | 384 | 350 | 263 | 333 | 303 | 302 | 218 | 254 | 208 | 247 | 254 |
| 37–40 | 1917–20 | 14–17 | 279 | 305 | 340 | 244 | 300 | 283 | 311 | 201 | 247 | 199 | 228 | 229 |
| 33–36 | 1921–24 | 10–13 | 241 | 242 | 287 | 218 | 240 | 239 | 237 | 183 | 216 | 183 | 198 | 198 |
| 31–32 | 1925–26 | 8–9 | 217 | 208 | 228 | 198 | 205 | 207 | 207 | 166 | 184 | 158 | 180 | 162 |
| 29–30 | 1927–28 | 6–7 | 186 | 197 | 198 | 179 | 180 | 180 | 183 | 156 | 170 | 142 | 159 | 153 |
| 28 | 1929 | 5 | 166 | 164 | 170 | 163 | 162 | 165 | 153 | 145 | 153 | 160 | 150 | 134 |
| 27 | 1930 | 4 | 144 | 145 | 153 | 150 | 145 | 149 | 143 | 145 | 135 | 155 | 133 | 150 |
| 26 | 1931 | 3 | 137 | 131 | 134 | 143 | 127 | 132 | 143 | 137 | 145 | 110 | 131 | 153 |
| 25 | 1932 | 2 | 123 | 130 | 122 | 131 | 114 | 118 | 120 | 124 | 136 | [2] | 113 | [2] |
| 24 | 1933 | 1 | 120 | 123 | 114 | 126 | 109 | 110 | 118 | 126 | 117 | [2] | 138 | [2] |
| 23 | 1934 | 0 | 95 | 130 | 107 | 116 | 106 | 106 | 113 | 118 | 107 | 110 | 108 | 110 |

1. Prior to 1889.
2. Fewer than 10 engineers reported.

## Table XI. Comparison of Median Monthly Engineering Earnings in 1929, 1932, and 1934, of Selected Age Groups of Engineers Reporting, by Type of Education

Without regard to kind of engineering employment reported

| Type of Education | Engineers Whose Age Was— | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 60 in 1929 | 63 in 1932 | 65 in 1934 | 52 in 1929 | 55 in 1932 | 57 in 1934 | 44 in 1929 | 47 in 1932 | 49 in 1934 | 25 in 1929 | 28 in 1932 | 30 in 1934 | 23½ in 1929 | 26½ in 1932 | 28½ in 1934 |
| | Median Monthly Engineering Earnings | | | | | | | | | | | | | | |
| Postgraduates | $484 | $435 | $376 | $455 | $421 | $386 | $421 | $365 | $339 | $180 | $188 | $186 | $145 | $157 | $166 |
| Nonengineering graduates | 493 | 400 | 370 | 482 | 427 | 387 | 414 | 384 | 353 | 166 | 190 | 197 | 152 | 149 | 164 |
| First-degree engineering graduates: | | | | | | | | | | | | | | | |
| Chemical and ceramic | 510 | [1] | [1] | 493 | 420 | 426 | 523 | 443 | 425 | 179 | 185 | 198 | 150 | 149 | 170 |
| Civil, agricultural, and architectural | 424 | 367 | 331 | 407 | 334 | 296 | 358 | 307 | 285 | 187 | 187 | 179 | 155 | 164 | 163 |
| Electrical | 484 | 415 | 408 | 438 | 420 | 379 | 428 | 353 | 349 | 167 | 178 | 180 | 137 | 152 | 162 |
| Mechanical and industrial | 506 | 416 | 370 | 483 | 390 | 346 | 440 | 351 | 333 | 180 | 175 | 180 | 141 | 152 | 165 |
| Mining and metallurgical | 493 | 420 | 400 | 437 | 356 | 340 | 458 | 374 | 347 | 183 | 162 | 183 | 156 | 149 | 153 |
| College course incomplete: | | | | | | | | | | | | | | | |
| Civil, agricultural, and architectural | 315 | 273 | 257 | 318 | 262 | 240 | 302 | 258 | 236 | 184 | 168 | 156 | 166 | 149 | 145 |
| Mechanical and others[2] | 420 | 335 | 300 | 423 | 333 | 320 | 401 | 326 | 301 | 193 | 174 | 170 | 178 | 148 | 153 |
| Noncollegiate technical course: | | | | | | | | | | | | | | | |
| Civil, agricultural, and architectural | 347 | 267 | 256 | 286 | 247 | 220 | 293 | 240 | 227 | 187 | 154 | 142 | 160 | 163 | 160 |
| Mechanical and others[2] | 380 | 300 | 227 | 402 | 311 | 297 | 354 | 289 | 261 | 186 | 156 | 159 | 150 | 150 | 150 |
| Secondary-school education | 360 | 311 | 283 | 353 | 311 | 298 | 308 | 273 | 252 | 183 | 168 | 153 | 160 | 130 | 134 |

| Type of Education | Per Cent of Increase or Decrease— | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 1929 to 1934 | 1929 to 1932 | 1932 to 1934 | 1929 to 1934 | 1929 to 1932 | 1932 to 1934 | 1929 to 1934 | 1929 to 1932 | 1932 to 1934 | 1929 to 1934 | 1929 to 1932 | 1932 to 1934 | 1929 to 1934 | 1929 to 1932 | 1932 to 1934 |
| Postgraduates | −22 | −10 | −14 | −15 | − 7 | − 8 | −19 | −13 | − 7 | + 3 | + 4 | − 1 | +14 | + 8 | + 6 |
| Nonengineering graduates | −25 | −19 | − 8 | −20 | −11 | − 9 | −15 | − 7 | − 8 | +19 | +14 | + 4 | + 8 | − 2 | +10 |
| First-degree engineering graduates: | | | | | | | | | | | | | | | |
| Chemical and ceramic | [1] | [1] | [1] | −14 | −15 | + 1 | −19 | −15 | − 4 | +11 | + 3 | + 7 | +13 | − 1 | +14 |
| Civil, agricultural, and architectural | −22 | −13 | −10 | −27 | −18 | −11 | −20 | −14 | − 7 | − 4 | 0 | − 4 | + 5 | + 6 | − 1 |
| Electrical | −16 | −14 | − 2 | −13 | − 4 | −10 | −18 | −18 | − 1 | + 8 | + 7 | + 1 | +18 | +11 | + 7 |
| Mechanical and industrial | −27 | −18 | −11 | −28 | −19 | −11 | −24 | −20 | − 5 | 0 | − 3 | + 3 | +17 | + 8 | + 9 |
| Mining and metallurgical | −19 | −15 | − 5 | −22 | −19 | − 4 | −24 | −18 | − 7 | 0 | −11 | +13 | − 2 | − 4 | + 3 |
| College course incomplete: | | | | | | | | | | | | | | | |
| Civil, agricultural, and architectural | −18 | −13 | − 6 | −25 | −18 | − 8 | −22 | −15 | − 9 | −15 | − 9 | − 7 | −13 | −10 | − 3 |
| Mechanical and others[2] | −29 | −20 | −10 | −24 | −21 | − 4 | −25 | −19 | − 8 | −12 | −10 | − 2 | −14 | −17 | + 3 |
| Noncollegiate technical course: | | | | | | | | | | | | | | | |
| Civil, agricultural, and architectural | −26 | −23 | − 4 | −23 | −14 | −11 | −23 | −15 | − 9 | −24 | −18 | − 8 | 0 | + 2 | − 2 |
| Mechanical and others[2] | −40 | −21 | −24 | −26 | −23 | − 5 | −26 | −18 | −10 | −15 | −16 | + 2 | 0 | 0 | 0 |
| Secondary-school education | −21 | −14 | − 9 | −16 | −12 | − 4 | −18 | −11 | − 8 | −16 | − 8 | − 9 | −16 | −19 | + 3 |

1. Fewer than 10 engineers reported.
2. Includes chemical, ceramic, electrical, industrial, mining, and metallurgical engineers.

Thus, while the range in the median monthly earnings of the former was from $225 for first-degree electrical engineers to $250 a month for first-degree chemical and ceramic engineers, it was from $200 for engineers with secondary-school education to $229 a month for mechanical and industrial engineers with incomplete college courses in the case of the "other" engineers. Beginning at 5 years after graduation, the effect of a formal education on engineering earnings was accentuated. For example, at 11 years after graduation, the average monthly earnings of first-degree civil engineers were greater than those of the "other" engineers of this professional class. The median monthly earnings were $305 for graduates, $257 for those whose college courses were incomplete, and $254 for civil engineers who had attended noncollegiate technical schools. Similarly, in the case of first-degree electrical engineers and mechanical and industrial engineers, earnings were greater than those reported by the members of these professional classes whose college courses were incomplete or who had attended noncollegiate technical schools.[9]

It will also be noted that while mechanical engineers with incomplete college courses had the highest earnings of any of the groups of "other" engineers, their earnings differed very little from those of first-degree civil engineers. Thus, at 11 years after graduation the latter reported median earnings of $305 a month as against $319 a month for mechanical engineers with incomplete college courses. The corresponding figures at 29 years after graduation were $407 and $423 a month.

Furthermore, from 5 to 37 years after graduation, there was a fairly uniform relationship in the ranking of the earnings reported by the several types of education. Relatively, this uniformity was most marked among the "other" engineers. Thus, while secondary-school engineers remained tenth in order, civil engineers whose college courses were incomplete, or who had attended noncollegiate technical schools, held respectively eleventh and twelfth places. Over the same period, first-degree chemical and ceramic engineers were first in order. They did, however, rank tenth at 2 years after graduation. Among the remaining types of education such shifts as did occur were not very pronounced. Even in 1934, the same relative positions were maintained.

With advancing age, the 1929 data show that there was a considerable advantage in engineering earnings in favor of the graduates. Thus, between civil engineers who had

9. The term, "mechanical and all others" shown in table IX under "college course incomplete" and "noncollegiate technical schools" includes chemical and ceramic, electrical, industrial, and mining and metallurgical engineers.

first degrees and those who had incomplete college courses, the differences for men 23, 33, 43, 53, and 60 years of age were \$24, \$45, \$55, \$93, and \$109 a month, while between those with first degrees and noncollegiate technical school educations, the corresponding differences were \$20, \$48, \$65, \$118, and \$77 a month.

There was also a distinct variation in the earning capacities among both graduate and "other" engineers. Thus, at 10 years after graduation, the 1929 median monthly engineering earnings of graduates ranged from \$290 for civil engineers to \$368 for chemical and ceramic engineers. Graduates' median earnings 30 years after graduation ranged from \$408 for civil engineers to \$492 in the case of chemical and ceramic engineers. For "other" engineers, the range in earnings of men whose age corresponded to 10 years after graduation, that is, 33 years was from \$242 to \$300 a month, and at 53 years of age, or corresponding to 30 years after graduation, the range was from \$290 to \$422 a month. At both of these age points, the lowest earnings among "other" engineers were reported by noncollegiate technical-school civil engineers, the highest by mechanical and industrial engineers with incomplete college education.

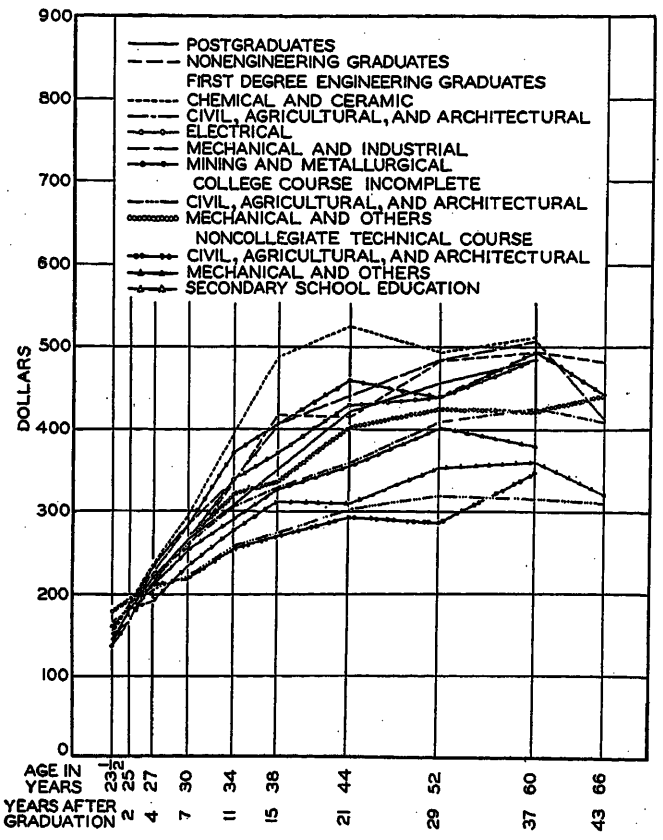



**Figure 2. Comparison of medians of monthly rate of compensation according to age, 1929**

Includes compensation for all kinds of engineering services reported

A further advantage of formal engineering education was that graduate earnings from engineering work continued to increase for several years beyond the point of maximum earnings of "other" engineers. The earnings of the latter either remained stable or declined at 53 years of age.

Consideration will now be given to the effect of the depression on earnings of men with advancing years and experience and different educational backgrounds.

Over the period 1929–34, the data in table XI indicate that the graduates who were $23\frac{1}{2}$ years in 1929 and $28\frac{1}{2}$ years in 1934 received increased earnings for all kinds of engineering, except in the case of mining and metallurgical. There were, however, no increases reported by any of the "other" engineers of corresponding ages. By contrast, for the selected age groups of 52 to 57 and 44 to 49 years, decreases in earnings occurred among both graduate and "other" engineers in almost equal measure. For example, for engineers who were 44 years in 1929 and 49 in 1934, the earnings of the graduates declined from 19 to 24 per cent, while those of the "other" engineers fell by 18 to 25 per cent.

On the other hand, for men with identical years of experience, the earnings received in 1934 by both graduates and "other" engineers were all less than those which were obtained in 1929. Thus, in table XII it will be noted that at 2 years after graduation the earnings obtained for engineering services in 1934 were less than those received in 1929 by from 32 to 41 per cent for all types of education, except nonengineering graduates and those engineers with a secondary-school education. In the case of nonengineering graduates, the earnings were 24 per cent less and for engineers with secondary-school educations they were 29 per cent less.

Again it will be noted that the decreases reported by men with 5 years' experience were, in general, greater than those for men who had had but 2 years' experience and also greater than the declines in earnings reported for men with from 10 to 37 years' experience.

**Table XII. Percentage Decreases in Median Monthly Engineering Earnings Over Period 1929–34 for Corresponding Years After Graduation, by Type of Education**

Without regard to kind of engineering employment reported

| Type of Education | Per Cent of Decrease in Earnings at Specified Years After Graduation | | | | | |
|---|---|---|---|---|---|---|
| | 2 | 5 | 10 | 20 | 30 | 37 |
| Postgraduates | 32 | 34 | 24 | 26 | 21 | 21 |
| Nonengineering graduates | 24 | 33 | 30 | [1]8 | 23 | 23 |
| First degree engineering graduates: | | | | | | |
| Chemical and ceramic | 34 | 36 | 33 | 31 | 14 | [2] |
| Civil, agricultural, and architectural | 32 | 32 | 30 | 25 | 29 | 27 |
| Electrical | 34 | 33 | 31 | 20 | 18 | 19 |
| Mechanical and industrial | 39 | 35 | 32 | [1]10 | 30 | 30 |
| Mining and metallurgical | 37 | 42 | 37 | 32 | 22 | 27 |
| College course incomplete: | | | | | | |
| Civil, agricultural, and architectural | 33 | 30 | 31 | 26 | 24 | 21 |
| Mechanical and others[3] | 34 | 37 | 36 | 34 | 27 | 25 |
| Noncollegiate technical course: | | | | | | |
| Civil, agricultural, and architectural | 41 | 26 | 31 | 27 | 23 | 33 |
| Mechanical and Others[3] | 36 | 37 | 34 | 29 | 31 | 24 |
| Secondary-school education | 29 | 28 | 34 | 18 | 23 | 19 |

1. Despite the fact that at 20 years after graduation, nonengineering graduates and mechanical and industrial engineers show only 8- and 10-per cent decreases in earnings, the consistency of the remaining decreases shown is too regular for these particular differences to have any effect on the general argument.
2. Fewer than 10 engineers reported.
3. Includes chemical, ceramic, electrical, industrial, mining, and metallurgical engineers.

# Modern Trolley-Coach Operation

By EDWARD DANA

THE BOSTON Elevated Railway serves a population of about 1,531,000 people, distributed over an area of 111.56 square miles and segregated in 14 municipalities, including both towns and cities. Within its territory the railway supplies practically all of the public transportation, except taxicabs. The backbone of its system is formed by its rapid-transit division, with elevated lines, subways and some leased surface right-of-way. The rapid-transit lines are confined to Boston and Cambridge.

The territory is covered with a network of surface-car lines, with motor-bus lines and, recently, with a few trackless-trolley lines. These surface lines serve partly as feeders for the rapid transit and partly to meet local service demands.

The fare with transfers to and from the rapid-transit lines is 10 cents; that for local riding on surface lines is 5 cents. About 30 per cent of the riders pay the lower fare.

Such a unified system of local transportation as that of the Boston Elevated provides an unusual opportunity for adapting each type of service to the best advantage within certain limitations. The expensive subways and elevated structures in fixed locations, however, provide little flexibility. They are dependent largely upon the surface railways, trackless trolleys, and motor buses as feeders.

The surface railway situation in Boston is unusual, in fact is unique, in that in and even beyond the congested business section the cars run through subways and on overhead structure, which make them to this extent a part of the rapid-transit system, with which these structures connect.

While the surface subways and viaduct expedite the movement of surface cars, they also decrease the flexibility of the surface lines. It is probable that the use of subways for surface cars is a temporary expedient in urban transportation, the logical use of such expensive way and structure being for rapid transit.

The shifting demand for urban and suburban transportation in a group of communities like metropolitan Boston renders necessary a ready adaptability of services. Thus in spite of heavy investment in track and overhead construction, it has been necessary to abandon many miles of surface railway when the demand for service was greatly reduced, or when the track was wearing out and the density of traffic would not warrant rebuilding.

The motor bus and, later, the trackless trolley entered the picture at the time when something was urgently needed to meet this situation. The Boston Elevated began to use the motor bus in 1922 and in replacing uneconomical rail lines or in giving modern transportation to communities not previously adequately served increased its bus mileage from 63,959 revenue-miles in 1922 to 10,485,554 revenue-miles in 1936. At the same time the surface-car mileage fell from 37,195,035 revenue-miles in 1922 to 24,254,263 revenue-miles in 1936. The combined mileages of the 2 services show a reduction from 37,258,994 revenue-miles in 1922 to 34,739,817 in 1936, or about 6.8 per cent.

The experience of the Boston Elevated Railway with the trackless trolley has to date been on a small scale and extends back only to April 11, 1936, when a car line in Cambridge was replaced by a trackless-trolley line. Since this line was opened the weather has been favorable so that neither on it, or a line started early in 1937, has there been opportunity to observe operation under conditions such as prevailed during parts of the two preceding winters. The railway has now 49 vehicles in operation.

The Cambridge line serves the Harvard square business district, and residential and business districts of East Cambridge. The terminals are important interchange points for car lines from Boston and for local radiating car and bus lines.

The Cambridge trackless-trolley route is 2.6 miles long, one-way mileage, requires 10 trackless trolleys and furnishes a headway of 5 to 6 minutes in rush hours and 12 minutes out of the rush hours. It replaced a car line.

In another part of the elevated territory, in Malden and Everett, 3 trackless-trolley lines have been installed during 1937, all terminating at one end in the main elevated-line terminal in Everett.

One of these, the Linden line, connects the terminal with an outlying residential section of Malden, and serves also certain business sections of Everett. The Linden line is 3.6 miles long, requires normally 13 vehicles, and gives a 5 to 6-minute time in rush hours and a 15-minute normal time headway. It replaced in part a car line and in part a bus line.

The second Everett line connects the rapid-transit terminal and an important cemetery, which gives the line its name, Woodlawn. The Woodlawn line connects the business section with several residential districts. It is 2.6 miles long, partly over the Linden line route, requires 11 vehicles, and operates on a 3- to 4-minute headway in rush hours, and a 12- to 15-minute headway at other hours. This route replaced a car line.

The third Everett trackless-trolley route operates out of the rapid-transit terminal and connects it with Malden square, 3 miles away by trackless-trolley route. Part of the route is over the Linden line. Here the rush-hour headway is from 5 to 6 minutes and the normal headway is 15 minutes. Seven vehicles are required for this service. The 3 Everett lines operate from the same carhouse

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where 8 additional trackless trolleys are available as "spares."

Other lines are in the preparatory stages as this is written, all designed primarily to serve as feeders for the rail lines and to furnish attractive local service also. The fares on the lines mentioned, without transfer to the rapid-transit lines, is 5 cents. The base fare in Boston, as stated, is 10 cents. In elaboration of the above expression "in the preparatory stages," following is the procedure locally.

**Trackless Trolley Lines of Boston Elevated Railway**

| Name of Line | Length of Route in Miles | Number of Vehicles for Regular Requirements | Spare Vehicles | Headway Rush-Hour | Headway Normal | Date Service Was Inaugurated |
|---|---|---|---|---|---|---|
| Harvard-Lechmere (Cambridge) | 2.6 | 7 | 3 | 5 to 6 minutes | 12 minutes | April 11, 1936 |
| Linden-Everett Terminal (Malden and Everett)* | 3.6 | 13 | 8 | 5 to 6 minutes | 15 minutes | January 9, 1937** |
| Woodlawn-Everett Terminal (Everett)* | 2.6 | 11 | 8 | 3 to 4 minutes | 12 to 15 min. | June 19, 1937 |
| Malden Square-Everett Terminal (Malden and Everett)* | 3.0 | 7 | | 5 to 6 minutes | 15 minutes | September 11, 1937 |

* These routes overlap to some extent. Total length of street traversed, 7.8 miles
** Part of this line began operation November 28, 1936

Prior to the inauguration of a new trackless-trolley line it is necessary to secure a permit covering the route from the city and town authorities within whose jurisdiction the route will lie, together with a location for the necessary poles, wires, and other appliances and apparatus. Before the granting of such a permit, it is necessary that a public hearing be held, notice of which must be published in one or more newspapers at least 14 days prior to date set for hearing. The granting of this permit must then be approved by the State Department of Public Utilities, after advertising public hearings. After the poles and all the overhead construction have been erected and installed, it is then necessary to secure a certificate of safe operation from the Department of Public Utilities.

Trackless trolleys have practically the same status as street cars in Massachusetts and are exempt from the requirements of the motor-vehicle law. In securing the necessary legal authority incidental to the operation of trackless trolleys, the procedure followed is that contained in the law governing street-railway locations.

The adoption of a new form of transportation, even one only so moderately novel as the trackless trolley, and its integration in a composite system, cannot be decided wholly from theoretical considerations. If a transportation system were being laid out as a new proposition, there would be much more freedom than exists in a situation like that of Boston.

The management of the Boston Elevated followed with interest the experiments with the modern trackless trolley beginning in Salt Lake City, in 1928, and early made plans for trying out the vehicle locally.

Extensive experience with the motor bus had demonstrated the advantages of an independent unit for existing rail routes on which the traffic had shrunk to or below the minimum at which car service is profitable, especially where the track needed replacing. The motor bus proved useful also in feeling out the traffic possibilities of a proposed route.

The trackless trolley occupies a place between the trolley car and the bus. It is really a trolley car which does not require tracks. It operates noiselessly as contrasted with the car and without fumes as contrasted with the bus. In common with the bus and in contrast with the car it permits curb loading eliminating the risk involved in crossing traffic before boarding and after alighting.

The trackless-trolley vehicle body is limited in size by street conditions. It probably will never be possible to build this vehicle with the capacity of a car running on rails. If a large number of people require service within limited periods, large vehicles are necessary. Trolley cars on rails are best for heavy peak loads, but where they have been ruled out on the basis of investment and operating cost, the large-body trackless trolley vehicle is next best.

Early trackless-trolley bodies were kept within bus size limits; but for use in cities with wide streets, vehicles wider than the early 96 inches were found practicable. Some designs went to 106 inches. The wider bodies make wider aisles possible and decrease the time required for passengers to board and alight.

In Boston a 100-inch width is used, as the probable maximum width for local street layouts.

The permissible length depends also on street conditions, particularly at intersections. A body with seating capacity for 40 persons is a popular size, the length being say around 33 to 34 feet. This compares with a length of 6 to 8 feet less for the 30-passenger trackless trolley, also a popular size and used where traffic demands do not warrant the larger vehicle.

As far as general design, seating, lighting, and other items the trackless trolley body utilizes the progress which has been made in the development of the comfortable and attractive bus body of today.

From the operating standpoint, the high acceleration rates and smooth pick-up of the trackless trolley permit it to make good speed amid vehicular traffic. This results from the large power capacity of the vehicle, from the characteristics of the series motor, which gives maximum torque at starting, and from the ease of control of the starting current by means of rheostats graduated in small steps. With these vehicles, the driver finds himself limited as to speed by his environment rather than the capacity of his equipment.

The pedal control here, as in the gasoline motor bus, greatly facilitates smooth operation, as compared with the trolley car, besides leaving the operator's hand free for other work. The absence of gear shift and clutch in the trackless trolley accentuates this advantage.

The replacement of trolley cars by gasoline-motor buses on a large scale is a serious matter from the power standpoint to railways that generate their own power. This is

the situation in Boston, where the Railway has 2 up-to-date power plants, one having an installed generator capacity of 120,000 kilowatts, the other of 60,000 kilowatts. There is an equally modern distribution system at 13,200 volts, 3-phase, with automatic supervisory control in several substations.

The trackless trolley tends to offset this power load loss, and the low power cost under these conditions is an argument in its favor.

The trackless trolley comes into prominence at a time when its designers can profit from experience gained in the development stages of other vehicles. In an earlier era of this development, when the trackless trolley was given a fair trial on Staten Island, N. Y., in Rochester, N. Y., and elsewhere it antedated the modern motor bus. The vehicle was a small car body mounted on a truck chassis with solid rubber-tired wheels. It proved not to be a formidable competitor of street railways, partly because it had little in the way of comfort and speed to offer the passenger, and partly because the trolley car enjoyed a high degree of popularity.

Since then the modern gasoline motor bus has been evolved, a distinctive vehicle, profiting of course by the marvelous development of the automobile. The pneumatic tire must be credited with a large share in the present-day status of the motor bus, and in turn of the trackless trolley. Not only tires, but bodies, steering gear, control and braking systems form the contributions of the motor bus to trackless trolley development.

Still closer approach to the trackless trolley was the gas-electric bus, for this, among other things, forced the development of the light-weight series motor. It is a short step from the gas-electric bus to the trackless trolley, in fact in one type of trackless trolley it is no step at all, that is in the so-called "all-service" vehicle used on a large scale by the Public Service Coordinated Transport. This vehicle is driven by an electric motor which uses central power station energy where wires are available and uses a gasoline or Diesel engine to generate power where wires are not available.

The trackless trolley undoubtedly owes something also to the research work done by the American Transit Association in developing the so-called "P.C.C." (Presidents' Conference Committee) car. This research extended to all of the elements of a modern rail car, many of which are found in the trackless trolley.

While undoubtedly the trackless trolley utilized developments in other vehicles, it in its turn has furnished incentive for further development of the high-speed light-weight motor. Motors of 125 horsepower are now in use in these equipments on 40-passenger trolley coaches, with a weight per motor of not much over 1,100 pounds. The combined weight of 2 65-horsepower motors, generally used on 2-motor equipments is several hundred pounds greater. The single-motor equipment also makes possible a saving in the weight of the control apparatus.

Most of the trackless-trolley equipments recently ordered are single-motor equipments. Lower cost, less weight, and simplicity are the ruling considerations, offsetting the higher energy consumption due to necessary abandonment of the series-parallel control which is standard on all d-c traction equipment.

In some ways the use of rheostatic control in the trackless trolley seems like a technical step backward. It took a long time to develop and perfect the series-parallel method of bringing a vehicle to speed, a method which is relatively economical. On the other hand the power item is not relatively as important as it once was. Modern power plants produce electrical energy at a much lower cost than formerly, whereas other items of transportation cost have gone up.

Again, the simplicity and smoothness of the rheostatic control offsets power costs. A great deal depends upon the skill of the operator as to the waste of power in the rheostats. A new technique must be learned, to prevent unnecessary running on resistance points.

The shunted field is an important feature of the single-motor equipment, which tends to improve operating efficiency and give better speed control. The design is such as to give a better free running speed and acceleration with one motor than with 2, and to permit better schedule performance.

The advantages of the single-motor equipment are so appealing that only the lack of availability of a suitable axle delayed its adoption on the 40-passenger trackless trolleys, although it was used earlier in the 30-passenger vehicle, where a suitable axle for a single 65-horsepower motor was available.

In the past, salient obstacles to the adoption of the trackless trolley have been the necessity for using 2 trolley wires and trolley poles, and the requirement that the mounting pole be sufficiently flexible to permit curb loading and passing of other traffic. Operating and construction difficulties connected with the double trolley have been overcome and with careful design the overhead need not be unsightly. Overhead intersections and switching involve complications but improvement in line equipment has kept pace with the vehicle. The double trolley is not the bugaboo that it once was.

The suddenness with which the trackless trolley has been accepted as a piece of rolling-stock in good standing is remarkable. It was not until 1935 that the number of vehicles in use was large enough to attract much attention. From 1928 to 1935 there was an average increase around 70 vehicles per year. The next year the number nearly doubled and as this is written there are more than 1,600 vehicles in service or on order, including the "all service" vehicles of Public Service.

There appears to be a growing tendency to order trackless trolley for service of medium density where moderate headways are required, leaving the extremes in both directions for the trolley car and the motor bus, respectively.

In all communities served by a public utility the patrons and the public are impressed by indications of progressiveness on the part of the utility. The addition of the trackless trolley to older equipment has a public-relations value in this direction. In the many cities where trackless trolleys have been recently adopted, an encouraging public appreciation has rewarded the management.

# Switching Surges With Transformer Load-Ratio Control Contactors

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## Introduction

THE INVESTIGATION described in this paper was undertaken to determine the magnitude and characteristics of the abnormal voltage transients accompanying the operation of load ratio control contactors on power transformers. As test results definitely established the fact that currents may be abruptly ruptured at other than normal current zero, accompanied by very severe over-voltages, the main purpose of the paper was directed to this phenomena, both from the experimental and theoretical viewpoint. It is believed that the subject will prove interesting to anyone concerned with switching surges in general, especially in view of the fact that certain aspects of the phenomena appear not to have been presented heretofore. Thus, the effect of current interruption at other than normal frequency current zero is gone into in detail; general equations on recurrent restriking are given; the extremely interesting possibility of restriking so as to practically discontinue the voltage transient is described; and the paradox of an increase in recovery voltage when shunt capacitance is increased is explained. These points are illustrated and supported by oscillographic evidence.

It should be noted, however, that in the experiments described, abrupt current rupture occurred only when values were 15 amperes or less, and were not obtained above 15 amperes. Furthermore, tests were limited to one type of circuit and to one type of switching device, namely, those used in connection with transformer tap changing equipments. Obviously the scope of the experiments is so limited that considerable caution must be used in forming general practical conclusions.

The now classical theory of circuit breaker recovery voltages, as first given by Park and Skeats[1] and subsequently extended by Boehne,[2] assumes that rupture of the current does not take place until a normal current zero. At this instant the current permanently extinguishes and the isolated part of the circuit, comprising the inductances of apparatus and the (small) capacitances of windings, bus bars, etc., undergoes a local oscillation. In a single frequency local circuit of this nature the oscillation results because the circuit capacitance is charged to the circuit voltage prevailing at the instant of normal current zero, and for a completely reactive circuit this is the normal

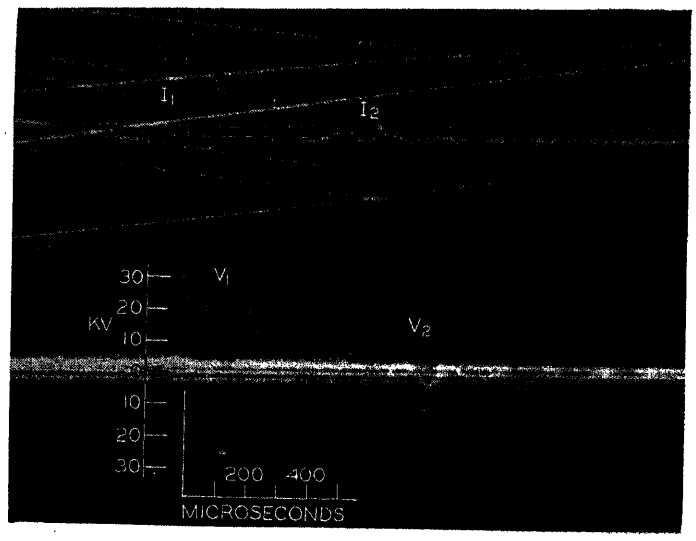



**Figure 2. Cathode-ray oscillograms of 2 switching transients**

frequency peak recovery voltage. It follows, then, that the transient oscillation has a maximum value not exceeding normal frequency peak recovery voltage; and the total voltage across the switch contacts, being the sum of the high frequency oscillation and the normal frequency voltage, cannot exceed double normal frequency recovery voltage, actually less on account of the decrements.

All of this has led to considerable speculation concerning the question: do currents extinguish precisely at a normal current zero?

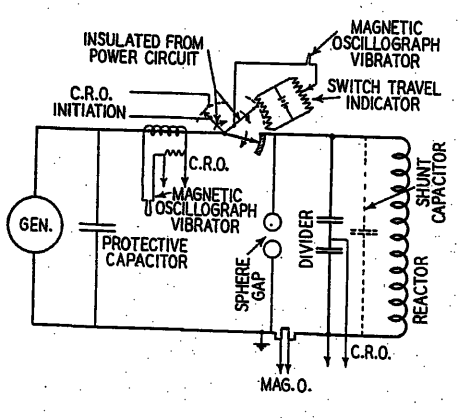



**Figure 1. Single-frequency test circuit**

## Current Interruption

A switch will endeavor to open the circuit at the instant when the contacts begin to part, but an arc forms and

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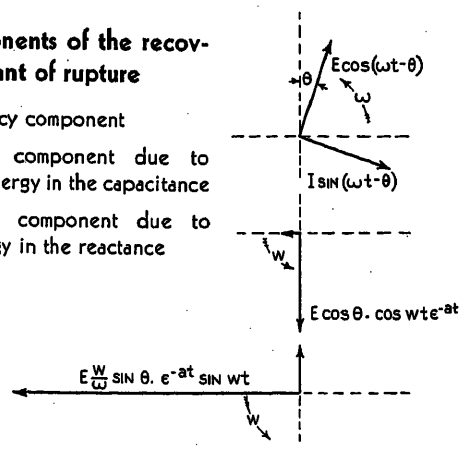
1. For all numbered references, see list at end of paper.

**Figure 3. Components of the recovery voltage at instant of rupture**

(*A*)—Normal-frequency component

(*B*)—High-frequency component due to stored electrostatic energy in the capacitance

(*C*)—High-frequency component due to stored magnetic energy in the reactance




maintains the circuit until it is disrupted by the surrounding dielectric. Ordinarily, this occurs so close to a normal current zero that it appears on the oscillograms as interruption at a current zero. In order to examine the exact instant of rupture in more detail, records were taken with the 3-element cathode-ray oscillograph developed by E. J. Wade.[3] A single cycle of normal frequency was drawn out so as to occupy the whole length of the film (24 inches) but of only half an inch amplitude; so that the point of rupture was very distinct. It was found that the contactor could abruptly interrupt the current at values of the order of 5 amperes, which in these tests corresponded to cut-off some 10 degrees from a normal current zero. Two examples are given in figure 2*a*. The ensuing high-frequency oscillations in the current waves through the reactor are clearly shown, and in figure 2*b* the corresponding high-frequency recovery voltages. The circuit consisted of a reactor of 0.25 henry inductance shunted by a capacitance of 0.003 microfarad. The natural frequency of the circuit was thus

$$f_n = \frac{1}{2\pi\sqrt{LC}} = \frac{1{,}000}{2\pi\sqrt{0.25 \times 0.003}} = 5{,}800 \text{ cycles per second}$$

or about 100 times normal frequency. In appendix I it is shown, on the assumption of abrupt current interruption that the recovery voltage is approximately:

$$e \cong E\left[\cos(\omega t - \theta) - (\cos\theta + \frac{a}{\omega}\sin\theta)\epsilon^{-at}\cos wt - \frac{w}{\omega}\sin\theta\epsilon^{-at}\sin wt\right]$$

in which $E\cos(\omega t-\theta)$ is the normal frequency voltage, $\theta$ the angle from a current zero at which interruption occurs, $(w/2\pi)$ the natural frequency, and $a$ the decrement factor. There are 2 components to the high-frequency oscillation. The cos $wt$ term is that present when interruption occurs at a normal current zero, $\theta = 0$, for then

$$e = E[\cos\omega t - \epsilon^{-at}\cos wt]$$
$$\cong E(1 - \cos wt)$$

for short times and no decrement. This is the recovery voltage of the prevailing theory[1] and is seen not to exceed twice normal peak voltage.

The sin $wt$ term exists only for finite values of $\theta$, but since $w/\omega$ is usually quite high (100:1 in figure 2) it is clear that even a very small value of $\theta$ will result in high voltages. It is this term which is responsible for the excessive voltages experienced during switching. It is:

$$E\frac{w}{\omega}\sin\theta = E\frac{\text{(natural frequency)}}{\text{(applied frequency)}} \times \frac{\text{(cut-off current)}}{\text{(normal crest current)}}$$
$$= \sqrt{\frac{L}{C}}\,\text{(cut-off current)}$$

This equation shows that:

(a). The higher the natural frequency the higher the voltage, hence the voltage increases inversely as the square root of the capacitance. (It will be shown later that this is not necessarily true if restriking occurs.)

(b). The voltage is directly proportional to the cut-off current. This cut-off current is probably a function of the switch speed, type of switch, and other factors.

Thus, if no restriking occurs, the recovery voltage consists essentially of 3 terms:

$$e = \underbrace{\left\{\begin{matrix}\text{normal}\\\text{frequency}\\\text{recovery}\\\text{voltage}\end{matrix}\right\}}_{I} + \underbrace{\left\{\begin{matrix}\text{high-frequency}\\\text{term depending}\\\text{upon the capaci-}\\\text{tor voltage at}\\\text{instant of cut-off}\end{matrix}\right\}}_{II} + \underbrace{\left\{\begin{matrix}\text{high-frequency}\\\text{term depending}\\\text{upon the reactor}\\\text{current at instant}\\\text{of cut-off}\end{matrix}\right\}}_{III}$$

of which the last is by far the most important. These components are shown as vectors in figure 3.

Since, however, the tendency is to rupture very close to a normal current zero, the probability of large cut-off currents, and correspondingly high voltages, is not great. The following results, obtained by E. A. Elge, from sphere gap measurements on a 0.25-henry reactor shunted by a 0.0003-microfarad capacitance, give the number of switch operations which were necessary to cause gap sparkover. It will be noted that the probability of voltages greater than 7 times normal is very much less than for the small voltages.

### Arc Voltage

The actual mechanism of current interruption by any switch must involve some sort of a rapidly increasing arc drop which breaks the circuit when the resulting transient switch current passes through zero. Mr. C. Concordia, in

**Table I**

| Gap Setting, Kv (Rms) | Times Normal Voltage | Switching Operations to Cause Gap Sparkover |
|---|---|---|
| 3.0 | 1.5 | 1 |
| 5.25 | 2.62 | 3 |
| 6.0 | 3.0 | 3 |
| 7.0 | 3.5 | 1 |
| 10 | 5 | 4 |
| 12 | 6 | 6 |
| 14 | 7 | 23 |
| 16 | 8 | 42 |
| 18 | 9 | 69 |
| 20 | 10 | 27 |
| 22 | 11 | 112 |
| 24 | 12 | 25 |
| 26 | 13 | None in 75 |
| 36 | 18 | 6 |
| 40 | 20 | None in 50 |

an unpublished report, has calculated the recovery voltage assuming the arc drop to increase linearly as a function of time, and under this assumption finds that for slow rates of increase of the arc drop the recovery voltage tends to become independent of the circuit constants, while for fast rates it tends to become independent of the switch characteristics. But the oscillograms of the present investigation show the rupture sufficiently abrupt with respect to the natural periods, so that for all practical purposes it is sufficient to regard the current interruption as instantaneous. The current cut-off is equivalent to the

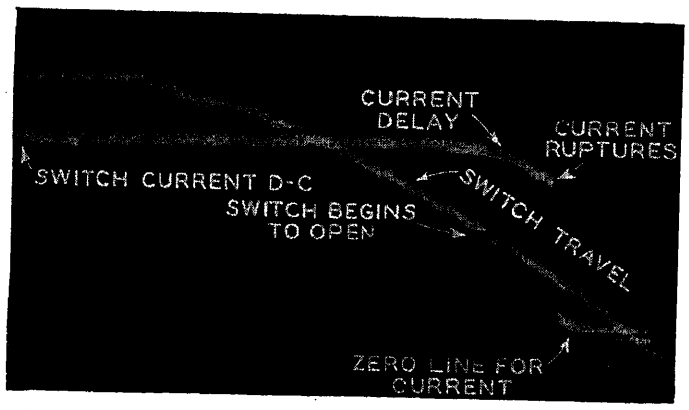



**Figure 4. Oscillogram of a d-c current interruption and switch travel**

application of a steep wave front. It is well known that a wave front even as long as 25 per cent of the natural period will succeed in developing at least 90 per cent of the oscillation that a rectangular wave front could develop (see, for example, figure 113 of reference 4). For circuits with much higher natural frequencies than those with which this investigation is concerned, it may be expedient to consider more carefully the arc characteristics. The abruptness of the cut-off is clearly shown on the oscillogram of figure 4 for the interruption of a d-c current.

## Restriking

When the switch arc extinguishes the first time, a high-frequency oscillation is initiated. This transient starts with the current in the reactor and the voltage across the capacitor at the instant of rupture as initial values, and if not interfered with, the transient develops as previously described. As the transient voltage increases, the switch contacts are opening, thus increasing the dielectric recovery strength of the switch. If the transient voltage overtakes the dielectric recovery, the arc will restrike, and the switch then makes a second attempt to open the circuit. At this second attempt the recovery voltage transient is very similar to that following the first attempt, except that the amplitude of the oscillation is reduced. In the meantime the switch has been continuously opening, acquiring greater dielectric strength, and therefore it will be a longer time before the arc again restrikes, if at all. Thus current interruption is a race between the rate of increase of dielectric strength and the rate of rise of the recovery voltage, and restriking gives the switch time to open.

The general equations of the restriking phenomena are given in appendix II. The principal term in the voltage transient following the $k$'th restrike is:

$$e \cong -wLI_k\epsilon^{-a(t-t_k)}\sin w(t-t_k)$$

in which $I_k$ is the initial current in the reactor at the start of the $k$'th restrike and lags the voltage by approximately 90 degrees, and $t_k$ is the instant at which this restrike occurs, counting time from the initial current rupture. The vector diagram of the successive restriking, taking cognizance of the above term only, is shown in figure 5*A*, the instantaneous values being the projections on the vertical axis. The sequence of events is as follows: at $t_0=0$ the switch ruptures the circuit for the first time and the voltage vector

$$e = -wLI_0\epsilon^{-at}\sin wt$$

begins to revolve at the high frequency angular velocity $w$, and to shrink exponentially. At time $t_1$ when the instantaneous voltage is $e_1$ the voltage is sufficient to break down the dielectric of the switch and the first restrike occurs. The current in the reactor at this instant is

$$I_1 = I_0\epsilon^{-at_1}\cos wt_1$$

and the new voltage transient is

$$e = -wLI_0\cos wt_1\epsilon^{-at}\sin w(t-t_1)$$

or the previous transient reduced by $\cos wt_1$ and starting at time $t_1$. By the same reasoning the voltage following the second restrike is

$$e = -wLI_0\cos wt_1\cos w(t_2-t_1)\epsilon^{-at}\sin w(t-t_2)$$

Successive restriking of this nature continues to take place until the dielectric strength of the switch has increased to a value such that the transient voltage is unable to break it down. Thereafter the transient voltage is simply a damped oscillation, shown in figure 5 as a logarithmic spiral.

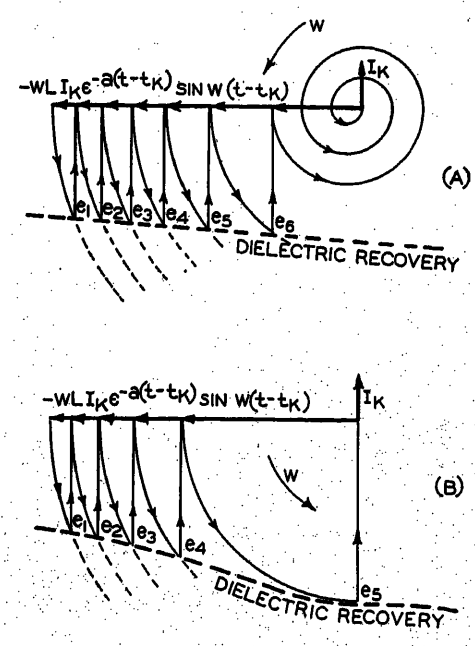



**Figure 5. Vector relationships in restriking phenomena**

(*A*)—Successive restriking with a final oscillation

(*B*)—Successive restriking without a final oscillation

If, now, the last restrike occurs at the crest of the oscillation, as shown in figure 5*B*, the current is zero, and there will be no damped oscillation associated with the electromagnetic energy, although an oscillation will exist due to the electrostatic energy which has been neglected in the foregoing.

### Effect of Dielectric Recovery Rate

In figure 6 the dielectric recovery is shown as a straight line starting at the same initial value, but with 4 different slopes, or rates. Only part of the first half cycle of each oscillation of voltage is shown. Actually, the transient is a damped oscillation about the time axis. In figure 6*a* the dielectric recovery (*d.r.*) is so fast that the oscillation reaches crest without restriking, and the recovery voltage (*r.v.*) is the maximum possible for a given angle of rupture $\theta$. If, now, the *d.r.* is slowed down, as in 6*B*, the rising *r.v.* meets the *d.r.* at point *a*, and then restrikes instead of rising on to the previous crest $V_1$, and the second attempt carries the crest to some value $V_2'$, less than $V_1$. In 6*c* the *d.r.* has been reduced so as to involve 2 restrikes, while in 6*D* it has been reduced to show 3 restrikes, and $V_4''' < V_3''' < V_2''' < V_1'''$.

### Effect of Initial Angle of Rupture

As previously discussed, for an unhindered oscillation the amplitude of the *r.v.* is directly proportional to the cut-off current, that is proportional to sin $\theta$ where $\theta$ is the angle from a current zero at which the switch makes its first attempt to open the circuit. But if restriking occurs this is not true. Figure 7 illustrates the effect of the cut-off angle $\theta$ when restriking occurs, the *d.r.* being the same for all angles. In 7*A* where $\theta = 4$ degrees, 3 restrikes occur in succession before the *d.r.* finally escapes the *r.v.* In 7*B* the angle is $\theta = 3$ degrees, and only one restrike occurs, and on this account $V_2'$ is very little less than $V_4$, although $V_1' = 0.75\ V_1$. In 7*C* at $\theta = 2$ degrees there is no restriking and $V_1'' = 0.5\ V_1$. A further reduction to $\theta = 1$ degree reduces the *r.v.* to $V_1''' = 0.25\ V_1$.

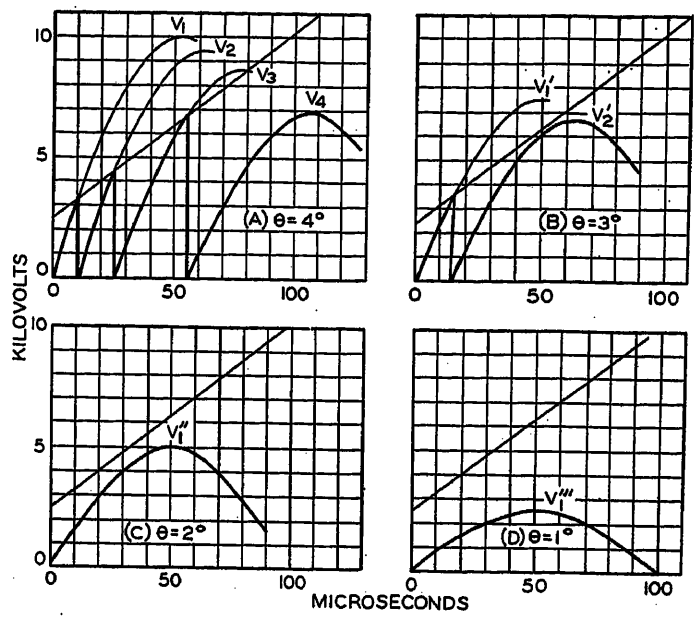



**Figure 7. Effect of initial angle of rupture**

Natural period—$T$ = 200 microseconds

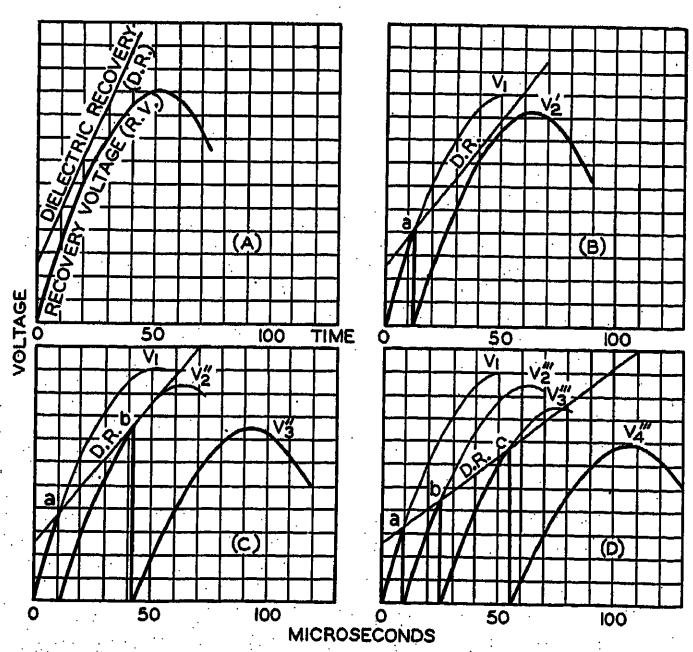



**Figure 6. Effect of dielectric recovery rate**

Initial angle of rupture—$\theta$ = 4 degrees
Natural period—$T$ = 200 microseconds

### Effect of Capacitance

When restriking occurs, it is quite possible to obtain higher *r.v.* by adding capacitance, which is quite contrary to the case when no restriking occurs. The addition of capacitance does 2 things: (1) it reduces the amplitudes proportional to $1/\sqrt{C}$; and (2) it increases the natural period proportional to $\sqrt{C}$. Therefore, as shown in figure 8, it may be that the number of restrikes can be reduced if the natural period is increased, and on this account a higher voltage produced than would result with more restrikes at a smaller capacitance. Thus in 8*A* 3 restrikes occur before the oscillation develops with a crest of $V_4 = 70$ per cent. Increasing the capacitance by 35 per cent as in 8*B* increases the natural period just enough to permit only one restrike, and the resulting crest voltage $V_2 = 76$ per cent; while in 8*C*, where the capacitance has been doubled, restriking is avoided entirely and the *r.v.* crest is $V_1 = 72$ per cent. A further increase in capacitance, as in 8*D*, can only result in a reduction of *r.v.* crest, in this case to $V_1 = 57$ per cent.

## Oscillographic Evidence

### Effect of Capacitance

The foregoing effects are well illustrated by the reactor voltage oscillograms of figure 9. In 9*A* the shunt capacitance was only 0.004 microfarad and the natural period 93 microseconds. A few restrikes are discernible at the beginning of the transient, near the crest of the normal frequency voltage. Normal voltage was 1,400 volts (crest), and the transient carried to 3.5 times normal.

For 9*B* the capacitance was 0.25 microfarad and the natural period 1,360 microseconds. This oscillogram exhibits a single restrike. The voltage is materially less than in 9*A* on account of the great increase in capacitance.

For 9*C* the capacitance was 0.5 microfarad and the natural period 960 microseconds. The transient was too slow and of too low amplitude to permit restriking.

### Dielectric Recovery

In figures 6, 7, and 8 the dielectric recovery was shown as a straight line starting at a finite value. Actually, this recovery must start at zero, and apparently at first increases very rapidly and then at a more uniform rate. But it must not be supposed that the *d.r.* is always at a uniform rate. The envelope of the restrike is, in fact, the curve of dielectric recovery against time; for such a curve gives the breakdown voltages at various instants. When matched with a record of the switch travel against time it is possible to correlate the *d.r.* with the switch opening. Records of this nature were taken as shown in the magnetic oscillogram of figure 4.

The erratic nature of some of the dielectric recoveries is illustrated by the oscillograms of figure 10. Thus in 10*A* 3 small restrikes are followed by a larger restrike, then another small one, and then a very pronounced final restrike, after which the switch succeeds in opening, and the circuit enters into its oscillation. In 10*B* the restriking repeats many times at essentially the same voltage before the switch suddenly becomes deionized and recovers. In 10*C* the restriking sequence starts to build up, but suffers a bad relapse lasting over many small restrikes before the circuit opens. In 10*D* a single restrike is followed by a half cycle of high-frequency oscillation, and then restriking occurs twice at the opposite polarity.

The envelope of restrikes has been plotted for most of the 74 oscillograms taken, and representative curves shown in figure 11. It is seen that the dielectric recovery is very erratic for this type of switch.

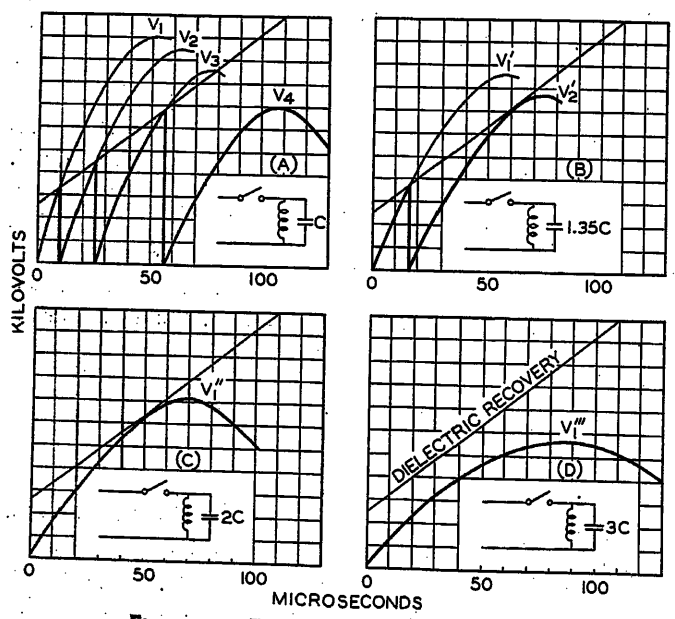



**Figure 8. Effect of shunt capacitance**

Initial angle of rupture—$\theta$ = 4 degrees
Natural period with C— $T$ = 200 microseconds

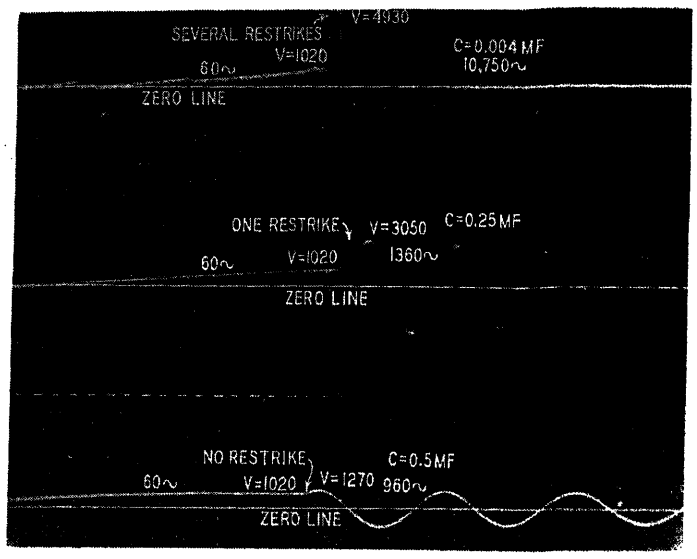



**Figure 9. Effect of capacitance**

Top—C = 0.004 microfarad, several restrikes
Middle—C = 0.25 microfarad, one restrike
Bottom—C = 0.5 microfarad, no restrikes

### Vanishing of the Oscillations

The higher up on the oscillation at which restrike occurs, other things being the same, the smaller the amplitude of the subsequent oscillation, and restrike on the crest practically discontinues the transient. The appropriate equations are given in appendix II, and the physical reason, as previously discussed, is simply that restrike at the crest of the voltage oscillation corresponds to zero current in the reactor, while immediately following restrike the voltage to which the capacitance is charged is the normal frequency voltage, so that the only energy supporting the subsequent oscillation is that of the capacitance charged to normal voltage.

This effect is illustrated in figure 12. These oscillograms are for a 125-volt d-c circuit, and as seen, the transient voltage at about 22 degrees results in a voltage of 8,400 volts (67 times normal). In 12*B* the restrike occurs at about 78 degrees and this is so close to a voltage peak that the subsequent oscillation is greatly reduced. In 12*C* and 12*D* the restrike occurs on the crest of the oscillation at about 90 degrees and the subsequent oscillation is barely discernible on the oscillograms. This small oscillation is really of normal voltage amplitude, but appears insignificant compared with the high transient voltage peaks.

### Shunt Resistors

The provision of a shunt resistor offers a parallel path for the reactor current after the switch has opened, and thereby limits the recovery voltage. There is a critical value of resistance $r = 0.5\sqrt{L/C}$ which suppresses the oscillations. In figure 13*B* is shown the effect of shunting a circuit of $L = 0.055$ and $C = 0.001$ with a resistance of

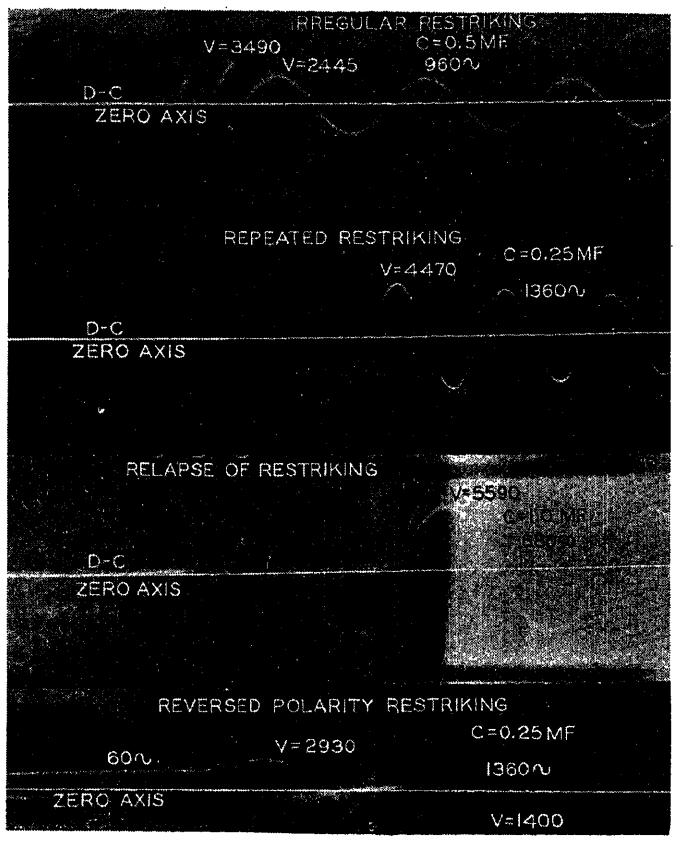



**Figure 10. Erratic nature of restriking**

5,000 ohms. The critical resistance in this case is $r$ = 3,700 ohms, so that there is still a tendency to oscillate with 5,000 ohms.

Figure 13*C* shows the effect of a Thyrite shunt. Since this material has a resistance characteristic which is low for high voltages and high for low voltages, it is to be expected that when used as a shunt resistor the higher voltages will be prohibited, but free oscillation can develop at reduced voltage. The oscillogram of 13*B* confirms this.

The result of a step-by-step calculation, according to appendix II, is shown in figure 14. This shows that with an appropriate Thyrite shunt there is no excessive voltage across the switch contact, and the transient is a smooth curve free of oscillations. The Thyrite shunt not only limits the recovery voltage, but also substantially reduces the rate-of-rise, thereby lessening the duty on the breaker.

## Tests

The special testing technique for this investigation was worked out and supervised by E. J. Wade, and it was only through the use of his 3-element cathode-ray oscillograph[3] that suitable data were obtained. Preliminary tests were conducted by E. A. Elge, of which figure 2 is a sample. A total of some 250 oscillograms, both magnetic and cathode ray, were secured; and these cover 2 different reactors, 6 different shunt capacitances, constant and Thyrite shunt resistors, 2 different load ratio control switches, and both a-c and d-c switching.

A photograph of the standard *LR*-17 switch used in these tests is shown in figure 15. This switch is comparatively "fast," having a total switching time of 0.007 second, and an initial rate of opening of 0.004 millimeter per microsecond. For comparison, a *LR*-28 switch having a switching time of 0.020 second, and an initial rate of opening of 0.0015 millimeter per microsecond was also tried.

The test circuit is shown in figure 1, the essential elements being in heavy lines and the recording and auxiliary elements in light lines. The inductance for most of the tests was an oil-filled commercial reactor rated *OT*-60-369-1590-77.4, for load-ratio control, and had an inductance of 0.0055 henry. The capacitance varied from the 0.002 microfarad of the cathode ray oscillograph divider to shunts of 1.0 microfarad. The power supplies consisted of a 1,000-volt 20-ampere a-c source, and a 125-volt 25-ampere d-c source. To protect these sources from excessive switching surge voltages, and also to simulate an "infinite bus," a large protective capacitor of 0.5 microfarad was across the power supply but on the line side of the switch. The transient voltage across the reactor was recorded by one of the tubes of the 3-element cathode-ray oscillograph, through the capacitance divider.

A current transformer with a resistor across its secondary was intended to yield both cathode ray and magnetic oscillograms of the switch current. But these proved disappointing, as the flux trapped in the core of the current transformer, upon interruption of the current through the switch, decayed exponentially through the resistor and gave an entirely erroneous picture of the current cut-off. This was confirmed by changing the value of the resistor,

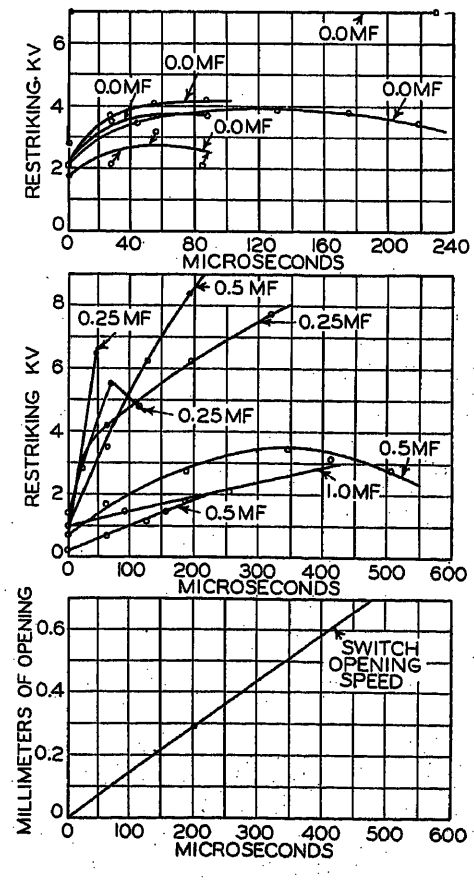



**Figure 11. Dielectric recovery**

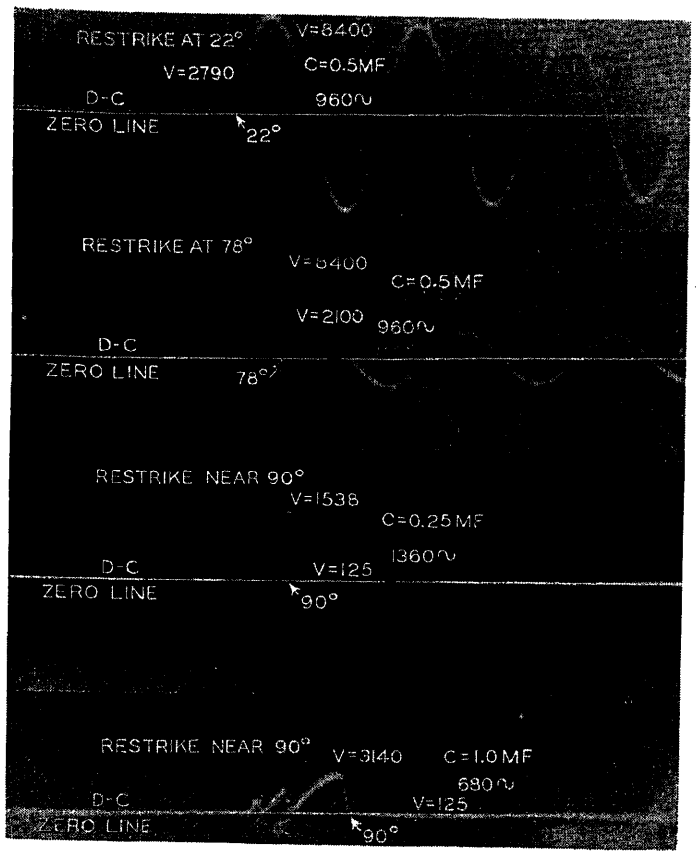



**Figure 12. Effect of the point on the high-frequency oscillation at which restrike occurs (d-c switching)**

which changed the time constant of the exponential decay. In addition, this current transformer broke down sometime during the tests and was defective for an unknown period. Magnetic oscillograms of the circuit were also obtained from a series resistor. These, however, did not show the point of current cut-off sufficiently distinctly to be of much use.

A sphere gap gave verification of the order of magnitude of the overvoltages. Since the voltage for a given circuit depends upon the intial angle of current rupture and on the number of restrikes, it was necessary to make successively more switching operations for each higher gap setting in order to be sure that the highest possible voltages were obtained.

The switch travel indicator for recording the rate of opening of the switch contacts was merely an auxiliary arm attached to the switch and arranged to move over an excited resistor as shown in figure 1. The vibrator of the magnetic oscillograph was connected between the switch auxiliary arm and a point on a potentiometer which was adjusted so as to give zero vibrator deflection just as the switch contacts began to part. A typical record is shown in figure 4. The total switch travel from the instant when its motion is initiated until it is completed is roughly a half cycle of a cosine curve (cos $at$), but over the range from the instant when the contacts begin to open until the current is finally interrupted, the switch travel is essentially at constant speed.

The control circuit of figure 16 was devised, so that the pressing of a button started in proper sequence the driving motors of the switch and of the magnetic oscillograph. A second auxiliary arm on the switch was arranged to initiate the cathode-ray oscillograph by making a contact prior to the opening of the switch.

All of the oscillograms were analyzed by W. D. Whinery, Jr., and the magnitudes, frequencies, number of restrikes, restriking peaks, and other pertinent information tabulated. The examples given in the paper are typical and were selected with a view to illustrating the various characteristics of the phenomena.

## Conclusions

This study has shown that, for the types of circuit and switches employed, switching surges may be characterized as follows:

1. The dielectric recovery strength of the switch was very erratic, and no correlation has been found with the factors involved. A 3-to-1 increase in switch speed did not make any material difference in the recovery rate.

2. The current interruption by the switch usually occurred at or very close to a normal-frequency current zero, but rupture at other than current zero was by no means uncommon. Apparently the current cut-off was sufficiently abrupt so that for all practical purposes it may be regarded as instantaneous. The highest a-c cut-off current observed was about 5 amperes at 10 degrees from a current zero. This, incidentally, is the order of current snapping which sometimes occurs in mercury-arc rectifiers. D-c currents were abruptly interrupted at about 20 amperes.

3. If no restriking occurs, the recovery voltage consists essentially of 3 terms:

$$e = \left\{\begin{matrix}\text{normal}\\ \text{frequency}\\ \text{recovery}\\ \text{voltage}\end{matrix}\right\} + \left\{\begin{matrix}\text{high frequency}\\ \text{term depending}\\ \text{on the voltage at}\\ \text{instant of current}\\ \text{current cut-off}\end{matrix}\right\} + \left\{\begin{matrix}\text{high frequency}\\ \text{term depending}\\ \text{on magnitude of}\\ \text{of the cut-off}\\ \text{current}\end{matrix}\right\}$$

The first term is, of course, normal voltage. The second term is a maximum for current interruption at a normal current zero, for the voltage to which the capacitance is charged is then a maximum. But this term never exceeds normal voltage. It is the third term

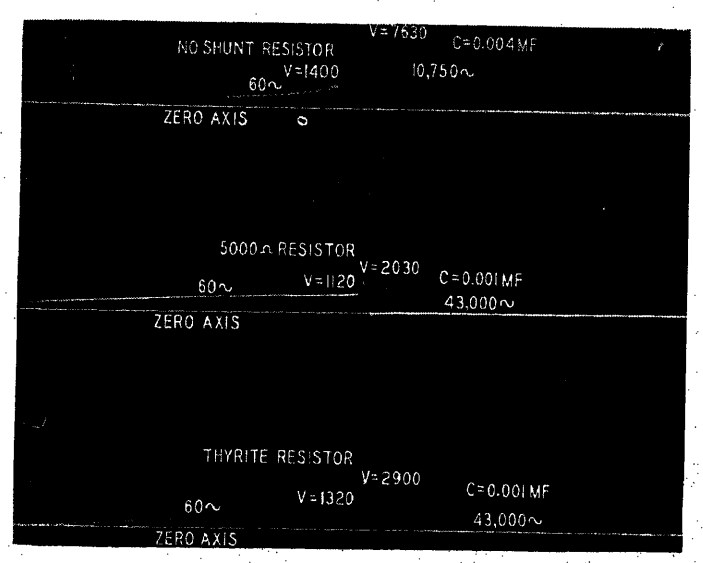



**Figure 13. Effect of shunt resistor**

which is responsible for the really high voltages. It represents the stored magnetic energy in the reactance, and is therefore greater the greater the current in the reactor at the instant of cut-off. Thus the further away from a current zero that rupture occurs, the higher the recovery voltage. The 2 high-frequency terms are in time quadrature and therefore do not add directly. Overvoltages of 18 times normal were obtained with a-c switching and 72 times normal with d-c switching.

4. Successive restriking was found to be the most influential factor of the recovery characteristic. Restriking was so abrupt as to be practically instantaneous and was followed by an immediate dielectric recovery.

5. The amplitude of the oscillation following the final restrike depends upon the point on the preceding oscillation at which restrike occurs, and if this happens near the crest, the transient can be reduced to normal voltage amplitude. A succession of restrikes reaching ultimate values many times normal, and then suddenly terminating in a very trivial oscillation, present a rather uncanny appearance on the oscillograms, but are simply explained and easy to calculate.

6. The addition of shunt capacitance will always decrease the recovery voltage crests if there is no restriking, but if restriking occurs it is possible to get higher voltages by adding capacitance; because the capacitance decreases the frequency to the same extent that it decreases the amplitude, and this may allow the switch to finally open with fewer restrikes.

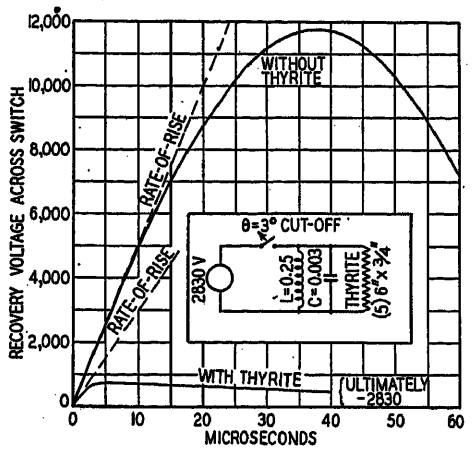



**Figure 14. Effect of Thyrite shunt on recovery voltage (calculated)**

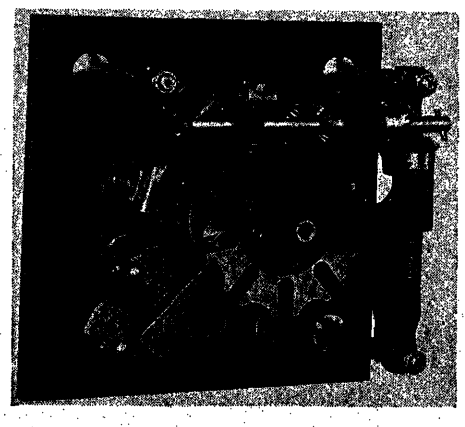


**Figure 15. Load-ratio control switch used in tests**

7. A shunt resistor can be chosen which will suppress the transient recovery voltage to any desired extent. This resistor may be either constant or of such a material as Thyrite. A Thyrite resistor not only suppresses the overvoltage, but also reduces the rate of rise.

# Appendix I

## Finite Current Cut-Off

This appendix describes the modification necessary in the conventional theory to account for the great amplitude of the high frequency oscillation in the recovery voltage. Referring to figure 17 there is shown a generator supplying current to a reactor $L$ having series resistance $R$, and shunted by a capacitance $C$ and a leakage

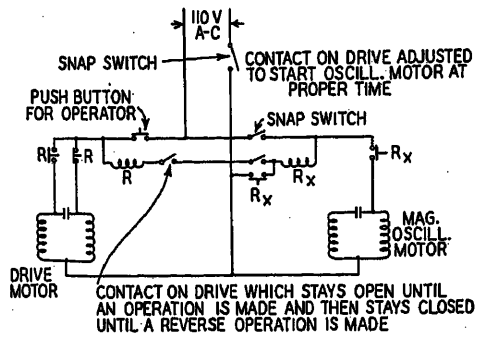



**Figure 16. Control circuit**

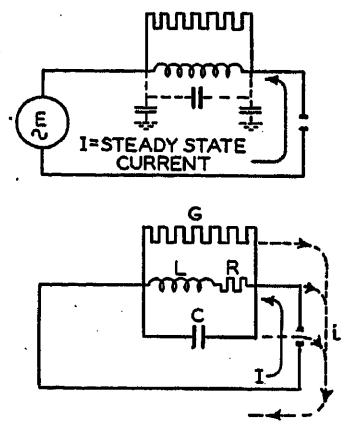



**Figure 17. The elementary circuit**

(A)—Actual circuit

(B)—Equivalent electric circuit

conductance $G$. The series resistance $R$, under high frequency conditions, will be many times the steady state d-c resistance of the winding. The capacitance $C$ is the effective circuit capacitance including the series and shunt capacitance of the reactor winding, leads, etc. It is of the order of 0.001 microfarad, unless extra capacitance in the form of an actual capacitor is deliberately added. It may be remarked here, that the smaller the inherent capacitance of the circuit, the more important it is; because the amplitude of the high-frequency recovery voltage is almost inversely proportional to the square root of the circuit capacitance. The leakage conductance $G$ is rather indefinite, unless a shunt resistor is connected across the reactor terminals. It will be shown that the high-frequency oscillation can be wiped out by a resistor of a few thousand ohms.

The conventional mathematical device for calculating recovery voltages (across the breaker terminals) as introduced by R. H. Park and W. F. Skeats,[1] consists in superposing an equal but opposite current through the breaker contacts at the instant of rupture. Thereafter, this superposed current cancels the steady state current through the breaker, and since there was no voltage across the breaker (the contacts being closed) associated with the steady state current, the "recovery voltage" must be due entirely to the superposed current. If, now, we assume the current to rupture at an angle $\theta$ prior to a current zero, the superposed current is, in operational form:

$$i = I \sin(\omega t - \theta) = I \frac{p\omega \cos\theta - p^2 \sin\theta}{p^2 + \omega^2} \qquad (1)$$

The operational impedance of the circuit, as viewed from the breaker contacts, is

$$Z(p) = \frac{R + pL}{LCp^2 + (LG + RC)p + (RG + 1)} \tag{2}$$

The operational equation for the recovery voltage then is

$$e = Z(p) \cdot i = \frac{I}{C} \frac{p(p + b)(\omega \cos \theta - p \sin \theta)}{(p^2 + \omega^2)(p^2 + 2ap + A^2)} \tag{3}$$

in which

$$a = \frac{1}{2}\left(\frac{G}{C} + \frac{R}{L}\right) \qquad b = \frac{R}{L} \qquad A^2 = \frac{RG + 1}{LC} \tag{4}$$

The solution of 3 is easily effected by the expansion theorem, and is

$$e = \frac{\omega I}{Cw^2}\left\{\sqrt{\frac{(1 + b^2/\omega^2)}{(1 + a^2/w^2 - \omega^2/w^2)^2 + 4a^2\omega^2/w^4}} \times \sin(\omega t - \theta + \phi_1 - \phi_2) + \sqrt{\frac{\left[1 + \left(\frac{b - a}{w}\right)^2\right]\left[\left(\cos\theta + \frac{a}{\omega}\sin\theta\right)^2 + \left(\frac{w}{\omega}\sin\theta\right)^2\right]}{(1 - a^2/w^2 - \omega^2/w^2)^2 + 4a^2/w^2}} \times \epsilon^{-at} \sin(wt + \phi_3 - \phi_4 + \phi_5)\right\} \tag{5}$$

where

$$w^2 = A^2 - a^2$$

$$\phi_1 = \tan^{-1}(\omega/b)$$

$$\phi_2 = \tan^{-1}\left(\frac{2a\omega}{a^2 - \omega^2 + w^2}\right)$$

$$\phi_3 = \tan^{-1}\left(\frac{w}{b - a}\right)$$

$$\phi_4 = \tan^{-1}\left(\frac{w \sin\theta}{\omega\cos\theta + a\sin\theta}\right)$$

$$\phi_5 = \tan^{-1}\left(\frac{2aw}{a^2 + \omega^2 - w^2}\right)$$

If, as would normally be the case, $w$ is large compared with $a$, $b$, and $\omega$, and $\omega$ is large compared to $b$, there is approximately $\phi_1 \cong 90$ degrees, $\phi_2 \cong 0$ degrees, $\phi_3 \cong 90$ degrees, $\phi_5 \cong 180$ degrees, $w^2 \cong 1/LC$ and 5 becomes

$$e \cong E\left\{\cos(\omega t - \theta) - \sqrt{(\cos\theta + \frac{a}{\omega}\sin\theta)^2 + \left(\frac{w}{\omega}\sin\theta\right)^2} \times \epsilon^{-at}\cos(wt - \phi_4)\right\} \tag{6}$$

where $E = \sqrt{R^2 + \omega^2 L^2}\, I$ = normal voltage

### Rupture at "Current Zero"

Putting $\theta = 0$, then $\phi_4 = 0$ and 6 yields

$$e = E(\cos\omega t - \epsilon^{-at}\cos wt) \tag{7}$$

and it is usually assumed that the decrement is negligible. Then there is the usual formula

$$e = E(\cos\omega t - \cos wt) \cong E(1 - \cos wt) \text{ for short times} \tag{8}$$

According to this, the recovery voltage consists of a simple oscillation about normal voltage as an axis, and the amplitude of the oscillation is the same as normal voltage.

### Rupture at Finite Current

Unless a shunt resistor has been added, $G$ will be so small that the approximation 6 holds, and it may be expanded into the form

$$e = E\left\{\cos(\omega t - \theta) - (\cos\theta + \frac{a}{\omega}\sin\theta)\,\epsilon^{-at}\cos wt - \left(\frac{w}{\omega}\sin\theta\right)\epsilon^{-at}\sin wt\right\} \tag{9}$$

and the last term is responsible for the very high voltages experienced. It is

$$E\frac{w}{\omega}\sin\theta = E\left(\frac{\text{natural frequency}}{\text{applied frequency}}\right)\left(\frac{\text{cut-off current}}{\text{normal crest current}}\right) = \sqrt{\frac{L}{C}}\, I_{c.o.} \tag{10}$$

This equation shows that:
($a$). The higher the natural frequency of the circuit the greater the amplitude. Since the natural frequency is very closely

$$w = \sqrt{A^2 - a^2} \cong \frac{1}{\sqrt{LC}} \tag{11}$$

it is clear that the amplitude of oscillation is inversely proportional to the square root of the capacitance. Hence, the addition of capacitance will decrease the amplitude.
($b$). The higher the current at which rupture occurs the greater the voltage. In fact, the recovery voltage is directly proportional to the cut-off current. It is not yet clear if there is a maximum cut-off current at which a given switch can rupture the circuit. If so, then the higher the normal crest current in a circuit. the smaller the recovery voltage, since it is the *ratio* of *cut-off* to *normal* current which is important in equation 11; and therefore if there is an upper limit to the cut-off current (for a given switch), normal current is important.

As an example let:

$E = \sqrt{2} \times 2{,}000 = 2{,}828$
$L = 0.25$ henrys
$C = 0.003$ microfarad
$\omega = 2\pi f = 377$
$a = 0.003 \times 10^6$
$b = 0$
$\theta = 10°$ ($\sin\theta = 0.173$)

$$w = \frac{1}{\sqrt{LC}} = 36{,}500$$

By 9, if $t$ is in microseconds

$$e = 2828\,[\cos(0.000377t - 10°) - (0.985 + \frac{3000}{377} \times 0.173) \times \epsilon^{-0.003t}\cos 0.0365t - \frac{36500}{377} \times 0.173\,\epsilon^{-0.003t}\sin 0.0365t]$$
$$= 2828\cos(0.000377t - 10°) - 6690\,\epsilon^{-0.003t}\cos 0.0365t - 47400\,\epsilon^{-0.003t}\sin 0.0365t$$

This has a maximum of 43,000 volts, or 15 times normal. The value of $a$ used in this problem corresponds to a leakage resistance of about 55,000 ohms.

### Shunt Resistor

The circuit can be rendered nonoscillatory by the addition of a shunt resistor such that

$$(a^2 \geq A^2) \text{ or } \frac{1}{4}\left(\frac{G}{C} + \frac{R}{L}\right)^2 \geq \left(\frac{RG + 1}{LC}\right) \tag{12}$$

or approximately

$$G \geq 2\sqrt{\frac{C}{L}} \tag{13}$$

Under this condition the high frequency oscillation is adequately suppressed. Taking the example in the previous case, and assuming a shunt resistor of 6,000 ohms, we have by 4

## Table II

| Event | Instant | Initial Conditions: Current | Initial Conditions: Voltage | Dielectric Strength | Switch: Voltage | Switch: Current | Reactor: Voltage | Reactor: Current |
|---|---|---|---|---|---|---|---|---|
| Begin to rupture $i_s(t_1, 0) = 0$ | 0 | $I_0 = -I \sin \theta$ | $E_0 = E \cos \theta$ | $f(t)$ | $i_s(t, 0)$ | $e(t, 0)$ | $i(t, 0)$ | |
| First rupture $E_s(t_1) = \bar{e}_s(t_1, t_1)$ | $t_1$ | $I_1 = i(t_1, 0)$ | $E_1 = e(t_1, 0)$ | $E_s(t)$ | $\bar{e}_s(t, t_1)$ | 0 | $\bar{e}(t, t_1)$ | $\bar{i}(t, t_1)$ |
| First restrike $i_s(t_2, t_2) = 0$ | $t_2$ | $I_2 = \bar{i}(t_2, t_1)$ | $E_2 = \bar{e}(t_2, t_1)$ | $f(t)$ | $i_s(t, t_2)$ | $e(t, t_2)$ | $i(t, t_2)$ | |
| Second rupture | $t_2$ | $I_3 = i(t_2, t_2)$ | $E_3 = e(t_2, t_2)$ | $E_s(t)$ | $\bar{e}_s(t, t_2)$ | 0 | $\bar{e}(t, t_2)$ | $\bar{i}(t, t_2)$ |

## Table III

| Event | Instant | Initial Conditions: Current | Initial Conditions: Voltage | Dielectric Strength | Switch: Voltage | Reactor: Voltage | Reactor: Current |
|---|---|---|---|---|---|---|---|
| First rupture $E_s(t_1) = \bar{e}_s(t_1, 0)$ | 0 | $I_0 = -I \sin \theta$ | $E_0 = E \cos \theta$ | $E_s(t)$ | $\bar{e}_s(t, 0)$ | $\bar{e}(t, 0)$ | $\bar{i}(t, 0)$ |
| First restrike $E_s(t_2) = \bar{e}_s(t_2, t_1)$ | $t_1$ | $I_1 = \bar{i}(t_1, 0)$ | $E_1 = E \cos(\omega t_1 - \theta)$ | $E_s(t)$ | $\bar{e}_s(t, t_1)$ | $\bar{e}(t, t_1)$ | $\bar{i}(t, t_1)$ |
| Second restrike $E_s(t_2) = e_s(t_2, t_2)$ | $t_2$ | $I_2 = \bar{i}(t_2, t_1)$ | $E_2 = E \cos(\omega t_2 - \theta)$ | $E_s(t)$ | $\bar{e}_s(t, t_2)$ | $\bar{e}(t, t_2)$ | $\bar{i}(t, t_2)$ |
| Third restrike | $t_2$ | $I_3 = \bar{i}(t_2, t_2)$ | $E_3 = E \cos(\omega t_2 - \theta)$ | $E_s(t)$ | $\bar{e}_s(t, t_2)$ | $\bar{e}(t, t_2)$ | $\bar{i}(t, t_2)$ |

$$a = \frac{1}{2}\left(\frac{167}{0.003}\right) = 28{,}000$$

$$w = \sqrt{A^2 - a^2} \cong \sqrt{\frac{1}{LC} - a^2} = \sqrt{\frac{10^6}{0.25 \times 0.003} - 28{,}000^2} = 23{,}450$$

Hence by 5 there is approximately

$$e = 2828\left(\frac{36500}{23450}\right)^2\left\{\frac{1}{2.42}\cos(0.000377t - 10°) + 11.28\,\epsilon^{-0.028t}\sin(0.02345t - 58.6°)\right\}$$

$$= 2828\cos(0.000377t - 10°) + 77500\,\epsilon^{-0.028t}\sin(0.02345t - 58.6°)$$

The high-frequency oscillation has a maximum at ($t = 73$) of 6,350 volts, and the total voltage does not exceed 3 times normal, as compared with 15 times normal for the case without shunt resistor.

Had the shunt resistor been "critical," as called for by 13—about 4,500 ohms—the transient term would have been of no concern. It is suggested that 13 be adopted as the proper criterion for a shunt resistor.

### Thyrite Shunt

When a Thyrite shunt resistor is employed to suppress the magnitude and rate-of-recovery of the transient, it is necessary to resort to step-by-step calculations. Assuming, as before, that the switch opens at an angle $\theta$ from a normal current zero, and neglecting the arc drop, the initial conditions immediately following rupture of the switch current are:

$$i_L = -I \sin \theta \tag{14}$$

$$e_c = E \cos \theta \tag{15}$$

$$i_s = 0 = i_L + i_R + i_C \tag{16}$$

Substituting increments for differentials there is

$$\Delta e_c = \frac{i_C}{C}\Delta t = -\left(\frac{i_L + i_R}{C}\right)\Delta t \tag{17}$$

$$e_c = E \cos \theta + \Sigma \Delta \theta_c \tag{18}$$

$$\Delta i_L = \frac{e_{av}}{L}\Delta t \tag{19}$$

$$i_L = -I \sin \theta + \Sigma \Delta i_L \tag{20}$$

$$i_R = \phi(e_c) = \text{Thyrite current as function of the voltage} \tag{21}$$

Herefrom the step-by-step calculation can be performed in the following sequence:

| $\Delta t$ | $t$ | $\Delta i_L$ | $i_L$ | $i_R$ | $\Delta e_c$ | $e_c$ |
|---|---|---|---|---|---|---|
| | 0 | | $-I \sin \theta$ | $\phi(E \cos \theta)$ | | $E \cos \theta$ |
| (1) | | (3) | | (5) | | |
| (2) | | (4) | | (7) | | (6) |

## Appendix II

### Recurrent Restriking

Current interruption at other than a normal current zero results in the initiation of a greatly magnified voltage transient. If this voltage transient is able to overtake the increasing dielectric strength of the opening switch contacts, the arc will restrike and thus postpone the final rupture of the circuit. A number of restrikes may occur in succession before the switch gap is able to sustain the recovery voltage. In effect, a series of restrikes is equivalent to circuit interruption at a lower current than prevailed at the first attempt; so that the transient recovery voltage is substantially reduced. Moreover, since the switch contacts have been continually parting during the restriking period, the dielectric strength of the opening switch has ample time to become established and effect the final rupture.

An additional interesting fact associated with restriking of the switch is the possibility of obtaining *higher* recovery voltages by increasing the circuit capacitance, which is quite contrary to the case when no restriking occurs. The reason for this is that the addition of capacitance not only reduces the crest of the transient recovery voltage (inversely as the square root of the capacitance), but also reduces the natural frequency in the same proportion. It is thus possible for the switch to open with fewer restrikes, or even to escape restriking entirely, if the natural frequency is reduced, and on this account a higher recovery voltage results. Of course, if capacitance is added beyond that necessary to just avoid restriking, there is a decrease of recovery voltage.

There are 2 kinds of "events" associated with recurrent restriking of the switch arc: (*a*) the characteristic transient during arcing and, (*b*) the characteristic transient when the switch is clear. Each of these transients depends upon the currents and voltages existing at the initiation of the event; and these initial values are determined from the corresponding end conditions of the preceding event.

The analysis consists, then, in deriving the appropriate equations for each kind of transient, and the formulation of a procedure for determining the integration constants in proper sequence. In the interests of simplicity a circuit consisting of $L$ and $C$ in parallel will be considered.

### Arcing Conditions

During arcing of the switch the voltage applied to the circuit is

$$e = E \cos(\omega t - \theta) - f(t) \tag{1}$$

in which $E \cos(\omega t - \theta)$ is the applied normal frequency voltage and $f(t)$ is the arc drop expressed as a function of time $t$. More generally, the arc drop depends upon the current, kind of contacts, and other factors, but will be here regarded merely as a function of the switch opening, hence of time. Park and Skeats[1] have given an example (their figure 12) in which the arc drop at the instant of clearing was taken into account in calculating the recovery transient. Recently C. Concordia, in an unpublished report, has calculated the recovery voltage assuming the arc drop to be a linear function of time $Kt$, and under this assumption has found for slow rates of increase of the arc voltage that the recovery voltage tends to become independent of the circuit constants, while for fast rates it tends to become independent of the switch characteristics.

Adhering, for the sake of generality, to $f(t)$ as the arc drop, the current through the inductance is

$$i = \frac{1}{L}\int [E \cos(\omega t - \theta) - f(t)]\, dt = A + \frac{E}{\omega L}\sin(\omega t - \theta) - F(t) \tag{2}$$

in which $A$ is an integration constant and

$$F(t) = \frac{1}{L}\int f(t) \cdot dt \tag{3}$$

If $i = I_j$ at $t = t_j$ then

$$i = I_j + \frac{E}{\omega L}[\sin(\omega t - \theta) - \sin(\omega t_j - \theta)] - [F(t) - F(t_j)] \tag{4}$$

The capacitance current is

$$i_c = C\frac{de}{dt} = -\omega CE \sin(\omega t - \theta) - C \cdot f'(t) \tag{5}$$

and the total switch current is the sum of (4) and (5) or

$$i_s = I_j + \frac{E}{\omega L}[(1 - \omega^2 LC)\sin(\omega t - \theta) - \sin(\omega t_j - \theta)] - [F(t) - F(t_j)] - C \cdot f'(t) \tag{6}$$

If $f(t)$ is known, or assumed, the transcendental equation 6 determines the instant $t_{j+1}$ at which the switch current is passed through zero; and then (1) and (4) give the capacitor voltage and inductance current at this instant.

### Nonarcing Condition

When there is no arc across the switch the differential equation is

$$\frac{d^2 i}{dt^2} + \frac{i}{LC} = 0 \tag{7}$$

for which the solution is

$$i = A \cos wt + B \sin wt \tag{8}$$

and

$$e = L\frac{di}{dt} = -wLA \sin wt + wLB \cos wt \tag{9}$$

in which

$$w = \frac{1}{\sqrt{LC}}$$

If $i = I_k$ and $e = E_k$ at $t = t_k$ these give

$$\bar{i} = I_k \cos w(t - t_k) + \frac{E_k}{wL}\sin w(t - t_k) \tag{10}$$

$$\bar{e} = -wLI_k \sin w(t - t_k) + E_k \cos w(t - t_k) \tag{11}$$

in which bars have been placed over the quantities to distinguish them from the corresponding quantities under the arcing condition. The voltage across the switch is

$$\bar{e}_s = E \cos(\omega t - \theta) - \bar{e} \tag{12}$$

and the dielectric strength of the open switch will be taken as a function of time $E_s(t)$. Here again, the dielectric recovery strength is probably a function of the previous arc current and other factors, but will be considered as a simple function of the switch opening, that is of the time. It is clear from the test results that $E_s(t)$ is not linear. In many cases it first decreases and then increases, and is sometimes very erratic.

### Restriking

Suppose the switch makes its first attempt to open the circuit at time $t_j = t_0 = 0$ at which instant

$$e(0) = E_0 = E \cos\theta + f(0) \tag{13}$$

$$i(0) = I_0 = \frac{-E}{\omega L}\sin\theta \tag{14}$$

Hence by (6) the switch current is

$$i_s(t, 0) = \frac{E}{\omega L}(1 - \omega^2 LC)\sin(\omega t - \theta) - F(t) + F(0) - C \cdot f'(t) \tag{15}$$

Equating (15) to zero and solving for $t = t_k = t_1$ gives the instant at which the current extinguishes, at which instant

$$\text{by (1)} : e(t_1, 0) = E \cos(\omega t_1 - \theta) + f(t_1) = E_1 \tag{16}$$

$$\text{by (4)} : i(t_1, 0) = \frac{E}{\omega L}\sin(\omega t_1 - \theta) - F(t_1) + F(0) = I_1 \tag{17}$$

Substituting (16) and (17) into (10) and (11) there is

$$\bar{i}(t, t_1) = I_1 \cos w(t - t_1) + \frac{E_1}{wL}\sin w(t - t_1) \tag{18}$$

$$\bar{e}(t, t_1) = -wLI_1 \sin w(t - t_1) + E_1 \cos w(t - t_1) \tag{19}$$

$$\bar{e}_s(t, t_1) = E \cos(\omega t - \theta) + wLI_1 \sin w(t - t_1) - E_1 \cos w(t - t_1) \tag{20}$$

This condition persists until a time $t = t_j = t_2$ such that

$$\bar{e}_s(t_2, t_1) = E_s(t_2) \tag{21}$$

when the arc restrikes. The end conditions at $t = t_2$ are then given by (18) and (19) as

$$\bar{i}(t_2, t_1) = I_2 \tag{22}$$

$$\bar{e}(t_2, t_1) = E_2 \tag{23}$$

and these substituted in (4) and (6) give the initial conditions for the next arcing event. The sequence is then repeated according to table II.

If the current rupture is assumed to be abrupt, the procedure can be simplified to the form of table III.

It will be noticed in the above tabulation that the initial voltage $E_k$ for each event (following restrike) is merely the applied normal frequency voltage at that instant; for the restriking of the arc places the capacitance directly across the applied voltage and we are neglecting the arc drop.

Of great interest is the possibility of discontinuing the high-voltage transient following a restrike near the peak of the voltage transient.

The dangerous component of the voltage transient is the term containing $I_k$ in equation 11, and therefore if $I_k = 0$ this term vanishes. But

$$I_k = -I_{k-1} \cos w\,(t_k - t_{k-1}) + \frac{E_{k-1}}{wL} \sin w\,(t_k - t_{k-1}) \qquad (24)$$

and thus the condition $I_k = 0$ is satisfied by

$$\tan w\,(t_k - t_{k-1}) = \frac{wLI_{k-1}}{E_{k-1}} = \frac{w}{\omega}\,\frac{\omega LI_{k-1}}{E_{k-1}} \qquad (25)$$

Now $w/\omega$ is usually large (say of the order 100 to 1) and therefore even for small values of $I_{k-1}$ equation 25 shows that the tan $w(t_k - T_{k-1})$ is large, so that the condition corresponds to a restrike near the peak of the voltage oscillation. A number of oscillograms illustrating this condition have been given in the text. Of course, tests with d-c are particularly favorable to this condition.

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# The Enlarging Concept of Engineering


By VLADIMIR KARAPETOFF, Fellow AIEE


IN proportion as the concept of "laws of nature" grows larger to include individual human behavior and group action, the engineer is called upon to apply his time-tested methods to broader problems of state and country. The usual definition of engineering, as the science and art of applying laws of nature to human needs, still holds; only the laws of nature cannot be limited any longer to those of levers and expanding steam. Sales engineering and works management have been the two windows through which the mechanistically minded engineer has been made to see broader aspects of his profession, involving fickle human will, prejudices, and emotional response. It is true that these propensities cannot yet be predicted with the same accuracy as the strength of a beam or the behavior of an electric generator, but the engineer has always included a lot of intuitive art (horse sense) as a part of his professional make-up anyway. As the laws of human behavior become better known we may expect an ever increasing influence of properly trained engineers upon our political, economic, and social life.

A person who can play fragments of half a dozen pieces on the piano in a crude fashion is not a musician worthy of that name. The new engineer whom I am picturing is not a man who barely has had short courses in elementary psychology and economics, in addition to his big courses in machine design and laboratories. My plea is primarily for a longer college course, following the example of the professions of law and medicine. Our nation must be awakened to the great possibilities of scientific planning and systematic gradual realization of an all-embracing economic and social program, a plan that would carry us as little scathed as possible beyond the present unrest and uncertainties. The men and women who know what is needed and what is possible to accomplish to save this country from a chaos do not yet call themselves engineers. They may be historians, sociologists, economists, psychologists, or what not. But once they are called upon to lay down definite plans and to execute them, they become engineers, for they will have to employ practically the same rigid methods of design and management as those used in building a mammoth bridge or running a huge automobile plant. Thus, these human engineers of the new kind should have considerable general engineering ability and training, and at the same time be experts in one of the lines of "social engineering." An analogy with a medical specialist readily suggests itself.

I am unalterably opposed to anything superficial in engineering training in colleges, for with the present spread of popular information superficial knowledge is readily picked up from the daily and weekly press and by simply keeping one's eyes open. The ranks of the new engineers should not be filled from among so-called practical youths who cannot master mathematics or mechanics. The social engineer has to be even more analytical than his older mechanistically inclined colleague, for he is to apply himself to much more difficult problems and to problems whose solutions cannot be looked up in a handbook like the size of an I-beam. The only choice left is to lengthen the course of training to five or even six years. No student should be allowed to specialize for at least three years; during these years he should be imbued with the general point of view of an engineer, using as illustrations some simple problems taken from two or three usual domains of engineering activity. This means a training both in the fundamental sciences and in applied situations. From there on, the attention devoted to one or two chosen specialties should be gradually increased, and the time devoted to the other engineering subjects tapered down.

Social engineers alone can convert our present society into a properly subdivided and inwardly correlated politico-economic unit wherein each of us could move in his proper sphere without dominating others or being dominated by them. My appeal is for such social engineers.


From an address delivered by the author before the trustees, the faculty, and invited guests of the Polytechnic Institute of Brooklyn, at the University Club, New York, N. Y., June 16, 1937, on the occasion of granting him an honorary degree of doctor of science. Doctor Karapetoff is professor of electrical engineering at Cornell University, Ithaca, N. Y.

# Network-Analyzer Solution of Multiple Unbalances

By EDWARD W. KIMBARK
MEMBER AIEE

SOME EXAMPLES of multiple unbalances on a 3-phase network are:

1. Two or more unsymmetrical short circuits at different points of a network. Faults involving more than one circuit are not unusual on multicircuit lines, and simultaneous faults sometimes occur even at geographically separated points, especially on systems grounded through high impedance. System stability or operation of relays during such faults may require investigation.
2. A short circuit partially cleared by the blowing of a fuse.
3. A short circuit on a line having series capacitors, the capacitors in the faulted conductor being short circuited by protective devices.
4. Two or more single-phase or unbalanced loads.

The solution for current, voltage, and power at specified points of such a network containing any one of the multiple unbalances listed above is greatly facilitated by the use of a network analyzer (a-c calculating board). The a-c board is a much more powerful tool than the d-c board for solving multiple unbalances, and its use for this purpose saves even more time and labor than it does in solving single unbalances. The technique of its use is of interest at this time in view of the increasing use and importance of network analyzers.

A number of different methods are available for the network-analyzer solution of multiple unbalances. The method to be preferred in any particular case depends on the nature of the problem to be solved and on the equipment available.

The methods may be broadly classified into symmetrical component methods and 3-phase methods. Several symmetrical component methods, which have been published,[1,2,3] will be summarized and compared with each other and with the 3-phase methods. The latter will be described in detail.

## I. Symmetrical-Component Methods

In the symmetrical component methods the 3-phase network is represented on the calculating board by its sequence networks, set up either together or in succession.

### A. Equivalent-Circuit Method

This method was devised by Miss Clarke[1] for the case of 2 simultaneous faults, and is suitable for all types of double unbalance. The 2 faults (or double unbalance) are represented by a 3-terminal equivalent circuit connected to the positive-sequence network at the 2 points of fault and the neutral point. In some cases the equivalent circuit must contain an adjustable source of voltage. The impedances of the equivalent circuit depend on the impedances of the zero-sequence and negative-sequence networks measured from the points of fault and on the types of faults or of unbalance.

The determination of the impedances of the equivalent circuit requires algebraic work which, however, has been done and tabulated for combinations of 2 short circuits. The equivalent circuit must be modified if any change occurs in the zero- or negative-sequence networks, as, for example, by the opening of a line; but it is not affected by swinging of the generators except in so far as this may require readjustment of the electromotive force of the equivalent circuit. The equivalent-circuit method has the advantage of requiring only one sequence network to be set up at a time, thus permitting a large power system to be represented with the minimum number of phase shifters and impedance units. It is particularly good for problems, such as stability studies, in which only the positive-sequence quantities are of interest. If zero- or negative-sequence quantities are desired the respective networks must be solved separately. The method is limited to two simultaneous faults (or a double unbalance).

### B. Shunt Method

This method, which was suggested by Professor W. V. Lyon,[2] is similar to the preceding one except that each fault is represented by a single impedance connected in shunt with the positive-sequence network at the point of fault. The impedance of each shunt depends not only on the impedances of the zero- and negative-sequence networks and on the types of all the faults, but also on the impedances of the positive-sequence networks and on the ratio of the open-circuit positive-sequence voltages at the points of fault. As a result, the impedances of the fault shunts are affected by swinging of generators if the ratio of open-circuit fault voltages is affected thereby, as it generally is. Professor Lyon has worked out expressions for the values of the shunts representing 2 faults. The method can be extended to any number of simultaneous faults by suitable algebraic determination of the values of the shunts.

### C. Connection Method

This method requires all 3 sequence networks to be set up at the same time, and is therefore limited to a smaller system than are the 2 preceding methods. Any number of simultaneous short circuits or open circuits or both may be represented by suitable interconnections of the sequence networks as has been customary for representing single short circuits, except that in some cases the connections must be made through insulating transformers or through phase converters. The phase converter is any device

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E. W. Kimbark is assistant professor of electrical engineering at the Polytechnic Institute of Brooklyn, Brooklyn, N. Y. This paper is based on a thesis submitted in partial fulfillment of the requirements for the degree of doctor of science, Massachusetts Institute of Technology, 1937.

1. For all numbered references, see list at end of paper.

which either automatically or by manual adjustment satisfies the conditions that its terminal voltages be exclusively of positive sequence and that its line currents be exclusively of negative sequence. A device of this kind, employing an induction machine as suggested in reference 3, has been successfully used with the Massachusetts Institute of Technology network analyzer. The connections for representing 2 simultaneous line-to-ground faults, one on phase $a$, the other on phase $b$, are shown in figure 1. The interconnections are not affected by changes

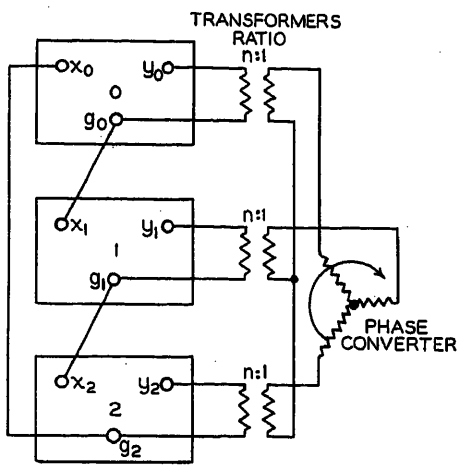



**Figure 1. Connections between the sequence networks for representing simultaneous AG-BG short circuits**

in the system, such as opening or closing of lines or swinging of generators, except in so far as these changes may necessitate readjustment of the phase converter, if one is used. This method dispenses with impedance measurements and the calculation required in the previous 2 methods for determining the fault shunts or the equivalent circuit, and is therefore more convenient if the size of system permits its use, particularly if zero- and negative-sequence quantitites are to be read. In case of simultaneous faults not all having the same phase of symmetry, the necessity for using a phase converter, which is not now standard equipment of any network analyzer, may be regarded as a disadvantage of the method.

## II. Three-Phase Methods

Although it has been customary to use the method of symmetrical components for fault studies on 3-phase networks, it is possible and often preferable to use either the phase quantities directly or substituted variables other than symmetrical components. This is particularly true when the values of phase currents and voltages are wanted, as in studies of relay operation. Two methods utilizing 3-phase set-ups will be described, both of which require the assumption that the positive- and negative-sequence networks are identical except as to generated electromotive forces, but neither of which requires the zero-sequence network to be like the positive- or negative-sequence networks. A method which did so restrict the zero-sequence network would not be of much value for representing a 3-phase power system, because of the great difference between the zero- and positive-sequence impedance of transmission lines, and because of the effects of various transformer connections.

The positive- and negative-sequence networks are, of course, identical except for the effects of polyphase rotating machinery, generators in particular. It is pertinent, therefore, to inquire as to the difference between the positive- and negative-sequence impedances of generators. Either the transient reactance ($x_d'$) or the subtransient reactance ($x_d''$) is use for the positive-sequence impedance of synchronous machines in fault studies, depending on how soon after the occurrence of the fault is the instant for which the fault currents are wanted. The following values of the ratios of negative-sequence reactance $x_2$ to transient and subtransient positive-sequence reactances are averaged from test results published by Wright.[4]

| Type of Machine | $x_2/x_d'$ | $x_2/x_d''$ |
|---|---|---|
| Round-rotor turbogenerators | 0.64 | 1.00 |
| Salient-pole machines with dampers | 0.64 | 0.96 |
| Salient-pole machines without dampers | 1.50 | 1.50 |

These ratios range from about 2/3 to 3/2; hence it would seem that in many cases the assumption that $Z_1 = Z_2$ would not be too bad, especially when it is considered that there are nearly always transformers and lines between the generators and the faults.

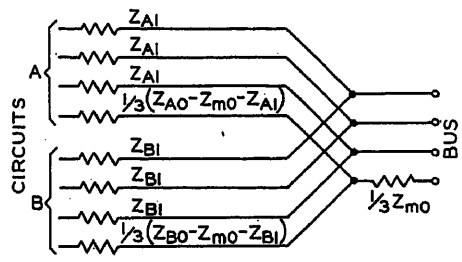



**Figure 2. Representation of 2 transmission lines with zero-sequence mutual impedance, connected to the same bus at the right-hand end, as represented in the 3-phase and neutral method**

In cases in which the difference between positive- and negative-sequence impedance may be of importance, it may be taken into account by a method described later in this paper.

### A. Three-Phase and Neutral Method

This method was independently devised and used on the Westinghouse and Massachusetts Institute of Technology network analyzers.

*1. Representation of System.* The power system is represented as a 3-phase 4-wire circuit. The 3 line conductors of each branch have impedances equal to the positive- or negative-sequence impedance $Z_1$ of the branch, while the impedance $Z_n$ of the neutral conductor is given by $Z_n = \frac{1}{3}(Z_0 - Z_1)$. Positive- and negative-sequence components of current are confined to the line wires and therefore produce the correct $IZ$ drops in the line-to-neutral voltage. If zero-sequence components of current are present, they have the same value $I_0$ in each line conductor. Assuming that the sum of these components, $3I_0$, returns in the neutral conductor, the drop in line-to-

neutral voltage produced in the branch by the zero-sequence current is the same for each phase and has the magnitude

$$I_0Z_1 + 3I_0 \times \frac{1}{3}(Z_0 - Z_1) = I_0Z_0$$

which is correct. Zero-sequence mutual impedance $Z_{m0}$ between 2 parallel transmission lines connected to the same bus at one end may be represented as shown in figure 2. Here the drop in line-to-neutral voltage of circuit $A$ is:

$$I_{A0}Z_{A1} + 3I_{A0} \times \frac{1}{3}(Z_{A0} - Z_{m0} - Z_{A1}) + (3I_{A0} + 3I_{B0}) \times \frac{1}{3}Z_{m0} = I_{A0}Z_{A0} + I_{B0}Z_{m0}$$

Shunt capacitance of lines, if appreciable, may be represented as in figure 3, in which $C_1$ is the positive-sequence capacitance and $C_n$ has the value $3\,C_0C_1/(C_1 - C_0)$, where $C_0$ is the zero-sequence capacitance.

The potential drops due to zero-sequence current are not correct unless the zero-sequence currents actually return in the neutral wire, as assumed. That is, in every branch of the 3-phase network, we must have

$$I_a + I_b + I_c + I_n = 0$$

or

$$I_n = -(I_a + I_b + I_c) = -3I_0$$

This requirement is automatically satisfied in all radial branches of the 3-phase network. If the network has one or more closed loops, the currents in general will not satisfy this requirement automatically but they may be forced to do so by inserting "forcing transformers" in series with one or more branches. Figure 4 shows several alternative arrangements of forcing transformers; scheme (*d*) is perhaps the most practical. The number of banks of forcing transformers is, in general, equal to the number of independent loops in the 3-phase network, but in some networks the impedances are so related that correct current distribution is obtained even though fewer or no banks are used. If there should be doubt in a specific case as to the proper number and location of forcing transformers, the best procedure would be to set up the network without forcing transformers and to measure the line and neutral currents in rectangular form in several branches of the network. The sum of the 3 line currents should then be compared with the neutral current. If the agreement should not be satisfactory, forcing transformers should be inserted, and the check readings should again be taken.

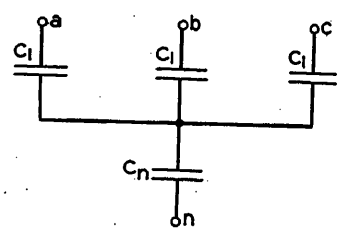



**Figure 3. Representation of shunt capacitance in the 3-phase and neutral method**

Generator voltages are represented by balanced 3-phase electromotive forces. Three phase-shifters connected in $Y$ may be used to represent either grounded or ungrounded generators; or 2 phase-shifters connected in $V$, to represent ungrounded generators. Phase-shifters with 3-phase output are not suitable because the internal impedance drops due to unbalanced loads produce unbalanced terminal voltages.

The terminal voltages of the phase shifters may be purposely unbalanced (as suggested by Professor L. F. Woodruff) to represent the effect of the difference between the positive- and negative-sequence impedances of a generator. To do so, the generator phase currents are measured with balanced phase-shifter voltage, and the negative-sequence current $I_2$ and the voltage $V_2' = I_2\,(Z_1 - Z_2)$ are computed from them. The phase-shifter terminal voltages are then changed by the addition of voltages $V_2'$, $aV_2'$, and $a^2V_2'$ to phases $a$, $b$, and $c$, respectively.

Transformer banks in the power system may be represented on the network analyzer by actual transformer banks or, in some cases, by simple series impedances, as shown in figure 5. The representation of $\Delta$-$Y$ banks by series impedances does not directly give the correct currents and voltages on the side of the transformer away from the fault (this is also true of symmetrical-component methods), and cannot be used in case of simultaneous faults on opposite sides of such banks.

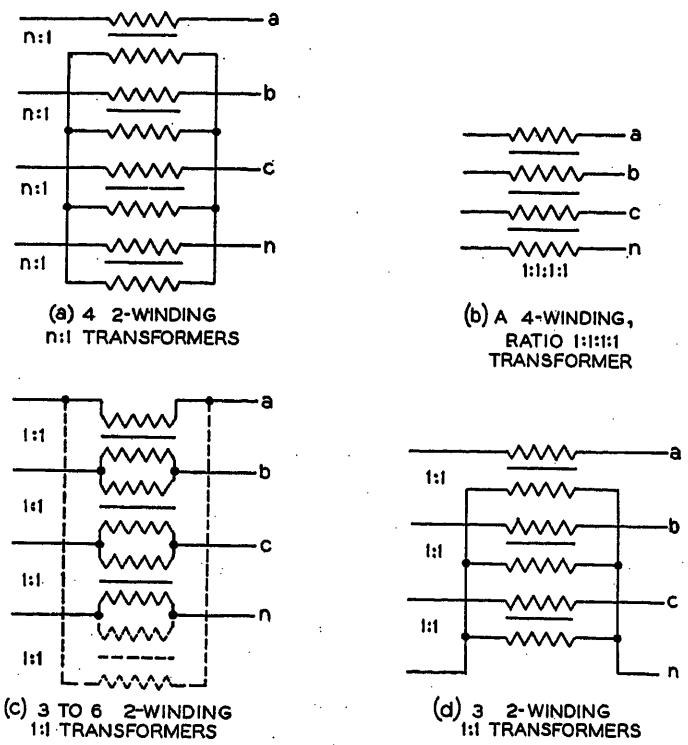



**Figure 4. Connections of forcing transformers for use in the 3-phase and neutral method**

*2. Representation of Unbalance.* Faults are applied by making the actual fault connection, connections to ground being made to the corresponding point of the neutral network. Any number of faults, on any phases, may be ap-

plied simultaneously without causing complications. Unbalanced loads or unbalanced series impedances are represented just as simply.

*3. Measurements.* The following quantities can be measured directly: line currents, residual current (in neutral), line-to-line voltages, line-to-ground voltages (measured line to neutral). Residual voltage can be read by the use of 3 potential transformers having their primary windings connected line-to-neutral and their secondary windings in series, or can be computed as the sum of the line-to-ground voltages. Positive-sequence and negative-sequence quantities are not so conveniently obtained, but they can be computed or measured by the same methods which can be used to obtain phase quantities from a symmetrical-component representation.

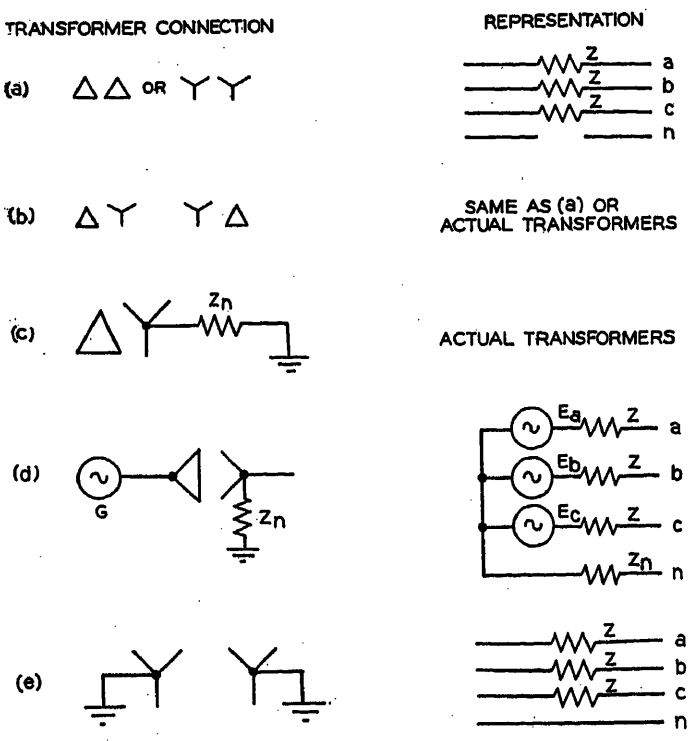



**Figure 5. Representation of transformer banks in the 3-phase and neutral method**

*4. Advantages and Disadvantages.* This method requires 4 impedance units per branch of the one-line system diagram, and thus is limited to smaller systems than are the equivalent-circuit and shunt methods. It requires 3 phase-shifters per generator, thus limiting the number of generators which can be represented and giving more trouble in adjusting the generator phase angles or outputs. Forcing transformers are required in many cases to give correct current distribution in the network. It is necessary to assume that the negative-sequence impedance of each branch is equal to the positive-sequence impedance.

On the other hand, the representation of simultaneous faults and unbalances of any kind is extremely simple. Phase and residual currents, line-to-line and line-to-neutral voltages can be read directly.

The best field of application is to networks of small or medium size and principally at one voltage, with only one or two equivalent generators, and to problems (such as relay studies) in which phase quantities are required.

### B. Three-Phase and Zero-Sequence Method

This method differs from the preceding one in that zero-sequence current and voltage are excluded from the 3-phase network and confined to a separate network. The fault connections and the methods of measurement are not quite as simple as in the method just described, but the correct current distribution is obtained without recourse to forcing transformers.

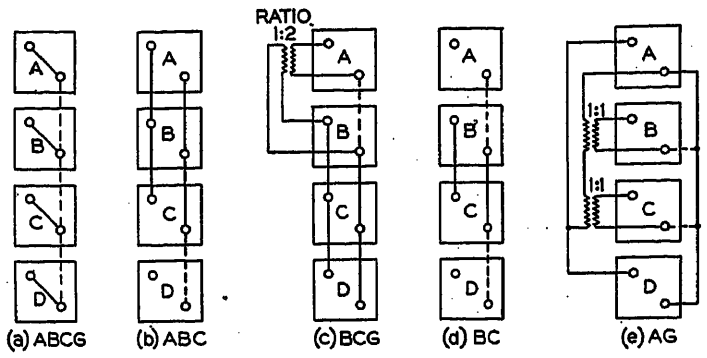



**Figure 6. Connections between the substitute networks for representing various types of short circuits, 3-phase and zero-sequence method**

The theory of the method is explained in the appendix.

Four substitute networks, designated as $A$, $B$, $C$, and $D$, are set up on the network analyzer. Networks $A$, $B$, and $C$ have in each branch an impedance equal to the positive- (or negative-) sequence impedance, while network $D$ (which might be termed the zero-sequence network) has an impedance equal to one-third the zero-sequence impedance of the corresponding branch of the power system. Expressed symbolically, $Z_A = Z_B = Z_C = Z_1 = Z_2$, and $Z_D = \frac{1}{3} Z_0$. Networks $A$, $B$, $C$ contain 3-phase electromotive forces, but network $D$ has none. The currents and voltages in networks $A$, $B$, and $C$ are the phase quantities minus their zero-sequence components. The current and voltage in network $D$ are related to the zero-sequence quantities as follows:

$$I_D = -3I_0 \quad \text{and} \quad V_D = -V_0$$

The connections between the substitute networks for representing various kinds of short circuits are derived in the appendix and are shown in figure 6. The dotted lines indicate connections which are put in merely for convenience in measuring line-to-line voltages. Note that the connections for faults not involving ground are, as in the preceding method, the actual fault connections; whereas for the $BCG$ and $AG$ faults direct connections are made in accord with the actual fault connections (regarding network $D$ as the ground), and are supplem

by connections through transformers to the unfaulted phases. Faults on phases other than those for which connections are given are represented by similar connections with an appropriate interchange of networks $A$, $B$, and $C$. Simultaneous faults are represented by making the connections for each fault just as for a single fault.

After having made the appropriate fault connections, the following quantities may be measured directly as indicated: line-to-line voltages, between corresponding points of networks $A$, $B$, $C$; line-to-ground voltages, between corresponding points of network $A$, $B$, or $C$ and network $D$; residual current, in network $D$; zero-sequence voltage in network $D$. Furthermore, the phase currents may be read by the use of a 3-to-1 current transformer with its primary winding plugged into network $D$ and its secondary winding connected to the measuring device in parallel with a cord plugged into the corresponding branch of the phase network. (See equations $A1$ to $A3$ of appendix.)

## C. Triple-Connection Method

This method, using a 3-phase and symmetrical-component representation, could be classified under either heading.

The procedure is as follows:

1. Set up each sequence network in triplicate, that is, set up 3 zero-sequence networks, 3 positive-sequence networks, and 3 negative-sequence networks. The 3 positive-sequence networks should differ from one another only in that the electromotive forces in any one of them are 120 degrees ahead of the corresponding electromotive forces in another and 120 degrees behind those of the third. Phase-shifters having a 3-phase output are suitable sources of the electromotive forces.

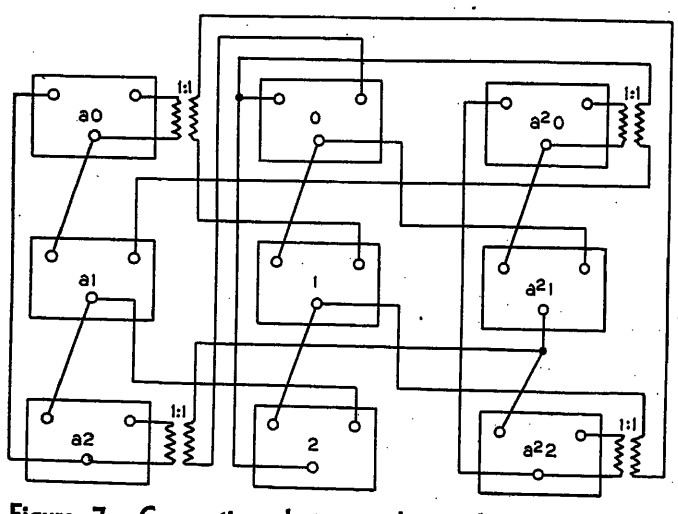



**Figure 7. Connections between the triple sequence networks for representing simultaneous AG-BG short circuits, triple-connection method**

2. At each point of fault make appropriate connections between the sequence networks to represent the given type of fault. These connections can be best understood by considering a particular case, such as simultaneous $AG$-$BG$ faults, figure 7. Let the current and voltage at the left-hand terminal of network 0 be $I_{x0}$ and $V_{x0}$, respectively, and at the right-hand terminal, $I_{y0}$ and $V_{y0}$. Then assume for the time being that the corresponding quantities of network $a0$ are $aI_{x0}$, $aV_{x0}$, $aI_{y0}$, and $aV_{y0}$, where $a = \angle 120°$, and that the corresponding quantities of network $a^20$ are $a^2I_{x0}$, $a^2V_{x0}$, $a^2I_{y0}$, and $a^2V_{y0}$, respectively; and similarly for the positive- and negative-sequence networks; that is, assume that all currents and voltages at the terminals of and within the networks of the left-hand column are equal in magnitude to, but 120 degrees ahead of, the corresponding currents and voltages of the middle column of networks, and that likewise the right-hand column is 120 degrees behind the middle column. These assumptions are justified by the fact the 3 columns are identical, except for the 120-degree phase displacement of the positive-sequence electromotive forces, and by the fact that the connections to be established between the networks have a cyclical symmetry. It will be recalled that the equations for the $AG$ fault at $x$ are:

$$I_{x0} = I_{x1} = I_{x2} \quad \text{and} \quad V_{x0} + V_{x1} + V_{x2} = 0 \tag{1}$$

which are satisfied by a series connection of the left-hand ($x$) terminals of networks 0, 1, and 2. Multiplying equation 1 by $a$ gives

$$aI_{x0} = aI_{x1} = aI_{x2} \quad \text{and} \quad aV_{x0} + aV_{x1} + aV_{x2} = 0 \tag{2}$$

which are satisfied by a series connection of the left-hand terminals of networks $a0$, $a1$, and $a2$. Similarly, multiplication of equation 1 by $a^2$ indicates a series connection of the left-hand terminals of networks $a^20$, $a^21$, and $a^22$. The equations for the $BG$ fault at $y$ are:

$$I_{y0} = a^2I_{y1} = aI_{y2} \text{ and } V_{y0} + a^2V_{y1} + aV_{y2} = 0 \tag{3}$$

and are satisfied by a series connection of the right-hand ($y$) terminals of networks 0, $a^21$, and $a2$. Multiplication of equation 3 by $a$ gives

$$aI_{y0} = I_{y1} = a^2I_{y2} \quad \text{and} \quad aV_{y0} + V_{y1} + a^2V_{y2} = 0 \tag{4}$$

which are satisfied by a series connection of the right-hand terminals of networks $a0$, 1, and $a^22$. Likewise multiplication of equation 3 by $a^2$ points to a series connection of networks $a^20$, $a1$, and 2. In making these connections, which are shown in figure 7, a sufficient number of insulating transformers must be used (in this case at least 4).

In every case, a fault which is symmetrical with respect to phase $a$ is represented by connections between networks in the same column, whereas a fault symmetrical with respect to phase $b$ or phase $c$ is represented by diagonal connections touching a different column in each row.

3. Read the sequence currents and voltages in any branches where they are wanted. The zero-sequence quantities are read in network 0, positive-sequence in network 1, and negative-sequence in network 2. It is also possible to read $a^2$ times the positive-sequence quantities in network $a^21$, $a$ times the negative-sequence quantities in network $a2$, etc. Then the phase quantities may be readily calculated by adding the proper components:

$$I_a = I_0 + I_1 + I_2$$

$$I_b = I_0 + a^2I_1 + aI_2, \text{ etc.}$$

Or, better yet, by combining the proper components through instrument transformers, the phase quantities can be read directly. Thus, $I_b$ can be obtained by paralleling the secondary windings of 3 current transformers, the primary windings of which are plugged into corresponding branches of networks 0, $a^21$, and $a2$; similarly $V_b$ can be obtained by connecting in series the secondary windings of 3 potential transformers. A switching arrangement might be built to facilitate rapid successive reading of the several phase quantities. The best arrangement appears to be to do all the measuring in only 3 networks (say networks 0, 1, 2) and to interchange 2 of these networks with others in the same row. To be more specific, to read $Ia$, current jacks are plugged into networks 0, 1, and 2, and the sum, $I_a = I_0 + I_1 + I_2$, is read. Then to obtain $I_b$, the jacks are left in position, network 1 without its electromotive forces is interchanged with network $a^21$ without its electromotive forces, and network 2 is interchanged with network $a2$. Or, to avoid the switching of the positive-sequence networks

with respect to their power sources, it would be better to interchange network 0 with $a0$, and network 2 with $a^2 2$, and to read the sum $aI_0 + I_1 + a^2 I_2 = aI_b$, which by a suitable rotation of reference axes in the measuring instrument may be read as $I_b$.

The triple connection method, like the single connection method, is applicable to any number of simultaneous faults, and does not require that the negative-sequence impedances equal the positive-sequence impedances. Unlike the single connection method, it does not require a phase converter for representing faults not symmetrical

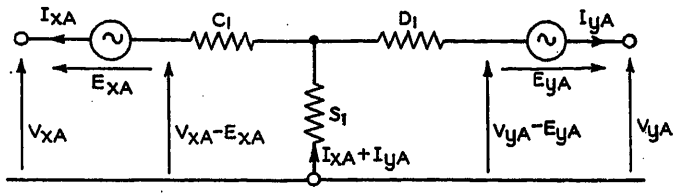



**Figure 8. Equivalent T circuit to which network A (3-phase and zero-sequence method) may be reduced, retaining the 2 points of fault and the neutral point. Networks B and C can be represented similarly**

with respect to phase $a$. Its principal disadvantage is the excessive number of impedance units required (approximately 9 units for each branch of the one-line system diagram), which makes the method impractical except for relatively small systems. An advantage is the possibility of directly reading the phase currents and voltages as well as their symmetrical components. The required number of impedance units can be decreased without losing the advantage of direct reading of phase quantities by setting up only three of the networks complete and the other six in reduced form (equivalent $T$ or $\pi$ in case of 2 simultaneous faults or a double unbalance). Readings are taken in the 3 complete networks, two of which are interchanged with reduced networks by a suitable switching device to read phase $b$ or $c$ quantities. The saving in number of impedance units entails the work of determining and setting up equivalent reduced circuits for each fault or system condition. If the direct reading of phase quantities be dispensed with, only one complete network need be set up at a time, the other eight being represented by equivalent circuits. However, in this case the equivalent circuit method might better be used.

## Conclusion

Some new methods have been presented, and some older ones summarized and compared, for solving networks with multiple unbalances by use of a network analyzer. For stability studies, especially on large systems, with 2 simultaneous faults, the equivalent circuit method appears to be the most suitable. For the rare case of more than 2 faults the shunt method may be employed. For studies of relay operation on smaller systems and in which swinging of generators is not an important factor, the 3-phase methods are best. Of these the 3-phase-and-neutral method is usually the simpler. However, on a network in which a large number of forcing transformers would be required to secure correct current distribution it appears simpler to use the 3-phase and zero-sequence method, in which transformers are used in the connections representing faults instead of as forcing transformers. In other problems, the network analyzer operator can select whatever method may appear best suited to the problem at hand.

## Appendix

### Theory of 3-Phase and Zero-Sequence Method and Proof of Connections for Representing Short Circuits

The method is based on a substitution of variables analogous to the one employed in the method of symmetrical components. Let $I_a, I_b, I_c$ be the line currents and $V_a$, $V_b$, $V_c$ the voltages to ground of the 3 conductors of the 3-phase system. Let new variables $I_A$, $I_B$, $I_C$, $I_D$ and $V_A$, $V_B$, $V_C$, $V_D$, defined as follows be introduced:

$$I_a = I_A - \frac{1}{3} I_D \tag{A1}$$

$$I_b = I_B - \frac{1}{3} I_D \tag{A2}$$

$$I_c = I_C - \frac{1}{3} I_D \tag{A3}$$

in which

$$I_A + I_B + I_C = 0 \tag{A4}$$

Also let

$$V_a = V_A - V_D \tag{A5}$$

$$V_b = V_B - V_D \tag{A6}$$

$$V_c = V_C - V_D \tag{A7}$$

in which

$$V_A + V_B + V_C = 0 \tag{A8}$$

The inverse transformations are as follows:

$$I_A = \frac{1}{3}(2I_a - I_b - I_c) \tag{A9}$$

$$I_B = \frac{1}{3}(2I_b - I_c - I_a) \tag{A10}$$

$$I_C = \frac{1}{3}(2I_c - I_a - I_b) \tag{A11}$$

$$I_D = -(I_a + I_b + I_c) \tag{A12}$$

$$V_A = \frac{1}{3}(2V_a - V_b - V_c) \tag{A13}$$

$$V_B = \frac{1}{3}(2V_b - V_c - V_a) \tag{A14}$$

$$V_C = \frac{1}{3}(2V_c - V_a - V_b) \tag{A15}$$

$$V_D = -\frac{1}{3}(V_a + V_b + V_c) \tag{A16}$$

Note that four new currents, $I_A$, $I_B$, $I_C$, $I_D$, are substituted for 3 old currents $I_a$, $I_b$, $I_c$ but that only 3 of the 4 are independent, as they are subject to the restriction expressed in equation $A4$. The

same remark applies to the substitution of voltages. The $D$ quantities are related to the zero-sequence quantities as follows:

$$I_D = -3I_0 \quad \text{and} \quad V_D = -V_0 \tag{A17}$$

Therefore the $A$, $B$, $C$ quantities are the phase quantities minus their zero-sequence components.

Let $I_A$ and $V_A$ be associated with a network $A$, $I_B$, and $V_B$ with network $B$, etc. The connections between networks $A$, $B$, $C$, and $D$ for representing various kinds of faults will be determined, but before doing so 2 general relations will be noted. First, as may be shown readily, the total vector power of corresponding branches of the substitute networks ($A$, $B$, $C$, $D$) is equal to the total vector power in the corresponding branch of the original 3-phase power network.

$$\overline{V}_A I_A + \overline{V}_B I_B + \overline{V}_C I_C + \overline{V}_D I_D = \overline{V}_a I_a + \overline{V}_b I_b + \overline{V}_c I_c \tag{A18}$$

(The bars over the $V$'s in this equation denote conjugates.) A relation of this kind—one side of the equation may be multiplied by a constant, however—must be fulfilled if a fault is to be represented by a connection between the substitute networks. For, if the fault has no impedance, the vector power in the fault branch is zero; if connections are made between the networks, either directly or through ideal transformers, the total vector power leaving the networks at the points of connection is likewise zero.

The second general relation concerns the exclusion of zero-sequence current and voltage from networks $A$, $B$, $C$ in accordance with equations $A4$ and $A8$. Consider the case of 2 simultaneous faults. Each of the networks $A$, $B$, $C$ may be reduced to an equivalent $T$ (figure 8), retaining the 2 points of fault and the ground or neutral point. These $T$'s, like the equivalent $T$ of the positive-sequence network, each contain 2 equivalent electromotive forces, denoted by $E_x$ and $E_y$, equal to the voltage at the points of fault before occurrence of the faults. The following equations express relations between fault currents ($I_x$ and $I_y$) and fault voltages ($V_x$ and $V_y$) of each network:

$$E_{xA} - V_{xA} = (C_1 + S_1) I_{xA} + S_1 I_{yA} \tag{A19}$$

$$E_{xB} - V_{xB} = (C_1 + S_1) I_{xB} + S_1 I_{yB} \tag{A20}$$

$$E_{xC} - V_{xC} = (C_1 + S_1) I_{xC} + S_1 I_{yC} \tag{A21}$$

$$E_{yA} - V_{yA} = (D_1 + S_1) I_{yA} + S_1 I_{xA} \tag{A22}$$

$$E_{yB} - V_{yB} = (D_1 + S_1) I_{yB} + S_1 I_{xB} \tag{A23}$$

$$E_{yC} - V_{yC} = (D_1 + S_1) I_{yC} + S_1 I_{xC} \tag{A24}$$

where $C_1$, $D_1$, and $S_1$ are impedances of the equivalent $T$, which are the same for all 3 networks. Adding each group of three equations gives:

$$\Sigma E_x - \Sigma V_x = (C_1 + S_1)\Sigma I_x + S_1 \Sigma I_y \tag{A25}$$

$$\Sigma E_y - \Sigma V_y = (D_1 + S_1)\Sigma I_y + S_1 \Sigma I_x \tag{A26}$$

where

$$\Sigma E_x = E_{xA} + E_{xB} + E_{xC}$$
$$\Sigma I_x = I_{xA} + I_{xB} + I_{xC}, \text{ etc.}$$

Since the networks contain only balanced electromotive forces (or at least electromotive forces having no zero-sequence components), $\Sigma E_x = 0$ and $\Sigma E_y = 0$. Therefore, unless one of the impedances should be infinite, if $\Sigma I_x = 0$ and $\Sigma I_y = 0$, then it follows that $\Sigma V_x = 0$ and $\Sigma V_y = 0$; or, more generally, if either $\Sigma V_x = 0$ or $\Sigma I_x = 0$ and if either $\Sigma V_y = 0$ or $\Sigma I_y = 0$, then all 4 quantities, $\Sigma V_x$, $\Sigma V_y$, $\Sigma I_x$, and $\Sigma I_y$, are zero. Although the demonstration has been given for the case of 2 faults, similar demonstrations can be given for one fault, or for any number of faults. As a result of such demonstrations it may be reasoned that the connections representing a fault must be of such nature as to insure either that $\Sigma V = 0$ or that $\Sigma I = 0$; if either of these conditions is fulfilled at every fault (not necessarily the same condition at every fault), it follows that both $\Sigma V = 0$ and $\Sigma I = 0$ at all faults and hence also throughout networks $A$, $B$, $C$.

Any connection between the 4 substitute networks may be described by 4 equations. For the connections to correctly represent a given type of fault, 3 of the equations must be derived from the relations between phase currents and voltages for the fault in question (table I of reference 1); the fourth must be either $\Sigma V = 0$ or $\Sigma I = 0$. The connections for representing various single faults (figure 6) are proven correct as follows:

AG FAULT

Relations of phase quantities: $V_a = 0, I_b = 0, I_c = 0$. Relations between substituted quantities satisfied by the connections:

$$V_A = V_D \qquad V_A + V_B + V_C = 0 \qquad I_B = I_C = I_A + I_D$$

Proof that the connections represent the fault: Since $V_A + V_B + V_C = 0$, it follows that $I_A + I_B + I_C = 0$. Substitute in the latter expression $I_C = I_B$ and $I_A = I_B - I_D$, obtaining $I_B - \frac{1}{3} I_D = 0$, or $I_b = 0$. By a similar process, obtain $I_C - \frac{1}{3} I_D = 0$, or $I_c = 0$. $V_A - V_D = 0$ is equivalent to $V_a = 0$.

BCG FAULT

Relations of phase quantities: $I_a = 0, V_b = 0, V_c = 0$. Relations between substituted quantities satisfied by the connections:

$$-\frac{1}{2} V_A = V_B = V_C = V_D \text{ and } -2I_A + I_B + I_C + I_D = 0$$

Proof that the connections represent the fault: From the voltage relation, $-\frac{1}{2} V_A = V_B = V_C$, it may be shown that $V_A + V_B + V_C = 0$, from which it follows that $I_A + I_B + I_C = 0$. Subtracting $I_A + I_B + I_C = 0$ from $-2I_A + I_B + I_C + I_D = 0$ gives $-3I_A + I_D = 0$, or $I_A - \frac{1}{3} I_D = 0$, or $I_a = 0$. From $V_B = V_C = V_D$, we obtain $V_B - V_D = 0$ and $V_C - V_D = 0$, or $V_b = 0$ and $V_c = 0$.

BC FAULT

Relations of phase quantities: $I_a = 0, I_b + I_c = 0, V_b = V_c$. Relations between substituted quantities satisfied by the connections: $V_B = V_C, I_B + I_C = 0, I_A = 0, I_D = 0$. Proof that the connections represent the fault: Since $I_D = 0$, $I_A - \frac{1}{3} I_D = 0$ or $I_a = 0$.

$$I_B + I_C = (I_B - \frac{1}{3} I_D) + (I_C - \frac{1}{3} I_D) = I_b + I_c = 0$$

Since $V_B = V_C$, $V_B - V_D = V_C - V_D$ or $V_b = V_c$. The connections also satisfy $I_A + I_B + I_C = 0$.

ABC FAULT

Relations of phase quantities: $I_a + I_b + I_c = 0, V_a = V_b = V_c$. Relations satisfied by connections: $I_A + I_B + I_C = 0, I_D = 0, V_A = V_B = V_C$.

ABCG FAULT

Relations of phase quantities: $V_a = V_b = V_c = 0$. Relations satisfied by connections: $V_A = V_B = V_C = V_D = 0$.

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# Modern Trolley-Coach Operation

By JAMES H. POLHEMUS


## Synopsis

This paper describes the operation of a modern trolley coach system. This system was installed one year ago with a single line and a few coaches. Now there are 7 lines in operation, the total route lengths exceeding 45 miles and requiring 40 coaches, each of which has a seating capacity of forty persons. The paper is generally divided into 2 parts, the first dealing with descriptions of the system and equipment, and the second part setting forth such experiences as have been gained in one year of operation.


ALTHOUGH there were earlier installations, the operation of modern trolley coaches may be said to date from 1928, when trolley coaches were put in operation in Salt Lake City. Systems were installed in more and more cities until today trolley coach operation is a factor in public transportation in 34 cities of the United States, not to mention the many European systems. It is the objective of this paper to discuss one of the most recently installed trolley coach systems, that of the Portland Traction Company in Portland, Oregon.

The Portland system consists of 45.5 miles of trolley coach line operating within the limits of the city and serving, together with 87.5 miles of street railway and 64.8 miles traversed by gasoline coaches, a population in excess of 300,000 people. Operation of trolley coaches started August 30, 1936, on the first line completed and additional lines were completed and put into operation until the contemplated program was consummated in May, 1937. The experiences throughout an over-all period of one year of operation are available although the completed system of 7 lines has been operating but 3 months. The system is now operating at the rate of about 385,000 coach miles per month and since the total mileage amounts to 3,300,000 coach miles in the 12 months of operation, the weighted average experience with this system amounts to about 8 or 9 months.

The overhead system is of the conventional 2-conductor type with the conductor tension at 3,000 pounds per conductor at 70 degrees Fahrenheit, with 100-foot spans in districts where coaches can operate at high speed. In the congested urban area, a tension of 2,000 pounds was used. The conductors are spaced 2 feet apart and the conductors nearest the curb are in general 12 feet from curb lines. A minimum clearance of 7 feet, 5 inches is maintained between inside conductors. The supporting structures are steel poles in the downtown areas and building pull-offs, if feasible, with wood poles in the outlying districts. The contact wire is 3/0 high-strength cadmium bronze alloy. On one of the 7 lines, the contact wire is round while wire on the remaining lines is grooved. Records are being kept to show the wearing ability of each, but it is yet too early to form even preliminary conclusions. The wire is lubricated with a light grade of mineral oil. The system operates with 600-volt direct current supplied by the affiliated Portland General Electric Company. Electric frogs of both shunt and series-operated type were installed and experience to date is in favor of the shunt type for system use as well as in the car barns. Porcelain strain insulators on pull-over wires have been found to be better than woodstick insulators when they can be located so that they will not be struck by a flying trolley. An interesting detail is that of passing tracks on which local coaches may draw up to the curb and allow express coaches to pass.

The Portland Traction Company now operates 140 trolley coaches over its 45 miles of trackless trolley routes. The coaches are 24 feet, 4½ inches over bumpers, 104 inches extreme width, weigh 20,400 pounds, and have seats for 40 passengers. The normal peak load is 60 passengers but 100 passengers have been carried during times of extraordinary traffic congestion. The rear axle ratio of 9.97 and 42-inch wheels at a motor speed of 3,360 rpm develop the maximum speed of 42 miles per hour. The traffic regulations permit a maximum speed of 35 miles per hour, requiring a motor speed of 2,800 rpm. Coaches are equipped with air brakes on all 4 wheels, all glass is shatterproof, and the windshield is cleaned with 4 pneumatically operated windshield wipers. Doors are operated by air engines under control of the operator and the exit door is also controlled by foot treadles. Auxiliary circuits, such as lighting, buzzer, door control, marker, tail and head lights, horn, and ventilating fans, are supplied with power from a 12-volt storage battery and generator system. The principal reason for the use of the 12-volt circuit is safety of passengers. Another reason is to insure continuity of lighting while the coach is passing under insulated spacers. One of the most unusual features of these coaches is that each is driven by a single motor. The motor has a rolled-steel frame and weighs 1,050 pounds. It has a one-hour rating of 125 horsepower and the output when accelerating on a grade is 225 horsepower. Four interpoles and low voltage per commutator bar provide freedom from flashovers. Other motor characteristics at the hourly rating of 125 horsepower are 600 volts, 173 amperes, 2,420 rpm, and 120 degrees centigrade rise by resistance. The maximum allowable motor speed is 4,000 rpm. The motor is self-ventilated and without covers. Radio choke coils are inserted in the trolley

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circuits on the roof of each coach to prevent the operation of the coach from interfering with radio reception.

The street cars replaced by electric coaches were operated by one man and there is no saving in the operators' wages per vehicle hour, but the increased speed has reduced the cost of operators' pay per vehicle mile.

In July, 1937, the average speed of all vehicles in the Portland system was 11.35 miles an hour, which is an increase of 11 per cent over the July, 1936, average speed of 10.23 miles an hour. A part of this is due to an increase



of speed of gas busses from 13.11 miles an hour to 13.40 miles an hour. The average speed of street cars decreased 4 per cent from 9.63 to 9.26 miles an hour, due to some of the higher-speed car lines being converted to electric coach lines. The average speed of electric coaches is 12.78 miles an hour and this is an increase of 23 per cent from the 10.35 miles an hour average speed of the street car lines that were changed to electric coach. Unloading at both ends has decreased standing time and has increased the average speed. At heavy loading points double ended loading likewise increases the average speed.

The rate of acceleration of electric coaches is 3.5 miles per hour per second and this is twice the rate of acceleration of the street cars replaced by the coaches. The free-running speed of the street cars was 27 miles an hour and of the electric coaches, 42 miles an hour. The coaches are operating on city streets where the speed is limited by law and the maximum possible speed is never used.

Accidents have been caused in some cases where automobiles, closely followed by street cars, have made sudden stops with the result that the auto was rammed by the street car. Electric coaches stop as fast as or faster than do automobiles and do not ram the rear end of motor vehicles that have suddenly stopped, but, if passengers are standing, rapid deceleration may throw some elderly person to the floor. Operators with a standing load of passengers at times must make a choice between a collision with another vehicle and the possibility of personal injuries to standing passengers. Some automobile drivers do not realize the rapid rate of acceleration of the electric coach and after passing to the left of an accelerating coach, reduce speed, cut to the right in front of the coach, and a collision results. In August 1937, street cars ran 4,299 miles per accident, electric coaches, 5,133 miles, and motor coaches ran 9,379, miles. Motor coaches run a smaller percentage of their miles in heavy traffic than electric coaches and street cars and have a lower exposure to accidents than street cars and electric coaches. The ratio of miles to accidents for electric coaches is increasing as the operators have more experience in operating these vehicles.

With respect to maintenance, tires are not purchased but are rented on a mileage basis. Traction company employes change tires that are worn or flat and the tire company dismounts the tires from the rims. Tire pressure is maintained by the traction company. Front tires on the coaches on a line which has many curves were found to wear rapidly and on these tires the normal pressure of 75 pounds was increased to 85 pounds and the tread wear was reduced.

New tires are averaging about 23,000 miles and retreads about 17,000 miles, a total of 40,000 miles to a casing. In a few instances a casing is given a second retread, thus giving a casing with 2 retreads a total life of 57,000 miles.

Maintenance of electrical equipment is confined largely to cleaning contacts on controls and cleaning motors. The voltage and current regulators on the 12-volt lighting and door control system must be checked frequently as these regulators are subject to burning if the contacts are not kept clean.

Inspection of all movable parts is done on a regular schedule and in this way maintenance is reduced and there is a greater reliability of service

Maintenance of bodies is confined, as yet, to tightening of screws and bolts. All metal bodies are not in need of much maintenance in the first year of their life and, except for adjustments of brakes and door operating engines, but little work is done on the bodies.

Accidents are with us always and there are at all times coaches in the shops for repairs necessitated by collisions. Both electric and gas welding reclaim parts that at first sight appear to be fit only for junk. Quick drying lacquers cover the new work and soon the coach is again on the street.

Lubrication of the conductor wires is accomplished by means of a truck with trolley busses and trolley poles mounted on a frame on the truck. The upper end of each pole carries a lubricator that is essentially a tank containing a lubricant with a wheel that has its upper rim on the conductor and the lower rim in the lubricant. The conductors are lubricated every 1,500 shoe passes. Much work on the overhead was not completed when the coaches were placed in operation and until this has been done no regular inspection of the overhead will be made. Many poles and anchors were set in damp soil and it has been necessary to retension conductors and brail wires. Manufacturers have not, as yet, furnished a reliable and rugged overhead switching device to change the path of the shoe from the main line to a branch line or a turnout, but are working on this problem with great hopes.

Plans are now being made for a regular inspection of the overhead distribution system and this inspection should keep the overhead in good operating condition. Linemen who had worked on the single-trolley system had much to learn about protecting themselves and their equipment when working on 2 conductors of opposite polarity only 24 inches apart.

In considering operating costs, it must be remembered that this system has been and, in many particulars, still is in process of development. For example, several thousand dollars was spent in training operators, mechanics, and other employes, practically none of whom had had previous experience with trolley coaches and these development costs are included in the operating costs to date. With this qualification, some operating and statistical data are offered, all applying to the 12-month period immediately following operation of the first line.

## Operating Expenses per Coach Mile

| | |
|---|---|
| Power | 3.23 cents |
| Conducting transportation expenses | 8.80 cents |
| Traffic expenses | 0.18 cents |
| General and miscellaneous expenses | 2.48 cents |
| Total operation | 14.69 cents |
| Maintenance of way and structures | 1.02 cents |
| Maintenance of equipment | 3.01 cents |
| Total operation and maintenance | 18.72 cents |
| Provision for depreciation | 4.47 cents |
| General taxes | 0.94 cents |
| Bridge rentals | 0.14 cents |
| Total operating expenses | 24.27 cents |
| Operating ratio | 93.70 per cent |
| Proportion of total operating expense assignable to pay-roll expense | 46.0 per cent |

These expenses are based upon the following statistics:

| | |
|---|---|
| Total coach miles | 3,288,647 |
| Total coach hours | 260,638 |
| Total passengers carried | 15,041,743 |
| Total passengers per coach mile | 4.57 |
| Kilowatt-hours used per coach mile | 4.04 |

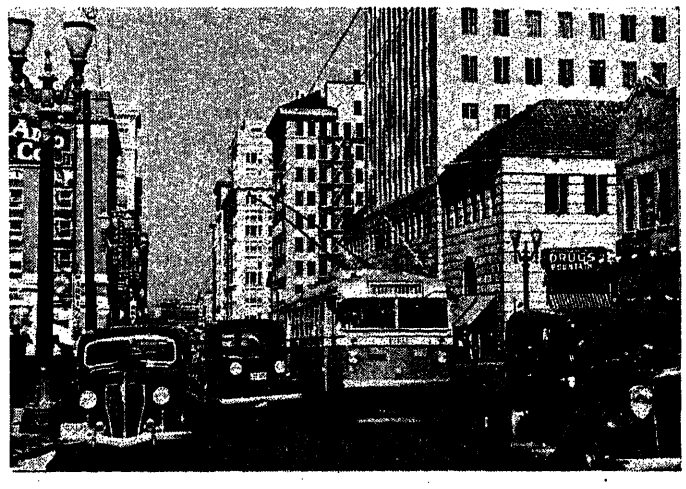
In the 34 cities in the United States where electric coaches are in operation, the coaches ordinarily seat 40 passengers and have both single-motor and 2-motor propulsion with the present trend toward the single-motor equipment. The single motor uses more power than does the dual motor but the saving in weight and cost in favor of the single motor compensates for the greater power consumption. The average speed of electric coaches in Portland is in excess of that in cities of similar size, or larger, and in some cases is 18 per cent greater.

The installation of electric coaches is the largest ever made at any one time in the United States, both in number of coaches and in the miles of route. The entire trolley coach system, consisting of 140 coaches and 45.5 miles of route, was put in operation within 9 months.

In general, the installation of electric coaches in Portland has left no regrets. Minor problems have been met and most of them have been solved. Manufacturers have been called upon to replace parts and have done so at their own expense. Voltage regulators on the first coaches received were replaced. The mounting of the 12-volt generator was improved. Brake lining did not give the expected mileage and was replaced with a different type. The recommended clearance between brake blocks and brake drums was increased and brake block mileage was very greatly increased and scoring of brake drums eliminated. Considerable change was made in the motor control by one manufacturer and additional change is still desirable.

The tire manufacturer has altered the tread in the hope of obtaining greater mileage. While operators were being trained and were gaining experience, tires suffered, particularly on account of rear wheels striking curbs while rounding curves, but, with the "breaking-in" period concluded, this sort of unusual wear has been almost entirely checked, with a resulting decrease in sidewall and tread damage.

The springs in the trolley base are light for the duty they are called upon to perform and in the near future it will be necessary to replace these springs. The springs are probably being permanently deformed and the tension slowly decreases until there is but little room left for adjustment. Some trouble has been experienced with defective castings but the manufacturer has replaced these castings in the overhead system with a new design and



better workmanship. Coils in the electric frogs have failed for no apparent reason and we have hopes of a new design for the overhead switching.

With the first schedule on a line changed from street cars to electric coaches the speed was slow until the operators had experience in operating coaches. Men experienced in operating motor vehicles made better operators than those without driving experience. The operation of street cars helped in combating traffic problems but experience in steering a vehicle seemed to be very necessary.

Street cars carry 5.51 passengers per car mile, electric coaches 4.79 passengers per coach mile, and motor

coaches 2.86 passengers per coach mile. The street car lines with heaviest travel were not changed to coach lines and these lines still carry the heaviest loads. The condition of track and possibilities of rerouting determined the lines where street car service was replaced by coaches. Density of traffic determined whether electric coaches or motor coaches would be operated on the line under consideration. In the future, track will be repaired but when the time comes for replacing rail, the track will be covered with pavement and the cars replaced with coaches. Some of the remaining street car lines are in territory with sparse population and these lines will be replaced with motor coaches.

In conclusion, it may be said that public reaction to the operation of trolley coaches has been good. Revenues have increased from lines replacing street railways, but it is too early to determine the amount of traffic drawn from paralleling street railway lines and it is known that there has been a certain amount of such diversion, notwithstanding that the lines have been several blocks apart. Experience to date indicates that the overhead system is operating satisfactorily. The type of conductor is being tested for wear, and tests are also under way to determine the best lubricant and method of lubrication. In this connection, it may be added that automatic lubrication from passenger vehicles is being tried. Wear records for trolley shoes are maintained and tests of other details concerning the coaches, such as lubricants and lubrication, brake linings and drums, and brushes on motors and generators, are under way. Tire treads of various kinds are also being tested. With another year of experience to draw upon, some more definite facts and figures will be available.

Collaborating in the preparation of the above data were Mr. W. H. Lines, vice-president and general manager of Portland Traction Company, Mr. Gordon G. Steele, general superintendent, Mr. James P. Tretton, superintendent of equipment, and Mr. E. W. Moreland, statistician.

## Engineering Curricula

IN AN ARTICLE entitled "What Should the Technical School Teach?" appearing in *Civil Engineering* for November 1937, pages 733–4, Scott B. Lilly, professor of civil engineering at Swarthmore College, asserted that "the great fear of the present executive is obsolescence—that some new process will develop which will make his whole plant valueless." Because of this fear many of the progressive companies are becoming ever more interested in the field of research. "Large companies maintain their own laboratories, while the small ones combine to form trade associations, hiring the best men they can find, and spending lavishly to discover new methods that will bring them added business."

Professor Lilly maintains that research has produced better materials, better manufacturing methods, and better design; moreover, it has affected the requirements for a four-year undergraduate course because of its demand for broader training. "The theory underlying a broad undergraduate training is that instead of trying to keep up with all the changes that are taking place in each field, a college should reduce the number of courses taught, do away with special curricula, and concentrate on the things it can do best. The time is still far distant when engineering will be all science. Many of the structures being built even today are standing not because the theory of design is absolutely correct, but because the computations result in a structure similar to one that has proved satisfactory. In some cases it may be years before theory catches up with practice. Nevertheless . . . colleges should teach the science of engineering—that is, . . . students should spend the major part of their four years on the underlying principles of engineering, devoting only a moderate amount of time to applications."

The author believes that teaching has been too much concerned with the formal processes involved. "Men have learned *how* to do things, rather than *why*. They learned rules. But would it not be better to teach all courses from the standpoint of developing principles? For years the student has asked why he must spend so much time on mathematics when practicing engineers have told him that they rarely, if ever, have occasion to use the calculus. He does not realize that he will use the type of reasoning he learned in the calculus, although unconscious of where he learned it. Mathematics, then, must be taught so that the principles remain, even though the formal processes, the rules, are forgotten."

A suggested new curriculum, designed to meet the demands of modern industry, would be identical for civil, mechanical, and electrical engineers for the first three years. "The courses would include mathematics, physics and chemistry, descriptive geometry, kinematics, mechanics (both analytic mechanics and strength of materials), electrodynamics, hydraulics, and thermodynamics. This work would occupy three-quarters of the student's time for the first three years. In the senior year, he would be allowed to specialize in that branch of engineering in which he is most interested. He would have had the basic courses in all three fields and could take any advanced course offered. Some attempt should be made in at least one of these selected courses to carry the man as far as he is able to go—to acquaint him with the frontiers of knowledge in that field, so that he can see that engineering is not a dead thing, but a living, growing profession that will demand his best efforts."

"The broad engineering education . . . must include courses that cover the human side as well as the material side of the profession. But a 'course' in college is not an end; if it fails to develop a keen desire to know more, to go into the subject more deeply, it may be worse than useless . . . The greater part of this kind of education must come after graduation — and this will be true no matter how many courses were taken in college. The most important thing, therefore, is to instill the desire to be well read and well informed, not as a window dressing, but as equipment to face social problems and do something about them."

# Stray-Load Losses of D-C Machines

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## Synopsis

This article describes a method of measuring stray-load losses which is readily adaptable to the test departments of the manufacturers. Usually no additional test apparatus will be required beyond that already available. The same arrangement used for a pump-back heat-run test is used with only slight modification. Experimental data are given showing the effect of speed, load, and field strength upon these losses.

STRAY-LOAD losses may be defined as the losses at any particular load which are not accounted for by the conventional methods of measuring and calculating losses. They are divided into 3 classifications according to the causes producing them, as follows[1]:

1. Loss due to eddy currents in the armature conductors.
2. Short-circuit loss of commutation.
3. Increased core loss caused by distortion of the main field by armature reaction.

Various methods have been proposed for taking these losses into account. It has been suggested that the no-load core losses plus armature $I^2R$ losses be multiplied by a constant whose value should be somewhere between 1.1 and 1.5.[2,3] Such a procedure is open to the criticism that it would require a great number of constants to take into account differences in design.[2]

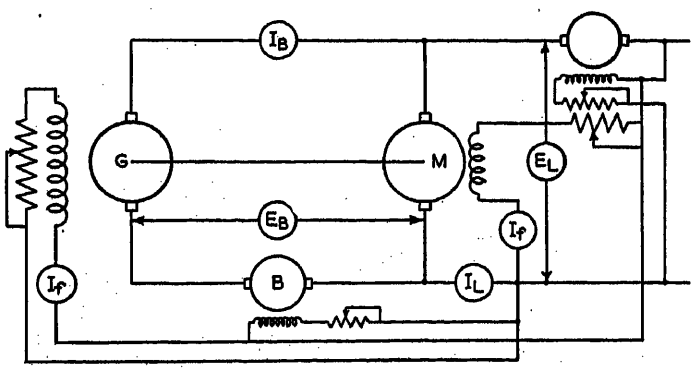



**Figure 1. Circuit used in determining stray-load loss of the set. Rotational losses supplied electrically**

Input-output tests have been made and data published.[2,4] The results of these tests were contradictory. One paper indicated high accuracy to be possible, whereas the other indicated that the method is not dependable.

Some work has been done on this problem[5] by using a generator with a compensating winding in the pole faces and comparing no-load losses with this winding unexcited to those when it is separately excited to various percentages of normal value. Of course, the first objection to this method is that most d-c machines do not have compensating windings. A further objection is that the additional loss determined in this manner is the result of field distortion and does not include losses in the armature conductors themselves due to eddy currents.

There is at present no standard way of directly measuring these losses, and according to the American Standards for Rotating Machines they are to be taken as one per cent of the output. This rule obviously makes no provision for differences in design and, in the case of adjustable-speed motors, charges the same loss to the machine at weak field and high speed as at strong field and low speed. That the latter is objectionable is clearly shown by the data given in this paper.

As a means of measuring stray-load losses, a direct measurement of total losses of 2 machines connected together in a modification of the familiar pump-back connection as shown in figure 1 is proposed. By subtracting the determinable losses from the total measured losses the total stray-load loss of the two is determined.

One of the contributions made by this paper is a method of allocating the proper proportion of the total stray loss to each machine when using the method described above; the other is informational in nature, that is, data are given on the stray loss resulting from operating d-c motors under varying conditions of speed, load, and field strength.

## Test Procedure

The circuit used for making the tests is shown in figure 1. *M* and *G* are machines of the same size, type, and design, and the brushes of both are set on neutral. They are therefore considered identical. Throughout any given test the field currents of the 2 machines were kept constant. The armature currents were varied by changing the booster (*B*) voltage.

The combined losses of the 2 machines *M* and *G* are

$$E_L I_L + E_B I_B = L_t$$

$L_t$ includes the armature $I^2R$ loss, commutating-pole-winding $I^2R$ loss, no-load core loss, brush-contact loss, windage and friction loss, and stray-load loss.

A paper recommended for publication by the AIEE committee on electrical machinery. Manuscript submitted April 22, 1937; released for publication October 8, 1937.

E. W. SCHILLING is associate professor of electrical engineering at Michigan College of Mining and Technology, Houghton, and R. W. KOOPMAN is assistant professor of electrical engineering at the University of Kansas, Lawrence. The authors are indebted to Mr. Scott Hancock, manager of the industrial motor engineering department of the Westinghouse Electric & Manufacturing Company, and to Professor G. W. Swenson, head of the department of electrical engineering of the Michigan College of Mining and Technology, for suggestions and information relative to this work.

1. For all numbered references, see list at end of paper.

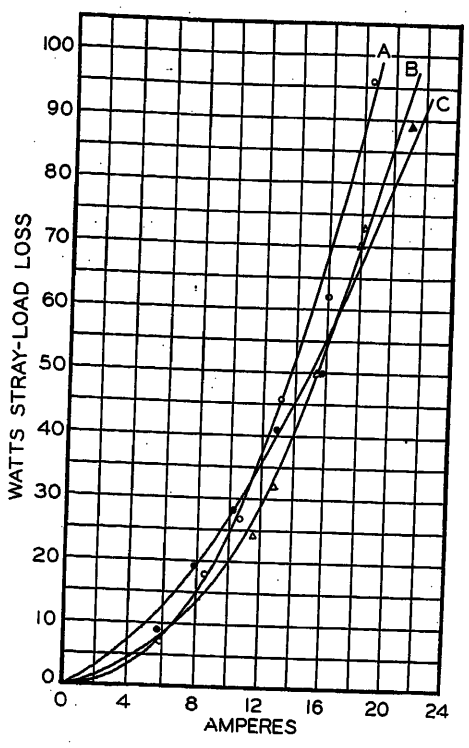



**Figure 2. Stray-load loss of set at 850 rpm, using circuit of figure 1, versus average armature current of the 2 machines**

*A*—Field current 0.50 ampere

*B*—Field current 0.66 ampere

*C*—Field current 0.80 ampere

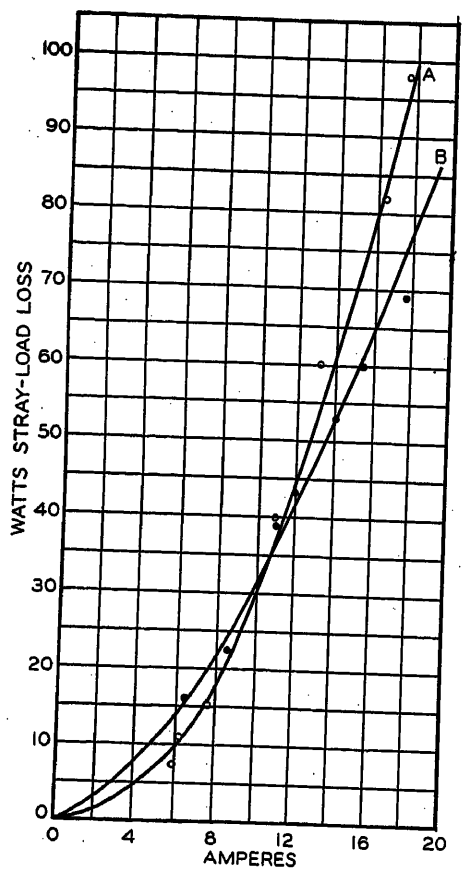



**Figure 3. Stray-load loss of set at 1,000 rpm using circuit of figure 1**

*A*—Field current 0.50 ampere

*B*—Field current 0.80 ampere

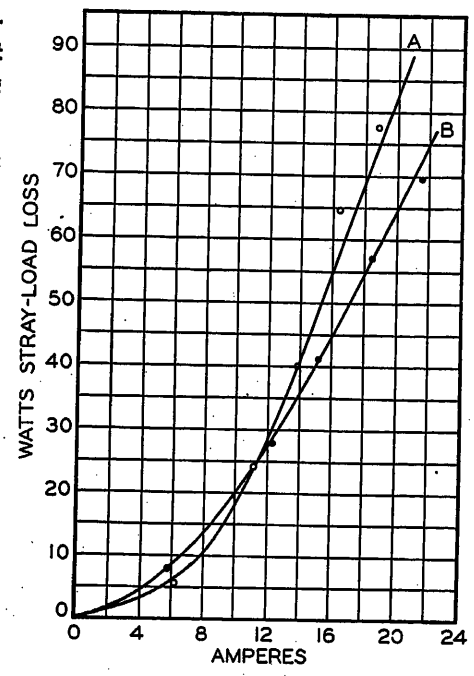
In order to insure that the various friction losses, the $I^2R$ losses, and, to a limited extent, the core loss would remain constant during the period required for taking the readings, it was necessary to run the machines until constant temperatures were reached. After this temperature was reached the brush contact drop was measured. Next the electrical input readings of $E_L$, $I_L$, $E_B$, and $I_B$ were taken. Immediately the line was opened, disconnecting the machine on the right; under this condition, the coupled machines come to rest, but the booster continues to circulate current of very nearly the same value as when all machines were in motion.

This convenience was of great value because the drops across the commutators and series resistances could be measured with very little loss of time and, consequently, with very little change in resistance between the time the input readings were taken and the time the resistance measurements were taken. As soon as the resistance measurements were completed the set was started again and run at the same value of armature current as before, in order that the temperatures would remain constant. The internal voltages of motor and generator were then computed. The field current of the motor was then changed to

**Figure 4. Stray-load loss of set at 780 rpm, using circuit of figure 1**

*A*—Field current 0.50 ampere

*B*—Field current 0.80 ampere



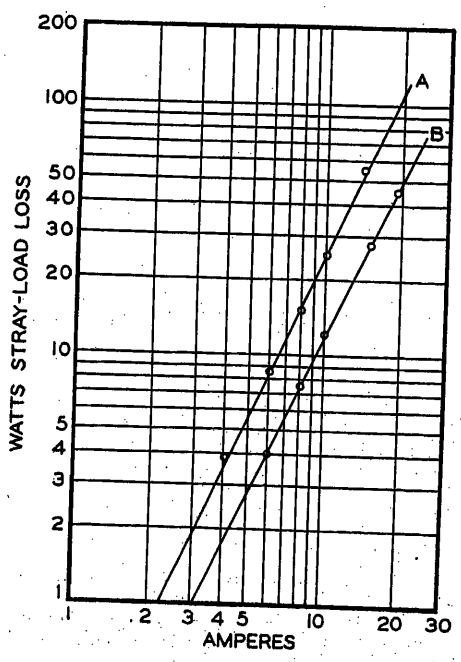




**Figure 5. Determination of exponent n at 850 rpm, 0.50-ampere field**

*A*—Loss versus average armature current of the 2 machines of set using circuit of figure 1

*B*—Loss versus armature current of one machine; losses separated according to scheme proposed

correspond to this voltage as read from the saturation curve, the booster circuit was opened, and the generator field current was adjusted to give the calculated internal voltage. The friction, windage, and core loss of the set could then be determined from the input to $M$ and its calculated $I^2R$ and brush-contact losses.

By taking the core-and-friction-loss readings immediately after each test, errors that result from wearing of brushes and from changes in bearing friction due to temperature changes were eliminated.

The stray-load loss of the set $L_s$ was taken to be $L_t$ minus brush contact loss minus $I^2R$ loss minus friction, windage, and core loss. A series of load-loss readings was thus taken at constant field current and speed for several values of $I_g$. These losses were then plotted against the average current of the 2 machines. Several different series of readings were taken using different speeds or field currents; these results are shown in figures 2, 3, and 4.

## Determination of Portion of $L_s$ Due to Each Machine

The curves mentioned above show how the total load loss of the set varies with average armature current, but do not give that due to each machine, because the armature currents are different.

We shall now describe the method used to separate $L_s$ into the components due to each machine.

Since we assume that the 2 machines are identical, and since they operate at equal field currents, the only variable affecting $L_s$ is the armature current. If the law of variation of $L_s$ with armature current were known it would be mathematically possible to calculate the portion of $L_s$ to be charged to each machine. Plotting $L_s$ versus average armature current gives us some idea of this law.

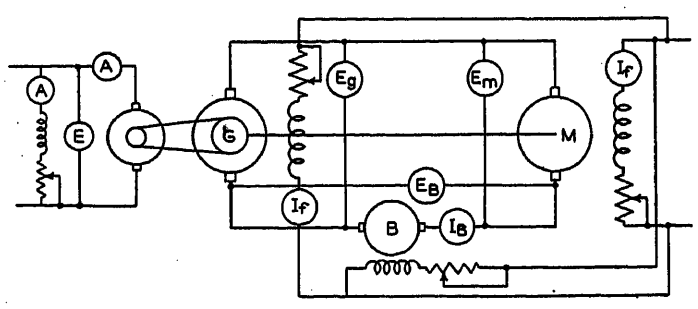



**Figure 6. Circuit for obtaining stray-load loss with same armature current in both machines**

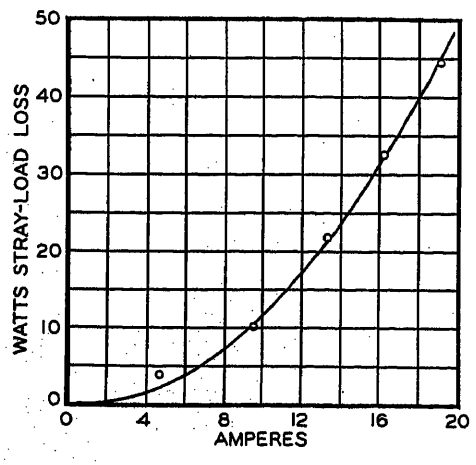



**Figure 7. Stray-load loss of one machine at 850 rpm, 0.50-ampere field, versus armature current. Curve calculated from test data obtained using circuit of figure 1. Circles represent test points obtained by using circuit of figure 6**

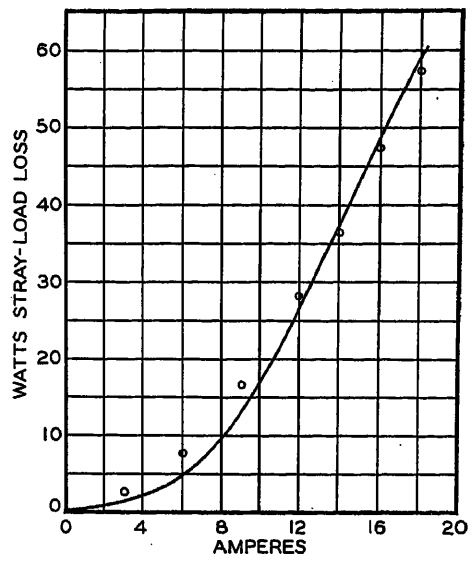



**Figure 8. Same as figure 7 but for 1,000 rpm, 0.50-ampere field**

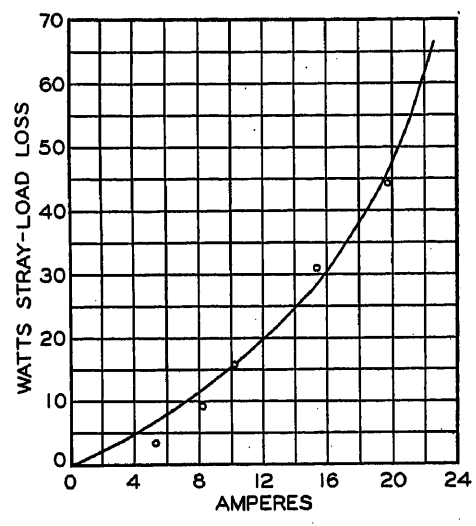



**Figure 9. Same as figure 7, but for 1,000 rpm, 0.80-ampere field**

Assuming that these curves can be expressed by $L_s = kI_a^n$ we can easily find $n$ by plotting on logarithmic paper as shown in figure 5*A*. Then at a particular value of $L_s$,

$$L_s = kI_G^n + kI_M^n$$

and the portions of $L_s$ chargeable to generator and motor respectively are

$$L_s \frac{I_G^n}{I_M^n + I_G^n} \quad \text{and} \quad L_s \frac{I_M^n}{I_M^n + I_G^n}$$

to the degree of approximation that $n$ approximates the true value of $n$ as it would be obtained by plotting the actual load loss of only one machine against its armature current.

Theoretically we could plot a curve of the load loss of one machine as obtained by using the approximate value of $n$ and obtain a new value of $n$, make a new separation, plot another curve, etc., until we approach the true value of $n$ as closely as we please. Practically, however, it is

necessary to make only one separation. That is shown in figure 5, where curve $A$ is the plot of $L_s$ versus average armature current and $B$ is the curve of the load loss of one machine plotted versus its armature current. There is scarcely any difference in the slopes of the 2 curves. The closeness with which the points fit the straight lines indicates that the equation $L_s = kI_a^n$ is correct to a high degree of accuracy.

In order to illustrate the method more clearly an example of a typical set of readings at 850 rpm and 0.5 amperes field is given.

$E_L$ = 94.80 volts
$I_L$ = 4.42 amperes
$E_B$ = 18.70 volts
$I_B$ = 11.05 amperes

| | |
|---|---|
| Generator brush contact drop (positive + negative) | = 1.40 volts |
| Motor brush contact drop (positive + negative) | = 1.80 volts |
| Generator armature current, $I_G$ | = 11.05 amperes |
| Motor armature current $I_M$ | = 15.47 amperes |
| Resistance of generator windings at operating temperature plus series resistance of 0.017 ohm | = 0.807 ohm |
| Resistance of motor windings at operating temperature plus series resistance of 0.012 ohm | = 0.847 ohm |
| *A.* Line supply watts | = 419 watts |
| *B.* Booster supply watts | = 206.6 watts |
| *C.* Total supply watts | = 625.6 watts |
| *D.* $I^2R$ generator | = 98.8 watts |
| *E.* $I^2R$ motor | = 203.0 watts |
| *F.* Brush-contact loss, generator | = 15.5 watts |
| *G.* Brush-contact loss, motor | = 27.9 watts |
| *H.* Core loss, friction, and windage of set | = 234.0 watts |
| *I.* Total of directly measurable losses ($D + E + F + G + H$) | = 579.2 watts |
| *J.* Stray-load loss $L_s$ = C − $I$ | = 46.4 watts |

## Determination of $L_s$ Chargeable to Each Machine

From figure 5*A*, $n$ = 2.16. Therefore the portion of $L_s$ chargeable to the generator is

$$46.4\ \frac{\overline{11.05}^{2.16}}{\overline{11.05}^{2.16} + \overline{15.47}^{2.16}} = 46.4\,\frac{179.35}{550.35} = 15.1 \text{ watts}$$

and that chargeable to the motor is 46.4 − 15.1 = 31.3 watts.

## Check on Procedure

As a check on the validity of the method which was used to separate losses, another series of tests was run on the set under the same conditions of speed and field current as before; but in this series the circuit of figure 6, in which the armature currents of the two were exactly the same, was used. In this test as in the other the same precautions regarding heating were observed. It was again possible to use the booster to circulate current for measuring $IR$ drops and thus save time, as no extra connections had to be made. The driving motor at the left in figure 6 was supplied from a variable-voltage generator. This voltage was reduced to a low value, and the field circuit

*A*—1,000 rpm; 0.50 ampere field current
*B*—850 rpm; 0.50 ampere field current
*C*—1,000 rpm; 0.80 ampere field current
*D*—780 rpm; 0.50 ampere field current
*E*—850 rpm; 0.80 ampere field current
*F*—850 rpm; 0.66 ampere field current
*G*—780 rpm; 0.80 ampere field current

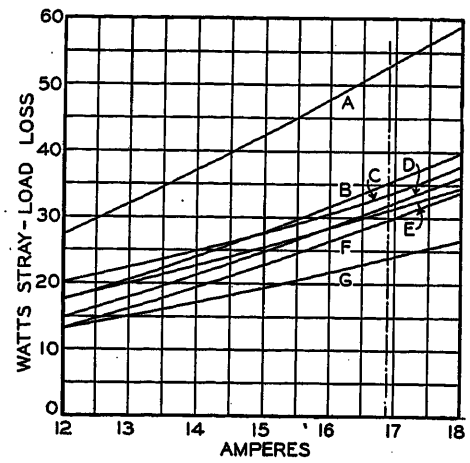



**Figure 10. Comparison of stray-load loss under different conditions of speed and field current**

of the motor opened. This stopped the set but still circulated current through the armature of the driving motor and thus simplified the measurement of resistance in this machine. The stray-load loss of the set is then equal to the booster output minus calculated losses of the set plus increased output of the driving motor between no current in the set and that current at which the test was run. Brush-contact drops were measured on all machines and these values used in calculating the brush-contact losses.

The stray-load loss under these conditions of operation should be the same for each machine. Figures 7, 8, and 9 were plotted from data obtained by applying the method of separation described in this paper to the curves of figures 2*A*, 3*A*, and 4*B*. The circles are test points obtained by using the circuit of figure 6. Here then are the results of obtaining the stray-load loss of a machine from 2 entirely independent and different tests. The results check as closely as could ever be expected in a test of this kind.

## Conclusions

In these tests a machine operating under different conditions of speed and field current shows a wide variation in load loss, as shown in figure 10. The broken vertical line indicates rated full-load current. The outputs of the machine are approximately the same at 1,000 rpm, 0.5 amperes field; 850 rpm, 0.66 ampere field; and 780 rpm, 0.80 ampere field, but the stray-load losses vary widely between these limits. This shows the need of a new rule for calculating stray-load loss for adjustable speed machines, as the present rule would charge the same loss at all three speeds. Another illustration of the inadequacy of the present rule is shown by figure 10. For instance, *B* and *C* intersect at about 14.8 amperes. The data given in this paper show that the load losses are equal at these intersections; yet the outputs are different in that they correspond to a speed of 850 rpm and field of 0.5 amperes for *B* and a speed of 1,000 rpm and field of 0.8 amperes for *C*. The present rule would charge different load losses for the 2 conditions.

All the curves taken with weak field show steeper slopes in the region of high armature current than those taken with the stronger field. The reason for this difference is that the armature current has a greater distorting effect on the resultant field when the main field is weak.

The advantage of using this method over the input-output test is that losses are measured directly, whereas in the input-output test they are taken as the difference between two relatively large quantities. The improvement in accuracy is obvious.

Another advantage is that very little wiring is required beyond that for the pump-back heat-run test as it is set up by many manufacturing companies. No special equipment is needed, and the labor required is comparatively low.

Its disadvantage is that the machines must be assumed to be identical.

The losses obtained were higher than expected, probably because the air gap was shorter than the average. This in itself is another fact which indicates the necessity of adopting a test procedure for determining stray-load loss.

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# The Library as an Engineering Tool

LITTLE excuse exists for those engineers who fail to furnish the correct answer to a current problem if it can be deduced, at least in part, from information available in libraries, according to an article by Gregory M. Dexter appearing in the November 1937 issue of *Mechanical Engineering*, pages 845–9. The author believes a library to be an engineering tool worthy of more than passing thought, because "some [engineers] find it easy to go along in the daily job without sensing or taking time to study the implications of new developments in unrelated or even in related fields of their daily activity. When suggestions are made for improved methods, many of them at some time say, 'it cannot be done.' They have not had sufficient interest or leisure to find out whether conditions have changed, new developments have occurred, or the previous failure did not arise from some fault in management or application of method."

Many engineering problems are settled easily by reference to the latest books; consequently, one of the most valuable source books for the engineer is the catalog of the large publisher of technical books. Yet often he will find that the best book on a particular subject is not published by one of the large technical publishing houses, and if he is thorough in his search for knowledge, he may find that the book he wants can be obtained only from some publisher of whom he has never heard.

"Many problems which engineers have to solve are so involved in technicalities, so unusual, or so special in application that no book available gives more than an elementary discussion. Places to which an engineer may turn then are the various departments of the federal and state governments as well as the numerous experiment stations.

"He should have always available a complete set of the indexes of federal publications which are obtainable from the Superintendent of Documents, Washington, D. C. . . . If the particular subject in which he is interested is not listed, a letter to the appropriate federal department often will bring him valuable information on unpublished data or other suggestions."

The author admonishes the reader that the titles to some of the general indexes are likely to deceive the engineer concerning their actual scope, and that valuable information sometimes may be obtained from the most unlikely appearing sources.

"Services of a librarian often are used in making searches for engineers. No disparagement of the value of such services is intended . . . . but engineers should recognize how much better results could be obtained by an engineer instead of a librarian. The engineer appreciates all ramifications of the problem he is investigating. He needs, of course, the facility a librarian has in knowing how to use a library. He needs persistence and imagination. Yet an engineer who knows his subject and has those qualities plus some knowledge of the library undoubtedly could do a better job of searching than a librarian. Merely glancing over an article would tell him whether it was worth abstracting or only listing in his bibliography.

"No engineer should entertain the idea that a library search is a method of avoiding original thinking. It is only a method of avoiding unnecessary expense in repeating mistakes that other men have made. It is a way of trying to start with new designs, inventions, or developments where other engineers and inventors have stopped."

The article contains comprehensive listings of book catalogs and indexes, government publications, guides and indexes to economic data, and general and special indexes. Most libraries have special bibliographic facilities of their own which should not be overlooked, and the author suggests ways of obtaining and using these special facilities.

# Oil Oxidation in Impregnated Paper

By J. B. WHITEHEAD
FELLOW AIEE

T. B. JONES
ENROLLED STUDENT

## Introduction

MUCH HAS BEEN written recently on the influence of oil oxidation on the properties and stability of impregnated paper insulation. It is thought by many to be a principal cause of deterioration in high voltage cables. Oxygen is highly soluble in cable oils; if present in appreciable quantity and at moderate temperature elevation, the oils oxidize rapidly with consequent loss of insulating value. However, the amount of oxygen remaining in a carefully dried paper cable is so small, and the oxidation process is so slow that it remains to be proved that it is more important in deterioration than other well-known causes.

In this paper we report a series of studies of the oxidation process in cable paper impregnated with oil containing different amounts of oxygen, as indicated by changes in well-known electrical quantities. Separate studies of the effect of equal amounts of air and of nitrogen, and of the behavior of the oil alone, and as affected by paper and metal, throw interesting light on the nature of the progressive changes found in the electrical characteristics.

## Experimental Method

One type of oil and one type of paper were used throughout. Ten layers of the paper were assembled in a small parallel-plate capacitor, equipped with the usual guards, and mounted in a Pyrex glass dish, and placed inside an evacuating and impregnating tank with temperature control. See figure 1. The paper is evacuated at 0.05 millimeter of mercury pressure to a standard degree of dryness and the oil admitted for impregnation. Before admission the oil is filtered, degassed, and saturated with oxygen at various pressures, and impregnation takes place in an atmosphere of oxygen at the same pressure. After impregnation the sample is kept at the same constant pressure and at a temperature of 80 degrees centigrade for about one week. Measurements of power factor and capacitance, as related to voltage and temperature (at end of test) were made at intervals. At the end of the run the power factor of the individual paper layers, and the electrical properties of the oil drained off the specimen, were measured. Additional studies were made on the oil alone and on the impregnated paper using nitrogen as impregnating atmosphere. The catalytic effect of several metals on oil oxidation was also measured.

A paper recommended for publication by the AIEE committee on research. Manuscript submitted September 16, 1937; released for publication October 15, 1937.

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1. For all numbered references, see list at end of paper.

*The Paper and the Oil.* A single grade of uncalendered chemical wood pulp "kraft" paper, as made by a well known manufacturer was used throughout. Its properties[1,20,21] are given in table I.

The oil, designated by the refiner as "highly refined paraffin" cable oil, was delivered protected by nitrogen atmosphere and so maintained until used. Its properties are given in table II.

*Test Capacitor.* The capacitor is of circular parallel-plate type; high-voltage electrode 13-centimeter diameter, low-voltage electrode 10.4-centimeter diameter, equipped with guard ring, radial width of gap and ring 1.25 centimeters; material, brass throughout.

Ten circular sheets of paper 15.6-centimeter diameter constituted the usual test sample. A constant weight was placed on the upper high-voltage electrode to ensure uniform pressure in all samples; air capacitance at this separation, 71 micromicrofarad . The capacitor is mounted in a shallow Pyrex glass dish, which is placed in a vacuum-tight, temperature-controlled impregnating tank shown in figure 1. The tank can be evacuated to 0.05 millimeter of mercury, and heated to 110 degrees centigrade. The oil is admitted through Pyrex tubing, and the removable top

**Table I. Physical and Electrical Properties of the Paper**

| | |
|---|---|
| Thickness | 0.0045 inch |
| Diameter | 6.00 inches |
| Specific gravity | 0.882 |
| Gurley air resistance | 640 seconds |
| Effective capillary radius | $8.2 \times 10^{-6}$ centimeter |
| Conductivity | $1.0 \times 10^{-18}$ mho per cubic centimeter |
| Power factor | 0.00140 |
| Dielectric constant | 2.41 |

Electrical measurements at 80 degrees centigrade

**Table II. Physical and Electrical Properties of the Oil**

| | |
|---|---|
| Pour point | 4.4 degrees centigrade |
| Flash point | 263 degrees centigrade |
| Specific gravity | 0.903 |
| Viscosity | 4.07 poises |
| Surface tension | 38.3 dynes per centimeter |
| Penetrative power | $6.52 \times 10^{-3}$ |
| Dielectric strength | 28,820 volts |
| Conductivity (20 minute) | $5.75 \times 10^{-14}$ mho per cubic centimeter |
| Power factor | 0.0005 |
| Dielectric constant | 2.204 |

Measurements at 40 degrees centigrade

**Table III**

| Pressure of Oxygen | Volume of Gas Absorbed | Per Cent of Oil Volume |
|---|---|---|
| 1 millimeter | 0.13 cubic centimeter | 0.013 per cent |
| 5 centimeter | 7.00 cubic centimeter | 0.7 |
| 10 centimeter | 14.00 cubic centimeter | 1.4 |
| 76 centimeter | 104.00 cubic centimeter | 10.4 |

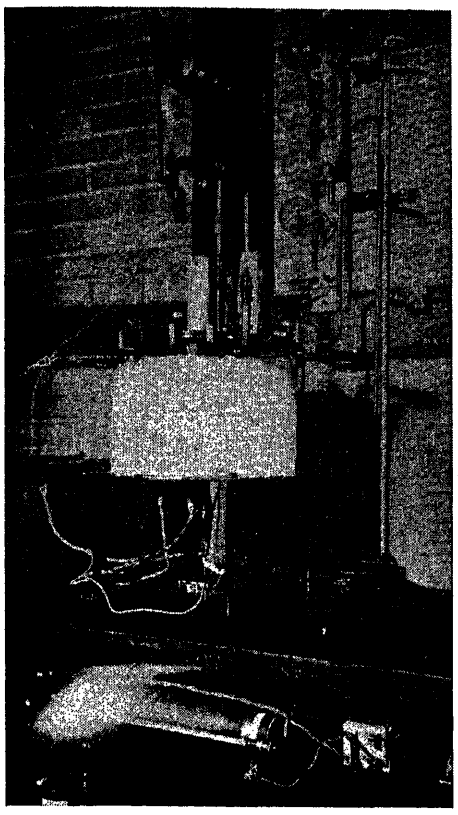


Figure 1. The test cell

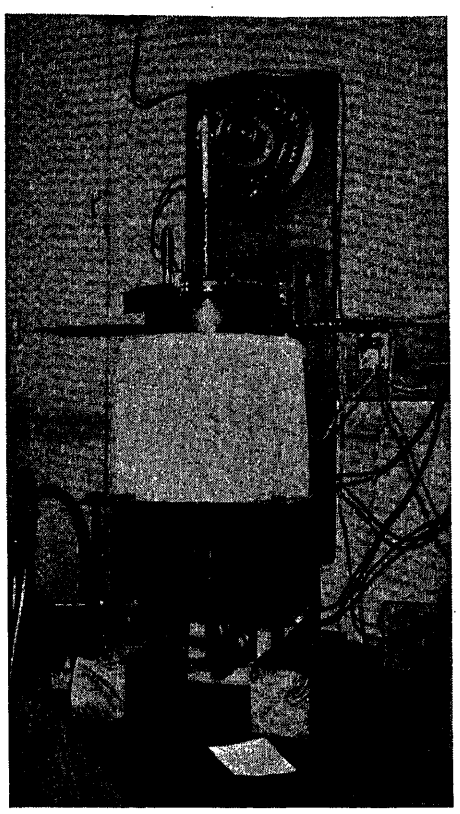


Figure 2. The oil filter cell

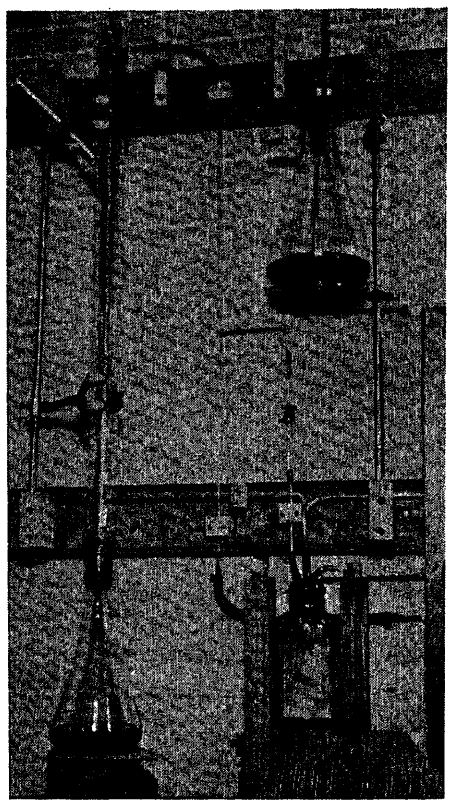


Figure 3. The degasification and dehydration apparatus

carries glass bushings for the electrical connections.

*Oil Purification and Oxidation.* The oil as received is first passed through the glass wool filter shown in figure 2, and then through the combined vacuum degasifier and dehydrater shown in figure 3. In the latter the oil passes down in a thin film over the turns of an open spiral of Nichrome wire in the inner of 2 coaxial glass tubes. The outer tube contains a heating coil; temperature in operation 80 degrees centigrade, pressure, 0.2 millimeter of mercury. After this treatment the oil had a power factor (60 cycles) of 0.0003 and a breakdown strength (standard disk gap) of 30,000 volts at room temperature.

*Oxygen Content of Oil.* Oxygen was admitted to the oil in different amounts, by exposing it to the gas at different pressures, in the apparatus shown in figure 4.

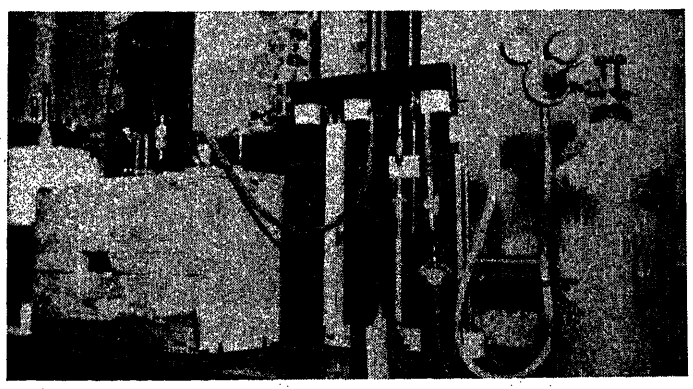


Figure 4. The oxidation apparatus

It has been shown that the volume absorbed-pressure relation is linear over a wide range,[22] for equal times and temperatures of exposure. In this work the oil was first raised to a temperature of 80 degrees centigrade, and evacuated to 0.1 millimeter of mercury. Then dry oxygen was admitted and the sample allowed to absorb oxygen for a period of 65 hours at constant pressure. The values of pressure adopted for study were 1 millimeter, 5 centimeters, 10 centimeters, and 76 centimeters of mercury. In what follows the different samples will be referred to in terms of these pressure values. The amount of oxygen absorbed in the several 1,000-cubic-centimeter samples at the respective pressures was found to be as given in table III. It will be seen that the relation between pressure and volume absorbed is approximately linear.

*Impregnation.* The test electrodes were washed in successive baths of soap and water, benzine, alcohol, or carbon tetrachloride, and distilled water, and dried. Ten layers of paper were placed between the plates and the whole placed in the impregnating and measuring tank. The temperature was raised to 105 degrees centigrade, and the pressure reduced to 0.1 millimeter of mercury. Frequent measurements of power factor and conductivity were taken in order to follow the drying process. Constant values indicating extreme state of dryness were usually reached in 72 hours; power factor, 0.00140; conductivity $1.0 \times 10^{-15}$ mhos per cubic centimeter. When these values were reached the temperature was lowered to 80 degrees centigrade and the oil, after treatment as already described, was admitted for impregnation.

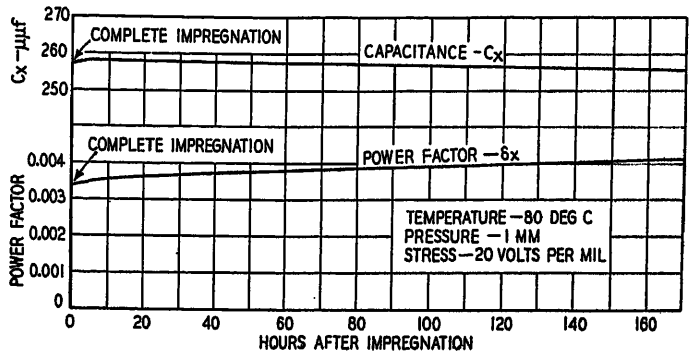



**Figure 5. Power factor and capacitance versus time**

In each case impregnation took place in an atmosphere of oxygen and at the same pressure and temperature at which the oil had been saturated. Thus for the 5-centimeter test the oil was preoxidized at 5 centimeters of mercury pressure and 80 degrees centigrade, and admitted to the dry paper at the same pressure and so maintained. The glass dish containing the capacitor was filled with oil and so remained throughout the test, so that there was a constant supply of oil and gas at constant pressure throughout the test. After admission of the oil the sample was allowed to stand for 24 hours to ensure complete impregnation. In the results reported below the end of this 24 hours is taken as *zero* time. Thus at this stage the oil had already been exposed to oxygen at 80 degrees centigrade during gas saturation, and paper impregnation, for a total of 89 hours. Electrical measurements were begun at this point, and consisted of power factor and capacitance at 60 cycles, and 20 volts per mil of paper thickness, 3 times a day; and a power factor-voltage run up to 150 volts per mil once each day. This program was followed for 168 hours, the duration of the normal test.

After the normal test, heat was removed from the tank (pressure constant) and during cooling the power factor-temperature curve of the sample taken for the range 80 degrees–25 degrees centigrade; a power factor-voltage curve was then taken at room temperature. The oil was drained from the sample for further test; the sample was then disassembled and consecutive measurements made of the power factor of each layer; the successive layers were carefully examined for any evidence of gas spaces, wax formation, or other significant condition.

At no time during the above tests was sustained voltage applied to the samples, and the electrical measurements 3 times a day were of brief duration and at low stresses. Thus the various behavior of the samples, as observed, is due to the oxidation process alone.

*Electrical Measurements.* Power factor and capacitance were measured on the transformer bridge developed in these laboratories by Seletzky[31] and McCurley.[24] It has a power factor accuracy of 0.0001 and can be balanced in less than 3 minutes. It lends itself readily to variations of setting needed for ranges of voltage stress, and for tests on single paper layers. The standard air capacitor is of flat type with electrodes 14 by 28 inches; the capacitance is 179 micromicrofarad. The output transformer feeds into a resistance-capacitance coupled amplifier. The detector is a vibration galvanometer; sensitivity, 40 millimeters deflection per microampere, at one meter distance of scale. A high sensitivity d'Arsonval galvanometer was used for d-c conductivity measurements, under methods described in earlier papers.[1]

## Experimental Results

Five series of observations were made of the influence of oil-absorbed oxygen on the behavior of impregnated paper. These will be referred to as the 1-millimeter, 5-centimeter, 10-centimeter, and 76-centimeter tests for pure oxygen. The fifth series covers a sample with oil treated at one millimeter *air* and impregnated and tested at one millimeter *air*, the process being identical in all other respects with the one-millimeter oxygen test.

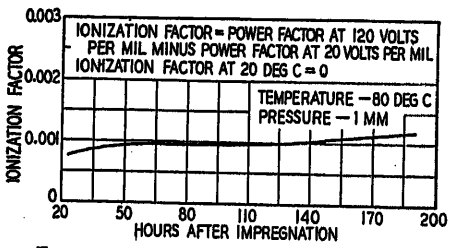



**Figure 6. Ionization factor-time**

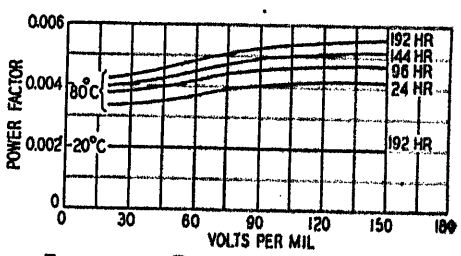



**Figure 7. Power factor-voltage**

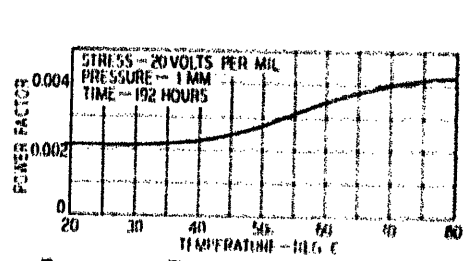



**Figure 8. Power factor-temperature**

*One-Millimeter Oxygen Test.* The results are shown in figures 5, 6, 7, 8, and 9. The capacitance, figure 5, is constant over the 168 hours of the test. The power factor rises very slightly from 0.0038 to 0.0042.

The power factor-voltage relations taken at 24-hour intervals are indicated in figure 7, and the resulting ionization factors in figure 6. The power factor-voltage curves at 80 degrees show a rising tendency at first, but evidently indicate an approach to a maximum value of

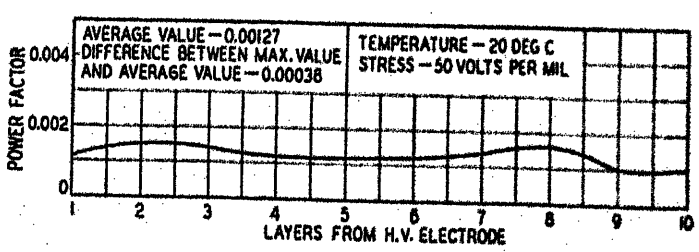



**Figure 9. Layer variation of power factor**

power factor. This behavior has been noted in earlier[1] studies of well-impregnated samples, although at lower stresses. The power factor at 20 degrees is constant between 20 and 150 volts per mil. These facts indicate the relative unimportance of gaseous ionization and suggest the presence of some type of oil ionization increasing with temperature and time, and voltage, up to a certain value. The increase with temperature, figure 8, is due to the increased mobility of the liquid ions; the increase with time to the increase of the number of ions with progressive oxidation or other cause; the increase with voltage is due to either increased mobilities, or new ions formed under increased stress, due to collision or other cause. The maximum of power factor results from a maximum conduction current when all ions are withdrawn as fast as formed. Other evidence in support of this view is given hereinafter. Other suggestions of mechanisms of the formation of new liquid ions are those of Inge and Walther[7] and Arman and Starr.[25]

Figure 9 shows the variation of power factor between successive paper layers. It is seen that the power factor is fairly uniform from layer to layer throughout and of a very low average value. The maximum variation is only 0.0006 power factor. The maximum of power factor occurs in the eighth layer from the high voltage electrode,

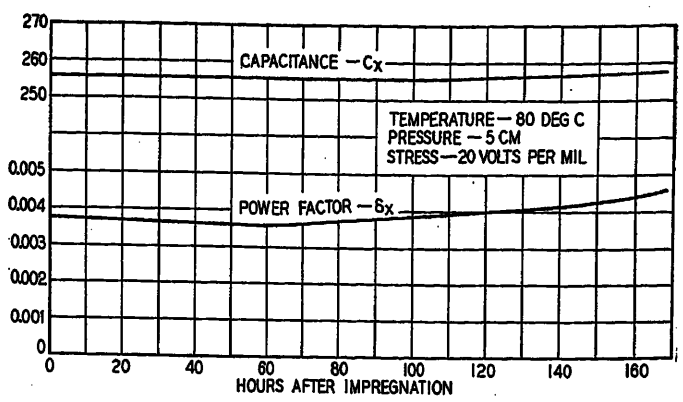



**Figure 10. Power factor and capacitance versus time**

creased rising tendency in the latter beyond 120 hours. This indicates that the 50-fold increase in oxygen content has a scarcely noticeable effect on these curves. The power factor-voltage curves, also, figure 12, except for some irregularity in the early stages, are substantially flat at 80 degrees up to about 100 hours, and do not rise above those of the one-millimeter sample until the end of the test, where the maximum value at 150 volts per mil is only 0.006. At 22 degrees the curve is definitely flat up to 150 volts per mil, at 0.0026 power factor; this is

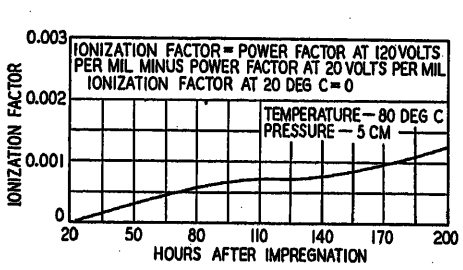



**Figure 11. Ionization factor-time**

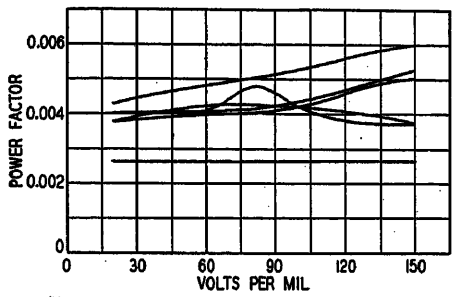



**Figure 12. Power factor-voltage**




**Figure 13. Power factor-temperature**

and not at the layers adjacent to electrodes as frequently observed. Indeed, at the electrodes the power factor is at its lowest values, indicating that at the low oxygen content here in question, the electrode-oil reaction does not appear within a period of 200 hours at 80 degrees centigrade. Apparently, therefore maxima of power factor in layers adjacent to conductor and sheath sometimes observed in new cables are due to some other cause.

*5-Centimeter Oxygen Test.* The results are shown in figures 10, 11, 12, 13, and 14. The capacitance-time, and power factor-time curves, figure 10, are closely the same as in the one-millimeter test, with a somewhat in-

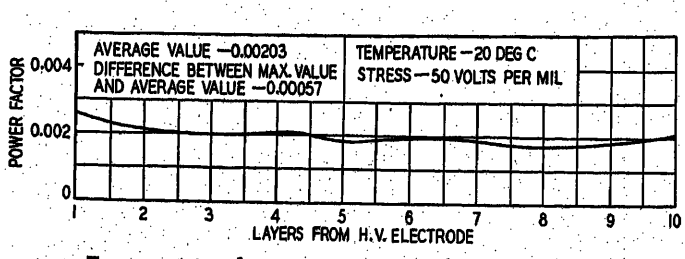



**Figure 14. Layer variation of power factor**

slightly higher than the corresponding curve, 0.002, at one millimeter, due probably to the increased oxidation. This, however, has little or no effect on the ionization characteristics, see figure 11. In fact up to 120 hours at 80 degrees centigrade, the electrical properties of this sample are substantially the same as those of the sample containing only one-fiftieth as much oxygen, and only slightly impaired beyond. The layer-power factor curve indicates the beginning of catalytic action of the brass electrodes.

These facts suggest that the deteriorating effects of small amounts of oxygen are either negligible or very long delayed in good cable insulation in normal service; also that a substantial amount of oxygen might be present in new cable, and not show itself for sometime.

*Tests at 10 Centimeters and 76 Centimeters of Mercury Pressure Oxygen Content.* In order to accelerate the oxidation process still further, similar tests at much greater values of oxygen content were made, that is, the oil was saturated with oxygen at 10 centimeters and 76 centimeters of mercury pressures, respectively. The results are shown in figures 15 to 19, respectively in which

the results at lower pressures are also included for convenient comparison.

Figure 15 shows the power factor plotted against oxygen content, as indicated by saturation pressure, for four different periods of time at 80 degrees centigrade after impregnation. Each curve thus represents an increased stage of deterioration, at any value of oxygen content. It is seen that for all curves the variation of power factor between one millimeter and 5 centimeters pressure is scarcely noticeable. Beyond 5 centimeters the increase with pressure is at first rapid, but then becomes slower again as the very high oxygen content of 76 centimeters is approached.

Figure 18 shows the power factor-temperature relation for each pressure. At low temperatures (20 degrees centigrade) the power factor is less than 0.004 for all values of oxygen content, and at 76 centimeters is only 1.8 times that at 1 millimeter. The differences are increasingly great, however, at higher temperatures. Thus the well-known influence of increased temperature in increasing the rate of oxidation is reflected in these power factor curves. In the 2 lower curves the practically linear increase may be explained as due to decreasing viscosity and increased ionic mobility. But the rapid rise in the 2 upper curves seems to require other explanation inherent in the oxidation process, such as the liberation of gas (hydrogen) and the consequent formation of water, and the formation of organic acids. Or more simply, we may note that the "velocity constant"[26] of the oxidation reaction increases exponentially with the temperature. If the reaction itself provides (even temporarily) an increase in the number of free ions, the observed increase in power factor is readily accounted for. Further evidence in support of this view is given later. No visual evidence of gas was found in the dismantling of any of the specimens. Figure 17 shows the temperature increase of power factor as function of the oxygen impregnating pressure.

Figure 16 shows the rapid increase beyond impregnating pressure 5 centimeters of ionization factor with value of oxygen content. The increase is very slight at one millimeter and at 5 centimeters, but very pronounced at higher impregnating pressure, as may be also seen in the power factor-voltage curves of figure 20 for 10 centimeters, and figure 21 for 76 centimeters. These increases of power factor with electric stress are not due to the liberation of gas, and to gaseous ionization; no free gas or other traces of ionization of this character were encountered. Rather the increase is to be attributed either to an increase in the number of ions due to some type of secondary ionization, or to an increase of ionic mobilities due to the stripping, under increased stress, of the outer envelopes of neutral molecules from the ions already present, or to both these causes. The flattening out of some of the power factor curves seems to support the latter view. Support of the former is found in the abrupt drop in power factor when the oxygen content and volatile products are withdrawn, as reported below; this indicates that during the oxidation process a large number of highly mobile ions are present.

Figure 19 affords a view of how the layer variation of power factor varies with oxygen content. As already stated a substantial amount of oxygen is needed to show itself in this way.

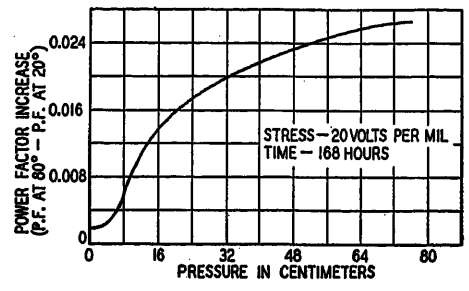



**Figure 17. Temperature increase of power factor**

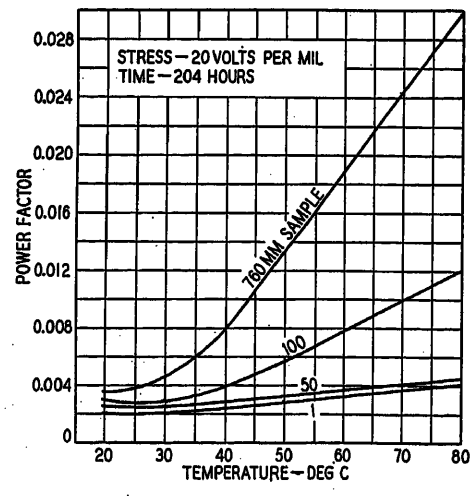



**Figure 18. Power factor - temperature**

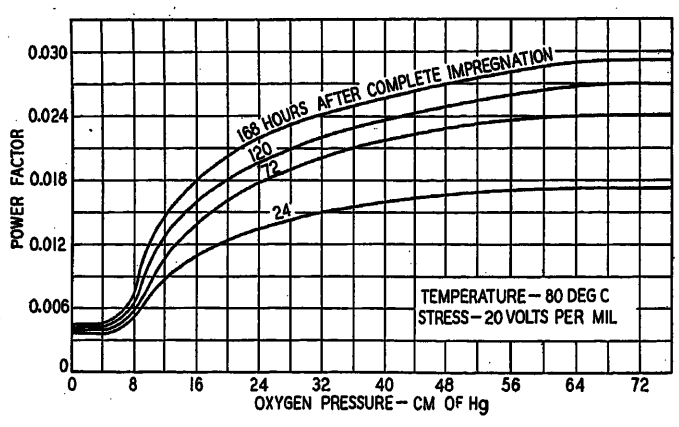



**Figure 15(above). Power factor-pressure**

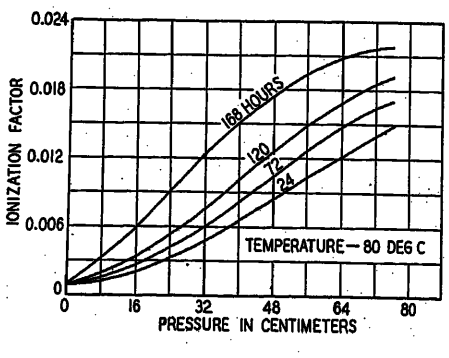



**Figure 16. Ionization factor-pressure at different times after impregnation**

It is interesting to note that the capacitance of all the impregnated samples over the whole range of oxygen content was the same, and remained constant over the duration of each test. This indicates that notwithstanding the heavy oxidation of the 10-centimeter and 76-centimeter samples, no appreciable molecular or ionic polarization was evident.

*Impregnation in Air at One Millimeter Pressure.* For comparison with the results using pure oxygen, a sample in which oil saturation and paper impregnation took place in *air* at one millimeter pressure, was tested, all technique being the same as for the sample impregnated at one millimeter of oxygen. The results are shown in figures 22, 23, and 24. Certain noticeable differences from the oxygen sample are evident. The capacitance, while constant over the duration of the test, has a substantially lower value, 243 versus 258 micromicroforad. The power factor-time curve for 20 volts per mil is about the same in the 2 cases. The power factor voltage curves

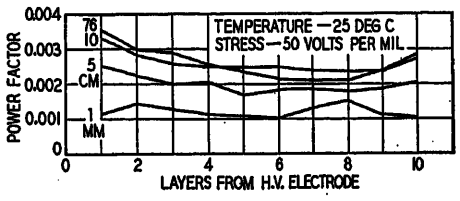



**Figure 19. Layer variation of power factor**

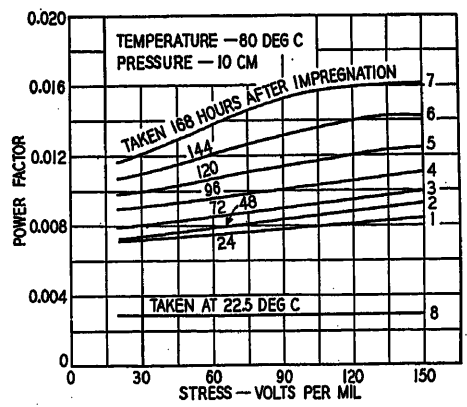



**Figure 20. Power factor-voltage**

at 80 degrees centigrade for oxygen are of uniform shape and progressively higher with time. Those for air show some irregularity, but at first become lower, and finally only become higher with time. The constant values at 20 degrees to 25 degrees after the oxidation runs are substantially the same. The power factor by layers after oxidation shows only small variations, with little evidence of increase at the electrodes. All of these facts indicate superior impregnation for the oxygen sample, probably due to its greater solubility in the oil. Penetration into the pores of paper is not as complete for the air sample and thus the capacitance is lower. For the same reason the ionization factor, and power factor-voltage curves are higher at the start, then decrease with slow improvement of oil penetration, and then increase again as the slow increase of oil conductivity due to oxidation makes itself felt. On dismantling the air sample

**Figure 21. Power factor-voltage**

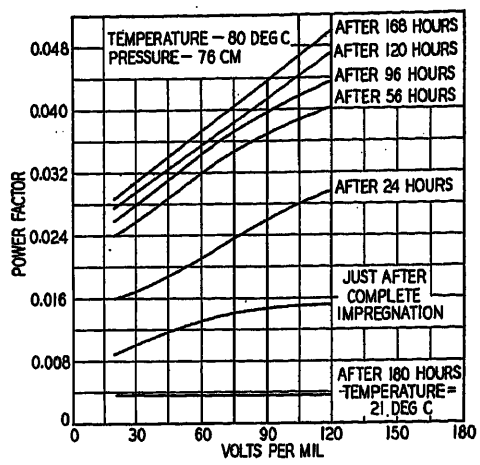
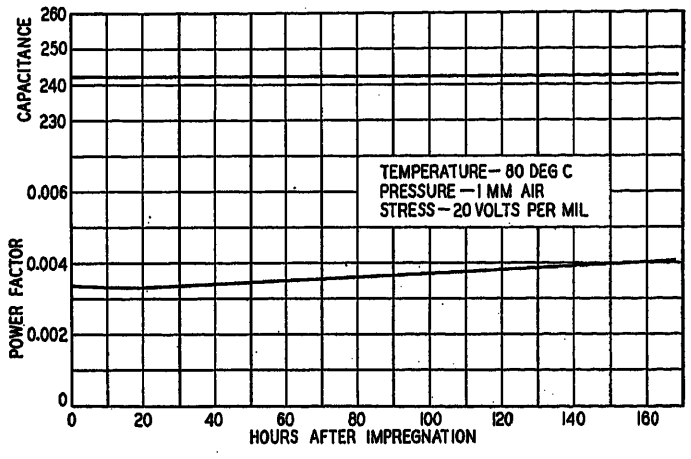



**Figure 22 (below). Power factor and capacitance versus time—air**




after the oxidation test, a few tiny bubbles of gas were evident in the paper layer next to the high voltage electrode, but in no other layers, and this may account for the slight rise in power factor for layer 1 seen in figure 24. In general it may be said that the sample impregnated in oxygen is superior to that impregnated in air, in the matter of impregnation, and shows no evidence of more rapid deterioration in the accelerated oxidation tests.

*Impregnation in Nitrogen at 10 Centimeters Pressure.* As a check to the deductions made from the results of the one-millimeter air test, a test was made using nitrogen at 10 centimeters of mercury pressure, for oil saturation and for impregnation. Figure 25 shows the variation of capacitance and of power factor over the duration of the test. On both curves the dotted lines give the measured values, and the full lines the trend of the average values. The values shown are for a stress of 20 volts per mil, and it was found that at this low and constant value neither capacitance nor power factor showed any tendency to change. However, power factor-voltage runs at intervals, up to 150 volts per mil, always resulted in a large increase followed by decrease to steady values at 20 volts per mil. The general sequence of these changes is indicated in the dotted lines of figure 25.

The decrease of the ionization factor, figure 26, and the continuous fall of the position of the power factor voltage curve with time, figure 27, are clear evidence of delayed impregnation. Power factor values at the end of the test

are generally of the same values as found in the one-millimeter oxygen test, showing the inert property of nitrogen and the very low oxidation activity at one millimeter oxygen content. The high position of the initial power factor-voltage curve is probably due to free nitrogen and gaseous ionization; small bubbles of gas were

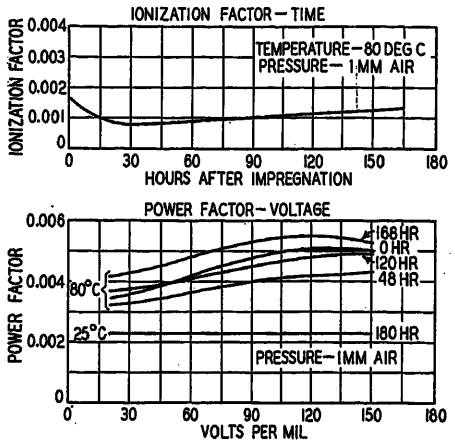


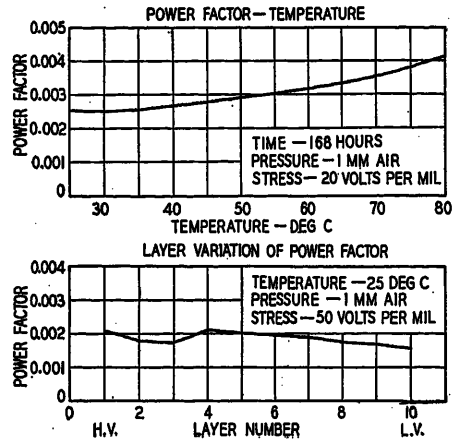

**Figure 23. Power factor-voltage and ionization factor-time**

found in the paper layers next to the electrodes but not elsewhere. Increasing the gaseous ionization by increase of voltage, seemed to stimulate the impregnation process, figure 25. The gas at the electrodes apparently also accounts for a slightly increased power factor (0.0032) of the paper layers next the electrodes, as compared with the approximately constant value (0.0028) of the interior layers.

It will be noted that the behavior of the one-millimeter air specimen presents several of the features of this specimen heavily saturated with nitrogen; for example, initial decrease in ionization factor, initial fall of position of successive power factor-voltage curves. There is a distinct indication that the nitrogen is playing its part in the one-millimeter air specimen.

*Properties of Oxidized Oil.* After each test the oil was drawn off the specimen and electrical measurements made on it. Thus there were available a series of oils oxidized for approximately 200 hours at 80 degrees centigrade in the presence of brass and paper, but at different constant amounts of contained free oxygen indicated by 0.013, 0.70, 1.40, and 10.4 per cent, respectively, of the constant volume of oil. The power factor-temperature curves of figure 28 and the power factor-voltage curves at 80 degrees, figure 29, show the relatively small difference in power factor over the range, pure oil—one millimeter—5 centimeter oxygen content, the rapid increase above 5 centimeters and the slower rate of rise toward 76 centimeters. The power factor-voltage curves of these deteriorated oils at 20 degrees centigrade were all found to be perfectly flat up to 60 volts per mil, but at 80 degrees centigrade all show the rising characteristics of figure 29, that is, some form of internal liquid ionization which increases with stress. The explanation is not obvious; possibilities in the order of their probability would appear to be increased ionic mobility, increase in free ions liberated during the

**Figure 24. Power factor - temperature and layer variation of power factor**




process of oxidation, and increased ionization by collision with increasing stress. The concurrent dominating influence of temperature is shown by the flat power factor-voltage curves at 20 degrees for all samples. The electrical characteristics of the deteriorated paper samples follow the same general trends as those of the oil withdrawn from them, indicating clearly the influence of the oil on the characteristics of impregnated paper.

*Influence of Brass and of Paper on Oil.* It has been assumed in the foregoing that the small increases in power factor found in the tests of the sample having one

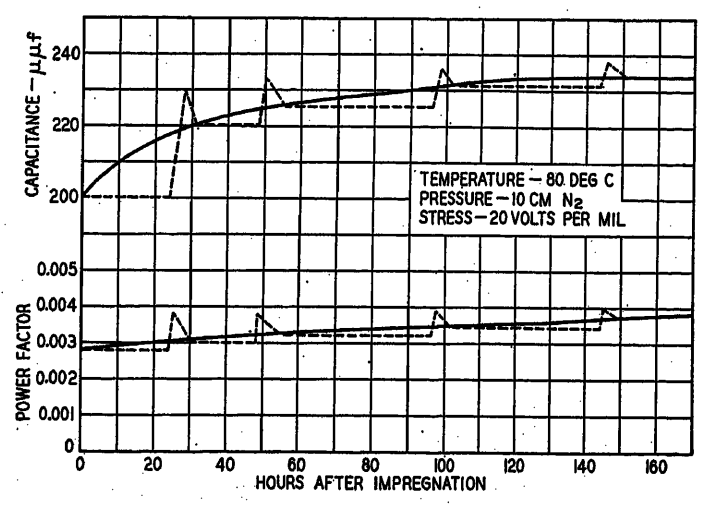



**Figure 25. Power factor and capacitance-time**

millimeter oxygen content were due to oil oxidation. However, during these tests the oil is in contact with both brass and paper and it remains to be seen whether or not these elements have any effect on the pure oxygen-free oil. In order to obtain a quantitative answer to this question, 3 identical pure samples of oil were prepared and heated for 48 hours at 80 degrees centigrade under the following conditions: (1) oil alone; vacuum 0.1 millimeter; (2) oil plus 800 square inches of paper; vacuum 0.1 millimeter; (3) oil plus 40 square inches of clean sheet brass; vacuum 0.1 millimeter. The heating took place in a Pyrex glass flask and before the oil was admitted paper and brass were given thorough degassing and dehy-

drating treatments at 105 degrees centigrade and 0.1 millimeter vacuum. At the end of each test the sample was cooled to room temperature, then placed in the test cell and a power factor-temperature run made. The results of the 3 tests are given in figure 30 (which also shows results of a similar test on the oil drawn from the 10-centimeter nitrogen sample after the deterioration test).

We note from figure 30 that in these 3 identical tests, contact with paper and contact with brass have each caused an increase in power factor over the values found for oil alone, and that these increases are greater with increasing temperature. These increases are thus not due to oxygen in the oil, and if due to oxygen at all it can only be that absorbed in the metal and on the surfaces of the paper fibers. The values of power factor at four

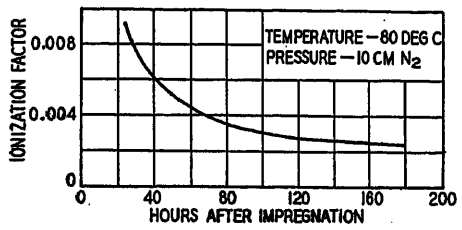



**Figure 26. Ionization factor-time**

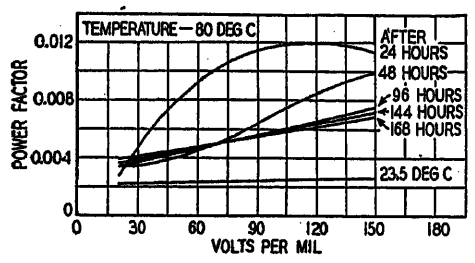



**Figure 27. Power factor-voltage**

temperatures are given in table IV. The fourth line, "brass and paper" is gotten by adding to the values for pure oil the *increases* in power factor caused by paper and by brass separately. As seen the values obtained by this simple approximate method of computing the joint total effect, agree closely with the measured values on the one-millimeter oxygen sample. In other words, in the latter sample contact with paper and brass alone are sufficient to account for the observed values; the small amount of oxygen present in the one-millimeter oxygen sample, in spite of the high temperature, 80 degrees centigrade, appears to play no part in the observed increases in power factor.

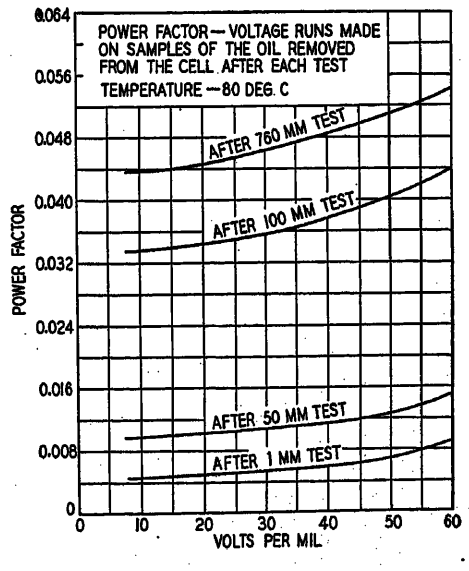
*Ionization in the Process of Oxidation.* Oxidation is very slow at 25 degrees centigrade; power factor voltage curves

**Table IV. Power Factor**

| | 20 Deg. C. | 40 Deg. C. | 60 Deg. C. | 80 Deg. C. |
|---|---|---|---|---|
| Pure oil | 0.00040 | 0.00076 | 0.00150 | 0.00300 |
| Plus paper | 0.00040 | 0.00086 | 0.00180 | 0.00390 |
| Plus brass | 0.00044 | 0.00095 | 0.00220 | 0.00480 |
| Brass plus paper | 0.00044 | 0.00105 | 0.00250 | 0.00570 |
| One-millimeter sample | 0.00044 | 0.00100 | 0.00240 | 0.00545 |

at this temperature for the whole range of oxygen saturation are flat and power factor values for oxygen saturation at 76-centimeter pressure are only about twice those at one millimeter. On the other hand, these differences are greatly increased as the temperature rises, as seen in figure 18. At low saturation (one millimeter and 5 centimeters) the power factor increases linearly with temperature, indicating increasing conductivity, and possibly a linear oxidation increase. However, for higher oxygen contents something else is going on as indicated by the more rapid

**Figure 29. Power factor - temperature**



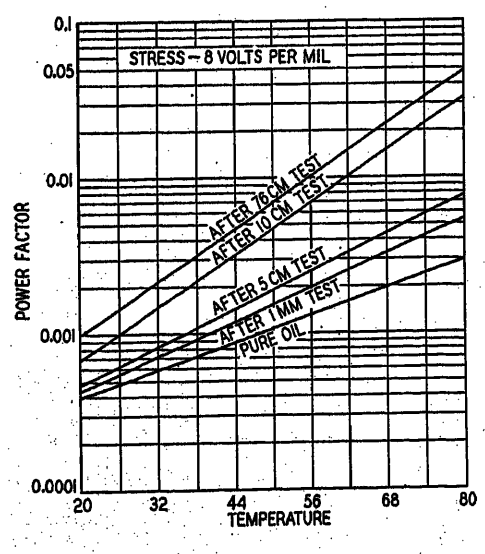




**Figure 28. Power factor-voltage**

rise of power factor with temperature. At 80 degrees the power factor of the 76-centimeter sample is now eight times that of the one-millimeter sample. These variations strongly suggest that the *process* of oxidation itself, as well as the oxidation products, contribute to the measured value of power factor. In order to test this question a sample of oil was thoroughly purified and degassed; then saturated with oxygen at 76 centimeters pressure, and maintained at this pressure and at 80 degrees

centigrade for 65 hours in a glass vessel. It was then admitted to the test cell under the same conditions, and the power factor measured at intervals over a further 72 hours. The sample was then evacuated down to 0.2 millimeter of mercury pressure, thus drawing off the oxygen and volatile oxidation products. Power factor observations were continued over a further 55 hours.

The results are shown in figure 31. Initially, the pure oil had a power factor 0.003 at 80 degrees; saturated with oxygen at 76 centimeters pressure, after 65 hours at 80 degrees centigrade in a glass vessel, the value rises to 0.01. At this value it was introduced into the power factor test cell. As seen from the curve a very much more rapid increase of power factor sets in. This is due to the catalytic action of the brass electrodes. The initial rate of rise is not maintained, however, and the power factor-time curve seems to be approaching a constant value. At 72 hours oxygen and volatile products were removed; the power factor dropped rapidly and within a short time reached a steady value about 25 per cent lower.

Evidently oxidation in the oil causes 2 types of power factor increase, one a permanent change due to nonvolatile products, as indicated in the final steady value of figure 31, and the other due to ions liberated in the process of oxidation, or to an ionized condition of the volatile oxidation products. This second source of ions disappears in the absence of free oxygen. It is known that oxidation may be accelerated by electrochemical processes,[27] indicating that the ions involved in oxidation reactions are associated with the conduction current. Apparently we have something of this kind here.

Power factor-voltage curves taken before and after the oxygen is removed indicate that both elements of power factor increase with increasing stress. Apparently

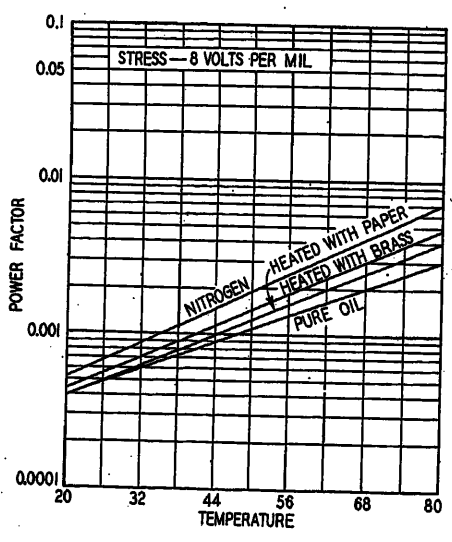



**Figure 30. Power factor - temperature**

the volatile active oxidation ions move faster, or cause more ionization by collision, as the stress increases. The rise of power factor due to the nonvolatile ions has been discussed in an earlier paragraph.

*Catalytic Action of Brass.* The catalytic action of certain metals in accelerating oxidation in oils is well known[27,28,29] though few quantitative studies have been reported. Copper and brass are among the most active metals, and consequently the problem of restricting oxidation in insulating oils is not only that of selecting oils inherently most highly stable against oxidation, but of

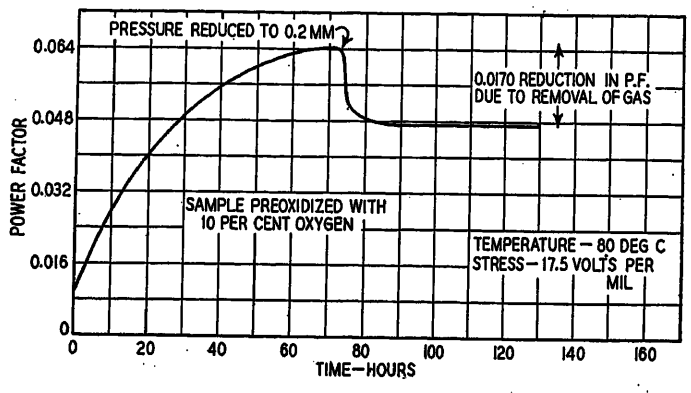



**Figure 31. Power factor-time**

basing this selection on the behavior in the presence of copper. For the contact of insulating oil with copper conductor, or other metal is unavoidable.

In the present work all electrical measurements have utilized brass electrodes. The resulting accelerating influence on oxidation has been evident at several points; for example, the more rapid rise of power factor-temperature curves of the samples containing more oxygen, figure 18. (Note however the apparent absence of the effect at low oxygen content.) In order to obtain evidence of the relative importance of the effect, oxygen absorption tests were run on 2 identical samples of oil, one containing 65 square centimeters of clean sheet brass. Each 1,000-cubic-centimeter sample of degassed oil was placed in a 2,000-cubic-centimeter glass suction flask exposing a surface arc of about 108 square centimeters of oil. The pressure was reduced to 0.1 millimeter, temperature raised to 80 degrees, and dry oxygen admitted at 76 centimeters of mercury pressure; the oxygen was maintained at this pressure and the amount entering each flask was measured at intervals. This amount is a measure of the oxygen entering into chemical combination. The results are shown in figure 32. The rate of absorption in both cases is at first quite rapid, and this probably represents solubility rather than oxidation. There is also some suggestion of an induction period, or delay in the final process, between 30 and 60 hours. The period beyond 150 hours probably best represents the relative rates of oxidation. As seen it appears that the oil alone is approaching a stationary or saturated condition with no further oxidation. The sample containing brass, however, is still absorbing oxygen rapidly indicating continuous auto-catalytic oxidation.

The general trend of the power factor-time curves of paper impregnated at high oxygen content, is much the same as the upper curve of figure 32. Other results, for example the higher power factors of paper layers next the electrodes, also indicate the powerful influence of the

brass electrodes, in the presence of appreciable amounts of oxygen, on the rates of oxidation, and consequent changes in electrical properties. The results throughout therefore involve not only oil oxidation, but especially oil oxidation in the presence of a metal catalyzer. This, however, is essentially the condition prevailing in practice. The separate influence of the oil alone is evident in several studies, but in view of the above facts, becomes of lesser interest for the practical problem. Further studies of autocatalytic action will be essential for complete understanding and control of oxidation deterioration in insulating oils.

## Conclusions

Accelerated oxidation tests have been made on an insulating oil, with oxygen introduced over the range 0.013 to 10.4 per cent, by volume. Similar tests were made on wood pulp paper impregnated with the oils with oxygen content maintained. The outstanding conclusion

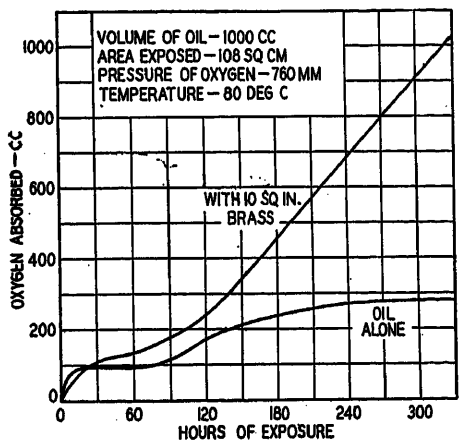



**Figure 32. Oxygen absorption-time showing the catalytic effect of brass**

of the work is the relative unimportance (over the duration of the tests—200 hours at 80 degrees centigrade), of small amounts of oxygen as a cause of change of electrical properties.

1. At impregnating pressures up to 5 centimeters of oxygen (0.7 per cent volume content) the electrical properties of impregnated paper show little or no instability due to oxygen content.

2. Power factor values and changes found in specimens impregnated in oxygen at one millimeter pressure, are completely accounted for by changes in the oil due to contact with paper and with metal electrodes in practically complete absence of oxygen.

3. Impregnation in oxygen at one millimeter pressure results in better characteristics than impregnation in air at the same pressure apparently due to the greater solubility of oxygen than of nitrogen.

4. A critical range of impregnation pressure is found between 5 centimeters and 10 centimeters (0.7 to 1.5 per cent volume content of oxygen). Power factor values increase rapidly with oxygen content, and also with time. Beyond 10 centimeters the rate of these changes falls off; at 76 centimeters a saturation condition represented by constant high values is indicated.

5. The *process* of oxidation in oil is a source of increased liquid or gaseous ionization, and of consequent increased dielectric loss in both oil and impregnated paper. Withdrawal of oxygen and volatile products causes large and immediate reduction of power factor.

6. Rising power factor voltage curves are found for all oil and impregnated specimens at 80 degrees. The rise is more rapid in specimens in which oxidation is in progress than those from which all gas has been withdrawn after oxidation. All such curves are flat up to 150 volts per mil at 25 degrees centigrade.

7. The change of power factor with temperature above 30 degrees centigrade is the most sensitive indicator of oxidation—better, for example, than the power factor-voltage relation.

8. Oxidation and deterioration of the oil is greatly accelerated by the catalytic action of brass. The behavior of impregnated specimens may be largely influenced by this effect.

9. Power factor tests of paper layers following oxidation runs show no increase in layers next the electrodes in the one-millimeter specimens, a very slight rise for the 5-centimeter specimens, and a definite rise above average values only for oxygen contents above 0.7 per cent by volume (5 centimeters pressure of oxygen impregnation).

10. The evidence of these tests is that the continued process of oxidation rather than the products of oxidation is the cause of oil and paper deterioration. Small amounts of oxygen either combine or go into solution without serious impairment of electrical properties.

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# Discussions

## Of AIEE Papers—as Recommended for Publication by Technical Committees

ON THIS and the following 13 pages appear discussions submitted for publication, and approved by the technical committees, on papers presented at the 1937 summer convention, Milwaukee, Wis., June 21–25; the Pacific Coast convention, Spokane, Wash., August 30– September 3, 1937; and the North Eastern District meeting, Buffalo, N. Y., May 5–7, 1937. Authors' closures, where they have been submitted, will be found at the end of the discussion on their respective papers.

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## The Saturated Synchronous Machine

**Discussion of a paper by B. L. Robertson, T. A. Rogers, and C. F. Dalziel published in the July 1937 issue, pages 858–63, and presented for oral discussion at the electrical machinery session of the Pacific Coast convention, Spokane, Wash., September 2, 1937.**

**R. H. Park** (The Calco Chemical Company, Inc., Bound Brook, N. J.): The following analysis of saturation phenomena which was worked out by the writer a year or so ago in an effort to develop a simplified yet adequate theory of saturation effects in salient-pole synchronous machines is submitted as discussion of Messrs. Robertson, Rogers, and Dalziel's paper with the thought that they or others may care to check experimentally the theoretical developments presented.

It should be unnecessary to point out that any useful theory must represent a good compromise between precision and convenience, and with this thought in mind it is believed that we are warranted in considering the usefulness of the assumption that the field pole tips and faces of salient-pole machines may be regarded, for purposes of calculation as not being subject to saturation effects, despite the fact that we recognize the fact that in many cases pole-tip saturation effects do exist to an at least appreciable extent.

With this assumption which will be utilized in what follows, and the further rather implied assumption that there is no significant saturation in the quadrature axis, we note that whatever the field below the pole faces there will be a definite magnetic potential between adjacent pole faces and that the magnetic field in the air gap will be the same as it would be if the rotor were unsaturated and the field current had some appropriate value say $I$ different from its actual value with saturation which we will designate as $I_s$.

Now as to the effects of stator saturation we may note that these may be thought of as equivalent to introduction into an unsaturated stator of suitable counter magnetomotive forces arising where the stator flux density is a maximum and producing a resultant distortion of the stator and air-gap fluxes relative to what would otherwise obtain.

We shall at this point introduce the postulate that the effect of this counter magnetomotive force may be regarded with sufficient accuracy as being equivalent to the effect of an added space fundamental component of armature current say $i_{sc}$ where

$i_s$ = actual (space vector of) armature current

$i$ = equivalent unsaturated armature current
$= i_s + i_{sc}$

Thus we will have

$I_{sc}$ = saturation component of field current
$= I_s - I$ (1)

$i_{sc}$ = saturation component of armature current
$= i - i_s$ (2)

Evidently by virtue of our definitions of $I$ and $i$ they must specify the magnetic state of the air gap, and hence the torque, these being what would obtain with these currents and no saturation.

As a consequence of our postulates we note that $I_{sc}$ must depend wholly on the value of flux in the pole, hence only on $I$ and $i_d$, i.e., in general $I$ = funct $(I, i_d)$ where the function in question may be specified in terms of a series of zero-power-factor curves.

But also the fluxes emanating from the pole face and between the pole tips tend to be substantially linearly related to $I$ and $i_d$ while there will be a general tendency for the fluxes emanating below the pole tips to be proportional to $I$, and hence there will be a tendency for $I_{sc}$ to be exclusively a function of a linear function of $I$ and $i_d$, i.e., it will be approximately true that

$$I_{sc} = F(\Phi) \quad (3)$$

where

$\Phi$ = *effective per unit field flux*

$$= I - ki_d \quad (4)$$
$$= \psi_d + x_{fs}i_d$$

$k$ = a constant

$x_{fs} = x_d - k$
= *field saturation reactance*

As regards the saturation component of armature current, in a stationary armature machine this may be assumed to be associated and in space phase with a flux $\bar{\phi}$ which is intermediate in size and phase between the space fundamental armature flux linkages and the air gap flux $\psi + x_l i_s$ so that we may assume in general that

$$i_{sc} = f(\bar{\Phi}) \quad (5)$$

where

$\bar{\phi}$ = effective per unit armature flux
$= \bar{\psi} + x_{as}i_s$

$x_{as}$ = *armature saturation reactance* (6)

though for most practical purposes it is possible that we could assume $x_{as} = 0$ with little error.

Evidently the character of the functions $F$ and $f$ may be determined by tests respectively at high field, low terminal voltage, and low field high terminal voltage and the results so obtained utilized for computing excitation under any arbitrary head conditions.

Just as we recognize that $\bar{\phi}$ is nearly equal to $\bar{\psi}$ so we may readily recognize that $\Phi$ will be nearly equal to the field linkages $\bar{\Psi} = \psi_d + x_d'i_d$, so that it would be expected that $x_{fs}$ is approximately equal to $x_d'$. Actually $x_{fs}$ must exceed the *saturated* value of $x_d'$ at any value of $\Phi$ since if $i_d$ is varied so as to hold $\Psi$ constant it will be evident from a consideration of the detail flux conditions in the pole that $I_{sc}$ will increase as $I$ increases.

Since $x_d'$ is known to vary considerably with saturation the suggestion is clear that $x_{fs}$ may and in fact should be assumed, in general, to vary with saturation. That is, we may take $x_{fs}$ = funct $(\Phi)$, a procedure which at once increases the range of validity of equations 3 and 4. Obviously $x_{as}$ could also be treated as a function of saturation. However this would appear to be an unnecessary refinement.

Tests to determine the variation of $x_{fs}$ with saturation are easily carried out by simply comparing the no-load and full-load saturation curves, after making allowance for stator saturation, and we see, therefore, that to the extent that stator

saturation may be ignored $x_{fs}$ is in reality identical with Potier reactance. This demonstrates that in general Potier reactance must tend, except for the effect of stator saturation, to equal and in fact to exceed transient rather than leakage reactance a fact which seems to have frequently escaped recognition. On the other hand Potier reactance, as ordinarily defined, is not identical with $x_{fs}$ since it does not make allowance for stator saturation, a circumstance which is believed to account in the main for the very large variations with saturation at high values of armature voltage which were reported in a recent paper by March and Crary.

To show an application of the theory developed we may note that under ordinary load conditions it does not appear that armature saturation of revolving field synchronous machines is of great influence on stability, and that in any case, if we disregard armature saturation, the steady state coefficient of synchronizing torque $I_s = dT/d\delta$

where

$\delta$ = displacement angle

and

$$T = \text{per unit torque} = i_q\psi_d - i_d\psi_q = i_qI - (x_d - x_q)i_di_q \quad (7)$$

is

$$T_s = i_q\frac{dI}{d\delta} + \{I - (x_d - x_q)i_d\}\frac{di_q}{d\delta} - (x_d - x_q)i_q\frac{di_d}{d\delta} \quad (8)$$

But for a machine connected to an infinite bus of voltage $e$ (external impedance included in machine constants) there is

$$(r^2 + x_dx_q)i_d = x_q(I - e\cos\delta) - r\,e\sin\delta \quad (9)$$

$$(r^2 + x_dx_q)i_q = r(I - e\cos\delta) + x_de\sin\delta$$

while since $I_s$ is assumed constant

$$\frac{dI}{d\delta} = -\frac{dI_{sc}}{d\delta} = \left\{\frac{\partial I_{sc}}{\partial I}\frac{dI}{d\delta} + \frac{\partial I_{sc}}{\partial i_d}\frac{di_d}{d\delta}\right\} \quad (10)$$

$$= a\frac{di_d}{d\delta}$$

where

$$a = \frac{-\dfrac{\partial I_{sc}}{\partial i_d}}{1 + \dfrac{\partial I_{sc}}{\partial I}} \quad (11)$$

Then if we introduce the quantity

$x_{ds}$ = *saturated synchronous reactance* $= x_d - a$

we find after some transformations

$$\frac{di_d}{d\delta} = \frac{e(x)_q\sin\delta - r\cos\delta)}{r^2 + x_{ds}x_q} \quad (12)$$

$$\frac{di_q}{d\delta} = \frac{re\sin\delta - x_{ds}e\cos\delta}{r^2 + x_{ds}x_q}$$

results which in conjunction with (8) and (10) permit ready evaluation of $T_s$ for any value of $\delta$.

For $r = 0$, for example, we find in detail

$$T_s = \frac{Ie\cos\delta}{x_d} + \frac{x_d - x_q}{x_dx_q}e^2\cos 2\delta + \frac{x_d - x_{ds}}{x_dx_{ds}}e^2\sin^2\delta \quad (13)$$

only the first 2 terms of which are retained in the absence of saturation.

In the special case in which $x_{fs}$ is assumed constant we have from (3) and (4)

$$\frac{\partial I_{sc}}{\partial I} = F'(\Phi)$$

$$\frac{\partial I_{sc}}{\partial i_d} = -(x_d - x_{fs})F'(\Phi)$$

$$a = \frac{(x_d - x_{fs})F'(\Phi)}{1 + F'(\Phi)}$$

which as saturation is sufficiently increased approaches in the limit $a = x_d - x_{fs}$, corresponding to $x_{ds} = x_{fs}$.

## Surge Protection of Distribution Systems

**Discussion and authors' closure of a paper by J. K. Hodnette and L. R. Ludwig published in the June 1937 issue, pages 683–8, and presented for oral discussion at the lightning protective equipment session of the summer convention, Milwaukee, Wis., June 24, 1937.**

**Herman Halperin** (Commonwealth Edison Company, Chicago, Ill.): I presume that the upper of the 2 curves marked *C* in figure 2 is for deion gaps and the other curve is for arrester gaps. Do the characteristics in figure 2 hold substantially for all voltage ratings?

Over 90 per cent of our 4,000-volt overhead distribution system has solid interconnections between the neutral of the 3-kv arrester and the secondary neutral, which is grounded to water pipes on the customers' premises. As a safety measure, the transformer case is not grounded. Our experience is that about one-quarter of one per cent of the transformers fail annually due to lightning even with this interconnection. Most of these are in older transformers, but occasionally a modern one fails. This experience tends to create some doubt in our minds as to the possibility of obtaining a comparatively high degree of protection if protector tubes with initial discharge voltages of 9 times normal voltage were used in place of the arresters that discharge at much less than half those values, except as applied to specially designed transformers.

Referring to the authors' expectation that the maximum surge currents on distribution lines "would be of the same order as those obtained on high-voltage transmission lines," this is not confirmed by measurements of arrester discharge currents, using surge crest ammeters. We have installed surge-crest-ammeter links in the ground lead of 3-kv arresters at about 320 scattered locations over the city of Chicago. During the years 1934–36 the links indicated sizable arrester discharge currents in 121 cases. In most cases the currents were less than 1,000 amperes, in 44 cases the currents were between 1,000 and 5,000 amperes, and in 6 cases the currents were from 5,000 up to 9,000 amperes, the maximum value.

Referring to the third paragraph of page 685, a few recent measurements in Chicago have indicated roughly the same order of surge current through adjacent phase and neutral arresters, indicating that the lightning discharge current divides rather evenly through several arresters that may be installed at one location on a 3-phase overhead line or circuit.

The arrester manufacturers have found from laboratory tests that modern distribution arresters can withstand surge currents greatly above 5,000 amperes, and this is substantiated by operating experience. It is gratifying, however, to learn of the authors' development of a device that can withstand successfully surge currents of the order of 50,000 amperes.

**W. H. Cooney** (General Electric Company, Pittsfield, Mass): The authors have outlined in a very comprehensive manner the surge voltages and currents which may be expected on distribution circuits and their views as to the requirements which protective devices must meet in order to provide a good quality of service.

The time-voltage curves shown in figure 2 are very interesting. Although it is not definitely stated, it appears that curve *A* on the "breakdown characteristics of distribution transformer insulation" is on a "single shot" basis, since curve *B* shows the probable voltage levels at which deterioration of insulation begins with repeated impulses. At one microsecond curve *A* shows a breakdown strength about 27 per cent higher than at 2.5 microseconds, a greater increase of strength with decrease of time than that shown by Messrs. Bellaschi and Teague,[1] but of about the same order as that shown by V. M. Montsinger[2] in his discussion of the Bellaschi and Teague paper.

The probable voltage level at which deterioration begins is shown by the authors as curve *B*, which is 90 per cent of curve *A* for time greater than 2 microseconds. This may be compared with Montsinger's discussion[2] which showed a corresponding representative value of 80 per cent, with a variation from 70 to 90 per cent depending on the kinds of electrodes used in the tests. It should be noted that the authors' curve *B* at one microsecond has dropped to 83 per cent of curve *A*.

Considering all data at present available, it appears that a deterioration level of 90 per cent is somewhat optimistic and that the probable value lies nearer 80 per cent.

The authors refer again to a ratio of impulse crest to 60-cycle crest breakdown of 2.2. Montsinger[2] has shown that such a ratio may range between 1.75 to 2.2 (depending on the type of electrodes) for repeated impulses, a variation sufficient to indicate that the ratio is a band rather than a definite value. In addition, now that data have been presented showing an increase of transformer insulation impulse

strength below 2 microseconds, a so-called impulse ratio has even less significance.

It would appear from figure 3 and from Mr. H. M. Towne's comparison of previously published Deion gap data with the data in figure 2 and table 1, that the authors consider satisfactory a very small margin between the performance of the protective device and the demonstrated strength of the transformer. While protection can be demonstrated by an AIEE impulse test with a new transformer it is doubtful whether this initial margin will be adequate for the deterioration due to repeated impulses and other conditions of service. The authors show that at one microsecond (figure 2) the deterioration level is 83 per cent of the impulse breakdown strength.

While a properly maintained and protected transformer should retain its initial impulse strength indefinitely in service, past experience has indicated that deterioration may occur on some percentage of distribution transformers in service. Some operating companies have recognized this fact by applying to transformers taken out of service only about 65 to 75 per cent of the original factory high-potential test.

It is not generally considered economically feasible to give distribution transformers the degree of maintenance and inspection given to substation and power transformers. As a result, some portion of the transformers in service may have low oil levels, thus exposing parts which are dependent on oil for full insulation; water may enter even into sealed transformers due to failure to close covers tightly after opening for inspection, tap change, etc.; and excessive overloads may be carried to the point of carbonization of insulation. Any of these factors tend to lower the impulse strength of the transformer.

In order to avoid trading on the margin of strength above the demonstrated value it would seem essential to provide a wide margin between the demonstrated impulse strength of the transformer and the voltage levels permitted by the protective device, in view of the effect of repeated impulse voltage and the possibility of deterioration of impulse strength in service.

### References


1. Bellaschi and Teague, Dielectric Strength of Transformer Insulation, Electrical Engineering, January 1937.

2. V. M. Montsinger's discussion of (1), Electrical Engineering, April 1937.


**L. G. Smith** (Consolidated Gas, Electric Light, and Power Company of Baltimore, Baltimore, Md.): In reference to section 4 on normal frequeny requirements of lightning protectors, it is believed that the lightning arrester designer should give the operator applying lightning arresters accurate data based upon numerous tests of the actual cut-off of the arrester. While it is the practice of the manufacturers to rate arresters in terms of maximum 60-cycle voltage which can be applied to the arrester, this voltage rating is below the actual maximum cut-off voltage of the arrester by some margin of safety. Unfortunately the margin of safety assumed by the various designers is extremely variable. It is believed that this margin has gradually been reduced in recent years by most arrester manufacturers. For this reason it is quite important that operating engineers applying arresters have definite test data showing the actual maximum cut-off voltage of the arrester.

As an example of the need for this information, the operating company may have used arresters of a certain rating on their system for a number of years with satisfactory results and it may be that the particular arrester on which the operating results were obtained had a considerable margin between its rated voltage and the maximum cut-off voltage, which margin may have contributed to the satisfactory operation of the arrester. Based upon this operating experience arresters of another type having a reduced margin of safety may be installed and arrester failures result, due to inability of the arrester to cut-off. In view of the fact that the characteristics and possible overvoltages vary with different systems and are not consistent for various lines on a given system, it is quite essential that the operating engineers have complete information on arrester characteristics so that they can apply arresters intelligently.

**H. M. Towne** (General Electric Company, Pittsfield, Mass.): The authors have presented a very interesting paper on a vitally important subject. The adequate protection of distribution systems from lightning has been given quite thorough study over the past 10 years, and practical operating benefits from these studies have been pyramiding over several years.

The problem of protection of distribution transformers involves many important aspects. First, the protective scheme must be simple and economical. Second, the degree of protection should be liberal—allowing ample margin between the discharge level of the protective device and the impulse strength of the transformer insulation after years of service involving the usual influences of excessive overloads such as possible carbonization and release of water; poor oil, or other weakening of insulations; moisture; any of which may occur on a percentage of transformers in service. Third, this liberal margin of protection should be realized as far as possible under the rare cases of steep wave and high-current lightning discharges, without sacrificing too greatly in the protection level or other factors of security for the greatly predominant, year in and year out, nominal discharge duty. Fourth, the overvoltage protection should not interfere with conventional and recognized good practices in primary fusing and overcurrent protection. Fifth, the lightning protective device should function so as to minimize any hazard of primary power voltage and current on the secondary or consumer's circuit—i.e., afford the greatest possible preservation and protection to that transformer insulation which separates the low voltage consumer circuit from the dangerous high voltage primary circuit—and minimize the primary power voltage or current reaching the secondary circuit attending the discharge of the primary lightning protective device.

Considerable has been written about the desired level of protection to allow for various factors not always present in limited laboratory demonstrations. In the August 1929 *Electric Journal*, A. L. Atherton stated:

> "The criterion should be not merely that a complete failure is not brought about by a single application of surge voltage, but that no damage is done." "Tests have been made . . . using surge voltages covering a wide range of both magnitude and duration, using a variety of insulating materials and making literally millions of observations as a means of securing both limiting and average values to cover the variations which are inevitable in small insulation samples. The indications are that the damage to insulation begins at possibly 2.5 times the value which would be used at line voltage, taking into account the factors of safety normally used in apparatus design for 60-cycle strength. Service experience where there has been opportunity to observe the lightning damage for several years unprotected and then protected has shown that about 90 per cent of the lightning damage is removed by this arrester (3-kv maximum arrester for 2,400-volt circuits) having 3.5 ratio. The modified auto-valve arrester (also for 2,400-volt circuit protection) with a ratio of 2.5 instead of 3.5 . . . has been observed . . . after a few thousand arrester years service no case of apparatus damage has been recorded. . . . Service records have been made with average transformer installations, including both old and new; and with various relations between transformer rating and line insulation."

In the AIEE paper "Development of the New Auto-valve Arrester" presented in January 1930, the authors, Dr. Slepian, Tanberg, and Krause state:

> "Extended tests in the laboratory on insulation protected with arresters have indicated that there is probably no deterioration of insulation with arresters having ratios not exceeding 2.5."

In discussing lightning arresters in the February 1930 *Electric Journal*, Edward Beck states:

> "A good lightning arrester should have a ratio of not more than 4 to 1." . . . "In the new autovalve arrester, ratios of 2.5 and less are secured. . . ."

Again, in the May 1930 *Electric Journal*, Dr. Fortescue discusses the general problem of protection and states:

> "Years of experience with . . . protective ratio between 3 and 3.5 have proved that approximately 90 per cent of the lightning troubles . . . are removed. . . . Several thousand arrester years of field experience with arresters employing a protective ratio of 2.5 has not brought to light any failures of apparatus thus protected. This experience very strongly substantiates the conclusion . . . that the protective ratio of 2.5 is the ideal. . . . It is generally

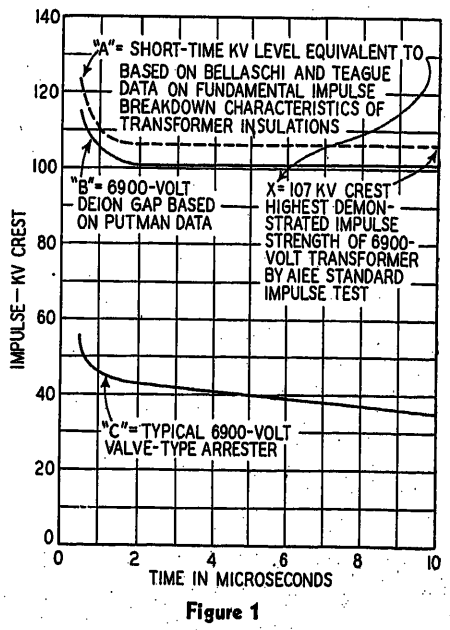



**Figure 1**

accepted that fibrous insulation—which constitutes a large part of the insulation of the transformer—will in course of time deteriorate when subjected to surges above 2.5 times the rating repeatedly. If the surges do not rise above this value, the life of the transformer is indefinitely long."

In view of what was apparently a very extensive study of the fundamental behavior of apparatus insulations in general, in both laboratory and field, as evidenced by these fairly recent articles advocating not more than 2.5 to 1 ratio, it is somewhat difficult to reconcile the present statement by Messrs. Hodnette and Ludwig that "a high degree of protection is obtained with a ratio of protective device discharge to normal frequency voltage of 9 to 1." To avoid trading on the factor of safety above the AIEE demonstrated test strength and also to allow for insulation deterioration which may occur over years of service due to the causes previously cited, it would seem that a much better degree of protection than 9 to 1 is highly desirable.

The authors' curves, figure 2, do not permit a clear understanding of the co-ordination and margin of protection. As pointed out by the authors, knowledge of the insulation strength of transformers to impulse voltages is necessary to intelligently co-ordinate and successfully apply protective devices. Since the curves are all to a percentage ordinate, it is difficult to gain the relationships on a kilovolt basis, utilizing the known demonstrated strength of the transformer insulations. One approach to the co-ordination picture is to start out with the demonstrated impulse test voltage, which is all the purchaser of a transformer knows about its lightning strength. As shown in the authors' table I, a purchaser knows that a 6,900-volt distribution transformer will withstand the 107-kv crest maximum test voltage of the AIEE standard impulse test for the $1^1/_2 \times 40$ full-wave condition. From this 107-kv full-wave test plotted at 6 or 10 microseconds, a curve for the short-time kilovolt strength of the transformer can be plotted using recently published data on the fundamental impulse characteristics of combined solid and liquid transformer insulations.

Messrs. Bellaschi and Teague have discussed the short-time impulse breakdown strength of transformer insulations in their AIEE paper "Dielectric Strength of Transformer Insulation" published in the January 1937 ELECTRICAL ENGINEERING. Their comprehensive investigation shows that the impulse breakdown strength of combined solid and liquid transformer insulation is but little, if any, higher for one-half microsecond to breakdown than at the full $1^1/_2 \times 40$ wave. They show average of tests to breakdowns on test samples, of 300 kv at 0.35 microsecond; 300 kv at 2.5 microseconds; and 280 kv at full 40 microseconds, and they state "these tests for a large number of repeated impulses confirm the constant strength over the impulse region even down to the very short times as previously established." Their curves, figures 6 (for insulation breaking down at around 140-kv crest), and 7 (for insulation breaking down at around 220-kv crest), show that the impulse breakdown is flat from 10,000 microseconds down to about 1 or 2 microseconds and then turns up slightly with the breakdown at 0.5 microsecond being only 12 to 16 per cent higher kilovolt value than for the full $1^1/_2 \times 40$ wave strength. Applying these fundamental data by Bellaschi and Teague to the known 107-kv test, the accompanying curve *A*, figure 1 is obtained, and such a curve should represent the lightning strength for all waves and equivalent to the 107 kv highest demonstrated test on AIEE full $1^1/_2 \times 40$ wave. Whatever margin of safety exists between the 107-kv full-wave test and actual breakdown could logically be expected to exist for the short time equivalent portion of the curve. Such a procedure results in an impulse level below which lightning stresses should be limited to avoid encroaching or trading on the factor of safety above the known demonstrated strength of the transformer.

While Messrs. Hodnette and Ludwig do not give an actual impulse volt-time breakdown curve for the deion protector, such curves were given by Mr. Putman in the February 1937 *Electric Journal*. By adding Mr. Putman's data for the discharge level of the 6,900-volt deion protector as curve *B* to the accompanying figure 1, it appears that the margin of protection to the insulation of a new 6,900-volt transformer is relatively small—unless the factor of safety in transformer insulation above its required AIEE demonstrated strength is quite wholly depended upon.

The authors show in their figure 2 that insulation deterioration from repeated impulses alone begins at about 90 per cent of the $1^1/_2 \times 40$ full wave strength, and they state that this factor is applicable to the figures in table I. Since table I highest test level of a 6,900-volt transformer is 107 kv, the limit above which repeated impulse stresses might cause deterioration is 90 per cent of 107 or 96 kv. It would, therefore, appear that the 102-kv discharge level (Putman's data) of the 6,900-volt deion gap would result in deteriorating stresses.

In discussing the deion gap the authors state that a series resistor, is used to limit the magnitude of the large power follow current, but no data are given regarding the ohmic value. Apparently the protection level of the device involves first the impulse breakdown voltage of the gap (Curve *B* of the accompanying figure 1) and then an *IR* voltage drop due to the discharge current through the series resistor. In evaluating the impulse protection level it is of course necessary to consider this *IR* drop which will exist as long as discharge current flows, which may be many microseconds. For instance, if the series resistance is 5 ohms, an *IR* drop of 100 kv will occur with a 20,000-ampere discharge current. A one ohm resistor would allow an *IR* drop of 50 kv at 50,000-ampere discharge current. On the other hand a one ohm resistor would seemingly be far too low to cause any appreciable reduction in the large power-follow current. Assuming a location of the transformer at a point on the feeder or branch circuit having a line to ground short-circuit current of 1,500 amperes root-mean-square, the line impedance would be 6,900/1,500, or 4.5 ohms, and a one-ohm resistor would only reduce the line to ground short-circuit power follow current through the deion gap from the 1,500 to 1,240 amperes root-mean-square. Similarly, if the transformer were located closer to the substation where a 3,000-ampere short-circuit current is available, a one-ohm resistor would only reduce the short-circuit power-follow current from 3,000 amperes down to 2,100 amperes root-mean-square. Any 6,900-volt sectionalizing fuse link up to 40-ampere rating will be melted in $^1/_2$ cycle at approximately 800 amperes root-mean-square. Then, assuming as low as 1,500 amperes available line short-circuit current, it would appear that the series resistor would have to be at least 4.5 ohms to avoid blowing a 40-ampere sectionalizing fuse or 18.5 ohms to avoid blowing a 15-ampere sectionalizing fuse. The authors may be willing to state the ohmic value of the series resistor and clarify its effects.

The curve *C* of figure 1 shows the discharge level and margin of protection which may be had with a typical 6,900-volt valve-type arrester applied with interconnection.

Such a margin of protection avoids dependence on the undemonstrated factor of safety and also allows for the possible service conditions and abuses which over years of operation may depreciate the transformer-insulation below its demonstrable strength by AIEE test when new.

The authors have cited considerable information on discharge current requirements of protective devices. Probably the most significant data on the required discharge capabilities of distribution system protective devices is the direct measurement of actual lightning current magnitude through individual distribution arresters on distribution systems of various voltage classes, by Mr. H. W. Collins, and also Mr. McEachron and Mr. McMorris. Out of 500 measurements, Collins found 20,000 amperes to be the highest discharge current. McEachron and McMorris data over more than 2 years, involving about 2,800 arrester-years of observation and about 1,000 measured discharges, shows only 2 discharges of 50,000 amperes, or 0.2 per cent. This means one 50,000 ampere discharge out of 1,400 arrester years, and a probability of a single arrester receiving 50,000 amperes discharge once in 1,400 years. 99.8 per cent of the measurements were below 22,000 amperes, and about 97 per cent were under 10,000 amperes. These data show that arresters with discharge capabilities of even 25,000 amperes will give highly satisfactory service performance, and that the authors' contention that 50,000 amperes discharge capacity will give satisfactory results is quite conservative. It is particularly significant that the highest measured discharge current has been proved to be well within the capabilities of available valve-type arresters such as the Pellet type; that is, modern arresters are withstanding the current magnitudes, current durations, the steep wave fronts, the multiple or repetitive stroke, the switching surges, etc., and giving protection to very old as well as new transformers.

While some types of earlier arresters gave some troubles from moisture, corrosion, etc., the modern arresters over the past 4 or 5 years are demonstrating an extremely low mortality rate from all causes.

The valve-type arresters, of course, discharge the short time lightning currents and at the same time prevent any dangerous primary power follow current from reaching the transformer tank and low voltage secondary service.

The authors' paper is a definite contri-

bution to the subject of transformer protection. It is obviously desirable that continued and concerted efforts be directed by the large manufacturers, as well as utilities, toward attaining a complete understanding of lightning protection requirements for virtually complete protection of distribution systems.

**C. S. Sprague** (Purdue University, Lafayette, Ind.): The authors have presented an interesting summary of the range of lightning exposures and of the characteristics of transformer insulation and of protective equipment under 60-cycle and impulse stresses.

Curve *D* of figure 2 brings out the inadequacy of the rod gap in protecting transformer insulation in the range from 6,800 to 13,800 volts. Apparently at still higher voltages the gap would be almost worthless for short-time impulses unless set at a considerably reduced spacing.

In figure 3 the comparison between Deion gaps and valve-type arresters does not seem to be applicable unless interconnection is used with the valve-type arresters. If interconnection is not used the effect of lead and ground impedance would be to materially raise the upper limits of the band between the 2 curves *D*. Although the lightning arrester with interconnection, provides a considerably lower impulse voltage than the deion gap, it should be kept in mind that the duration of the wave is considerably longer with the valve-type arrester.

At first glance it seems from figure 3, that the valve-type lightning arrester may provide relatively greater protection, in spite of the authors' closing statement that both types provide adequate protection as demonstrated by field records. This is particularly noticeable in the 11,500 volt and the 13,800 volt range where the deion gap impulse break-down voltage (curve *E*) is quite close to the minimum impulse strength (curve *C*). By reference to curves *A* and *B* of the authors' figure 2, it would appear that the voltage permitted by the deion gap is dangerously close to the value which will produce deterioration of the insulation. Perhaps the short duration of the voltage will account for the adequacy of protection claimed for the deion gap.

**J. K. Hodnette** and **L. R. Ludwig**: Complete protection of distribution system and the apparatus connected to them is the aim and object of distribution engineers. The manufacturer contributes to this program by continually improving distribution transformers and protective equipment, and by the accumulation of data on surge protection. It was the object of this paper to present data to enable a more intelligent use and application of distribution equipment toward this end. Data has been presented on transformer insulation and lightning arrester requirements so that operating engineers could get a broader picture of this important problem.

It has been pointed out in the paper that it is necessary to provide protection under the worst conditions which result from direct, or near direct, strokes of lightning rather than the average condition. In the past, much of the data on protective devices and distribution system protection have been obtained by field trials in the large metropolitan distribution systems. With the rapid expansion of distribution systems in rural areas these data are proving inadequate. As was pointed out by Mr. F. E. Andrews, currents much in excess of those formerly expected appear on distribution systems relatively often as evidenced by damage to cutouts, insulators, and other equipment. In most cases evidence of direct strokes on distribution systems is centered about apparatus damage. This emphasizes the fact that it is the conditions of direct strokes, or near direct strokes, to the line rather than induced surges which result in the major damage to distribution systems. It is imperative, therefore, that the protective equipment be designed for the worst conditions. Field experience has indicated that it is necessary to have a discharge capacity of 100,000 amperes to prevent damage from lightning.

Figure 2 of the paper presents data on the impulse characteristics of distribution transformer insulation as compared to characteristics of protective devices. In view of the large amount of discussion on this subject further explanation of this figure is given. The data, from which curve *A* representing the breakdown characteristics of distribution transformer insulation was drawn, were determined by tests on actual distribution transformers and supplemented by tests with models. In comparing this curve with previously prepared data, it should be noted that the time lag is plotted from the start of the voltage wave instead of the time lag above the 60-cycle breakdown value which has been the conventional method in the past. This curve was derived by applying impulse voltages and increasing them in steps until the transformer insulation failed. In this respect it is not a one-shot breakdown curve. Curve *B* was determined by applying impulse voltages slightly under the minimum strength and observing the effects. It is quite difficult to accurately establish values at short time lags due to the fact that the testing technique for testing short waves has not been completely developed. Also the variation in individual samples may be misleading. Much data is necessary in order to completely establish a curve of this nature. Points that were determined were established by applying short steep-front waves to distribution transformers and chopping them by a gap flashover. Repetition of this process established points below which the insulation would not fail.

With reference to the ratio between the impulse breakdown voltage, and the 60-cycle breakdown voltage, the ratio of 2.2 applies to a well balanced insulation structure. This value is generally applied to the ratio between the 60-cycle breakdown strength and the minimum impulse breakdown strength. This ratio does not hold for all insulation structures but depends upon the type of insulation and the electrodes used. Values considerably lower and higher than 2.2 have been found on special insulation structures. The data in the paper, however, applies to distribution transformers.

Insulation deterioration under impulse voltages appears to be associated with the formation of corona. Where the design is such as to eliminate or minimize the formation of corona, deterioration does not occur, or the voltage at which it does occur approximately coincides with the breakdown voltage. Corona under oil occurs at relatively high voltage stresses. The minimum voltage required to produce corona is in general in excess of the operating and test voltages applied to distribution transformers as covered in the paper. For this reason deterioration of the insulation of distribution transformers by impulse voltages takes place very near the ultimate breakdown level. In this connection the tests made by Messrs. Bellaschi and Teague, referred to by Messrs. Towne and Cooney, were made on insulation structures for power transformers and under conditions which would permit the formation of corona. In this respect distribution transformers are in a class by themselves, and the laws applying to the insulation of high-voltage power transformers do not necessarily apply to distribution transformers, due to the discontinuous nature of insulation curves at short spacings.

There is a decided difference in opinion among engineers regarding the deterioration of insulation of distribution transformers in service. Mr. Cooney states that a properly maintained and protected transformer should retain its initial impulse strength indefinitely in service. We agree with this statement. Past experience, however, has indicated that the mortality rate of old transformers is higher than those that have been in service a few years. This has been due largely to the deterioration of bushings and cables. Previously it was common practice to depend upon the cable insulation to a large extent in insulating the primary leads from the transformer case. Exposure to weather reduced this insulation so that failure of the bushings resulted at a much lower value. The coils, however, being submerged in transformer oil and protected from moisture and oxygen deteriorated very little. Also, these transformers were so designed and protected that no protection was afforded the secondary windings against overvoltage surges. Modern transformers are built with bushings of adequate size so that it is not necessary to depend upon the cable lead insulation, and balanced protection now prevents damage to the high-voltage as well as the low-voltage windings.

Moisture in oil has often been referred to as the cause of deterioration of distribution transformer insulation. A large percentage of the distribution transformers in service at the present time are operating with water in the bottom of the transformer cases. Modern distribution transformers are made tight which prevents the entrance of water and helps to protect the oil from excessive oxidation.

Excessive overloads have been referred to as the cause of insulation deterioration and ultimate failure. The deterioration strength of transformer insulation does not materially decrease until the temperature is reached which produces a chemical change in the insulation. This is usually evidenced by formation of gases. Sustained temperatures lower than this result in loss of mechanical strength but no rapid deterioration of the insulation. Thermal protective devices are available for use in dis-

tribution transformers which will eliminate the possibility of damage from this source. These devices, in the form of thermally operated circuit breakers, are placed in distribution transformers and adjusted so as to disconnect the transformer when the winding reaches a predetermined safe temperature.

It is apparent, therefore, that a great deal has been done in the design and construction of modern distribution transformers to prevent deterioration of any of the vital insulation members even after many years of service.

Until recent years, the accepted method of protecting distribution transformers against lightning was to connect lightning arresters to the primary leads and ground them to separately driven grounds. As pointed out by Mr. Sprague, the voltage to which the transformer was subjected was not only the discharge voltage of the arrester but the drop in the ground leads and in the ground resistance. Instead of limiting the voltage to 10 or 15 kv on a 2,400-volt transformer, it rose to 100,000 or 200,000 volts or more, depending on the grounding conditions and nature of the surges. Experiments have indicated the possibility of developing as high as 10,000 volts per linear foot in lightning arrester leads.

This represented the conditions in 1929 and 1930, when the 4 papers were written which were cited by Mr. Towne. These papers indicated the ratio of 2.5 as being ideal, and above which deterioration began. In this connection it is interesting to note that the first attempt to rationalize transformer insulation from the standpoint of surge voltages was made by Vogel in 1932 ("Factors Influencing the Insulation Coordination of Transformers," AIEE TRANSACTIONS, volume 52, June 1932, page 411). Past experience with arresters having a ratio of 3.5 had reduced lightning troubles by 90 per cent. It is apparent that under the existing conditions it was only necessary to get more experience to determine that the ratio of 2.5 reduced the troubles due to lightning by only 90 per cent. The uncontrolled factors were the dominating ones in 10 per cent of the cases. In other words, lightning arresters protected against small induced surges but offered no protection against direct or near direct strokes. The introduction of balanced protection eliminated the uncertain factors of lead drop and ground resistance drop, and reduced the problem of lightning protection to a scientific basis. We are still confronted, however, with the problem of protecting apparatus against maximum conditions of surge voltages which have always been the cause of apparatus damage and system outages. This can be accomplished with protective devices, connected to give 3-point protection and having adequate surge current discharge capacity, which limit the voltage to a value below the breakdown strength of the insulation under all conditions. The curves in figure 3, assume this balance protection and show that the margin between the insulation strength and discharge voltage is satisfactory. Laboratory tests under direct stroke conditions prove this fact ("Direct Stroke Protection of Distribution Transformers," by H. V. Putman, *Electric Journal*, February 1937). Field experience confirms it.

It is difficult to compare a conventional valve type arrester with the deion arrester since they have such widely different characteristics. The deion arrester is essentially an arc-discharge device which bypasses the surge current. The lightning arrester on the other hand, is an energy absorbing device depending on the energy to establish the cut-off voltage. Some lightning arresters have a resistance discharge characteristic so that the discharge voltage increases with increasing current. It is not possible to determine the maximum voltage which would be sustained from the characteristics as determined by the relatively low AIEE test. The deion arrester, since it is an arc-discharge device, has a very low sustained voltage. It is equipped with a series resistor to prevent system disturbances in the cases when there is a flow of dynamic current following flashover. This resistor adds little to the sustained voltage under abnormal conditions since it is provided with a shunt gap which flashes over at high surge currents removing it from the path of the surge current. Under these conditions the deionizing action set up by the surge current appeases the establishment of any dynamic follow current. These devices are insulated to withstand and receive the AIEE acceptance dielectric tests for distribution transformers.

Mr. Towne has aptly stated that practical operating benefits have been pyramided over several years, as a result of a thorough study of the protection of distribution systems from lightning. It is believed that additional benefits can be derived by applying the knowledge so far gained on transformer insulation and the frequency and intensity of lightning stroke currents. We should not compromise on this problem but strive to protect apparatus against the maximum conditions to which it is subjected. As a protective ratio of 2.5 to 3.5 was considered adequate in the past when we had to deal with the uncertainty of lead and ground resistance drops, it would seem only logical that a higher ratio would be satisfactory with these uncertainties removed. This can be done without danger of apparatus failure, and would result in better system protection, better protection to the consumer through a more adequately insulated and a more rugged and serviceable protective device.

## Distribution Lightning Arrester Performance Data

**Discussion and closure of a paper prepared by the lightning arrester subcommittee of the AIEE committee on protective devices published in the May 1937 issue, pages 576–7, and presented for oral discussion at the lightning protective equipment session of the summer convention, Milwaukee, Wis., June 24, 1937.**

**Herman Halperin** (Commonwealth Edison Company, Chicago, Ill.): The lightning arrester subcommittee also has prepared a general guide for use by utilities in testing lightning arresters. In this connection, the data on new arresters in the June 1937 ELECTRICAL ENGINEERING will be found helpful. The guide should be of particular value in testing line-type arresters rated at 15 kv and less which are removed from lines.

For the past 4 years, we have been testing used 3-kv arresters in Chicago before they are returned to stock for reuse. About 85 per cent of those that were mechanically satisfactory have been found electrically suitable for additional service. These tests have all been made with 60-cycle supply.

In connection with the guide, it is hoped that some utilities will make impulse as well as 60-cycle tests in order to determine what correlation exists between the 2 types of tests in indicating defects.

**L. G. Smith** (Consolidated Gas, Electric Light, and Power Company of Baltimore, Baltimore, Md.): These data are of value and necessary in applying arresters intelligently. However, it is hoped that these data will be expanded in the future so as to cover additional lightning arrester characteristics so essential for the correct application of arresters. In view of the fact that solid insulation is subject to a wide range of surges including those of very steep wave front and those of very high current it is highly desirable to know the voltage that will be passed by the arrester for all types of surges, including those of very steep wave front and for surge currents up to the point at which the arrester element flashes over. The ideal application of lightning arresters is one in which the arrester will always fail before the equipment protected, since the arrester represents a much smaller economic loss than for that which it protects.

**I. W. Gross** (American Gas and Electric Company, New York, N. Y.): In this report on distribution arrester characteristics, we have for the first time, to my knowledge, a rather complete over-all picture of the expected performance of present day commercial distribution arresters.

A study of the data in table I shows that in the distribution arrester class *variations* in terminal voltage, both on initial breakdown, and under discharge conditions, of the order of 30 per cent may be expected. This situation which, I take it, is due largely to manufacturing tolerances which it is not feasible to overcome economically, should be recognized in applying lightning arrester protection not only to transformers of present design but also to those now in service, if satisfactory results are to be expected.

There is one thing that should be pointed out in connection with the impulse voltage permitted by these distribution arresters, and that is, they permit some 30 to 70 per cent higher voltage across their terminals on breakdown than they allow during discharge at 1,500 amperes. And yet these voltages at breakdown are at a comparatively low rate of voltage rise, namely, 50 to 100 kv per microsecond as specified in the present AIEE standards. These same standards provide for rates of rise of some 1,000 kv per microsecond in the 115- to 138-kv class of arresters. It is hard to believe that natural lightning is so temperamental that it impresses voltages of 1,000 kv per microsecond on high-voltage lines and takes pity on the distribution systems in the 3-

to 9-kv class and reduces its destructive effects to a 50 or 100 kv per microsecond pattern.

In addition I wish to suggest that all lightning arrester manufacturers give data on their arresters on a common basis, that is, on the basis of average, maximum, or minimum voltage characteristics both for breakdown and *IR*-drop characteristics, with expected tolerances stated.

In closing, it is hoped the committee will continue its work in collecting and presenting authentic data of this type on arresters in the higher voltage classes in both the distribution and station types. Such information is decidedly helpful in applying protection to equipment with a reasonable degree of certainty that it will work in actual practice. It cannot be too strongly emphasized that such data are absolutely necessary in attempting to apply the lightning arrester as a protective device to a great deal of the equipment now in use, where such equipment has been weakened with age, or of older design not having the insulation strength of apparatus bought today.

**J. R. North:** Mr. Gross's constructive suggestions regarding desirable improvements in the Institute Standards for Lightning Arresters and test procedure are most welcome. Table I in the report shows a wide range between the minimum and maximum performance characteristics of different makes of arresters. The gap breakdown voltage is of the order of 130–150 per cent of the average *IR* drop, with rates of rise of 50–100 kv per microsecond.

The voltage rating of arresters represents the maximum allowable dynamic voltage across the arrester terminals under any conditions. As mentioned by Mr. Halperin, reports prepared by the lightning arrester subcommittee discussing testing procedure, application of arresters, and specific protection practices have been prepared and will be distributed to members of the protective devices committee and other interested parties.

It is hoped next year to be able to present a report containing similar performance data pertaining to station type arresters and to line type arresters rated above 15 kv.

## Expulsion Protective Gaps

**Discussion and authors' closure of a paper by W. J. Rudge, Jr., and E. J. Wade published in the May 1937 issue, pages 551–7, and presented for oral discussion at the lightning protective equipment session of the summer convention, Milwaukee, Wis., June 24, 1937.**

**E. J. Allen** (General Electric Company, Pittsfield, Mass.): The engineering data given in the paper sets forth the principal operating characteristics of expulsion gaps, based on 5 years' experience, and augmented by intensive development in the laboratory and field.

By way of explanation, the ordinate of the curves, on figure 10 in the paper, is plotted in terms of "'length of flame feet" which, of course, is visible, and was scaled from photographs of staged tests. These photographs were taken during power current interruption of corresponding crest currents shown on abscissa. This "length of flame" versus "current" interrupted relationship is practically independent of circuit voltage rating.

Also of equal interest, however, is the length of electrically conducting gases within the flame during power current interruption by the tube. The length of electrically conducting gases is an important consideration when applying expulsion protective gaps in service, to prevent these expelled gases from contacting other nearby metal parts of dissimilar potential, and thereby avoiding risk of faulting other phases. For example, conducting gases from the line end of an expulsion tube should not come in contact with nearby grounded metal structures; likewise the gases from a design having a grounded end of the tube should not come in contact with any line conductors, which of course, are insulated from ground.

However, the proximity of metal objects to the path of the discharge gases is not as serious a limitation to the successful service applications of expulsion protective gaps as might be anticipated. Tests have shown that the length of the electrically conducting gases extending from the open end of the tube during power current interruption never exceeds the length of flame. For example, during field tests on a 132-kv system, a grounded metal pipe was located 6 feet, 10 inches from the "tee" discharge deflectors located on the line end of the tube. With this set-up during power current interruption of 11,300 crest amperes by the expulsion gap, the arc did not follow the flame to ground. At distances of 6 feet or less, a power arc was maintained between the discharge deflector and grounded metal pipe. At 11,300 crest amperes power current interruption, however, the length of flame is approximately 9 feet. Hence in this particular series of tests, the length of the electrically conducting gases extended only two-thirds of the distance between the "tee" vent and the visible length of flame.

Typical tests such as described above indicate that the length of electrically conducting gases within the flame envelope attending power current interruption by the tube bears a complex relationship, as this depends not only on the current, but mainly on circuit voltage characteristics and design of the discharge deflectors.

It is believed, therefore, that the curve, figure 10 in the paper, can be safely used when applying expulsion protective gaps to obtain adequate clearance from electrically conducting discharge gases, thereby avoiding risk of faulting other phases. In practice, the expulsion tube can either be positioned in such a way as to provide necessary clearance of discharge gases using straight vents from the tube or if not, the path of the expelled arc flame can be diverted by means of "tee" (90 degrees) or Y (45 degrees) discharge deflectors attached to the lower electrode.

Another point mentioned in the paper concerns the rapid expulsion action of the tubes, and resultant power current interruption before system relays can function. The "First Report of Power System Stability" by the AIEE subcommittee on interconnection and stability (ELECTRICAL ENGINEERING, February 1937, page 261) recognizes that special tube-type protectors of a design described in the paper will increase the practical operating power limits.

System stability, or the ability of a system to stay together during a disturbance, is an important factor toward improving continuity of service. Line disturbances caused by lightning flashover of insulators with attendant load rejection will quite naturally tend to cause instability of transmission systems operating near the power limit. Even with ultrahigh-speed relaying and breakers on the faulted line, not equipped with protector tubes, the system is subjected to this disturbance for at least several cycles. Tests have shown that interruption of rated power current through an expulsion gap occurs within a cycle. Hence their net effect, by preventing flashover at the protected structures, is to reduce system outages and extend the stability limit, or power transmitting capacity of the system.

**R. L. Thomas** (Pennsylvania Water and Power Company, Baltimore, Md.): Too much emphasis cannot be placed on the statement made by the authors that proper mountings for expulsion gaps are absolutely vital. In a tabulation in the authors' paper there are statistics covering the operation of expulsion gaps on a 69-kv line of the Pennsylvania Water and Power Company in 1935 and 1936. Actually the statistics cover the line from Holtwood to Safe Harbor (Lehmans Farm switching station) owned by Pennsylvania Water and Power Company and the line from Safe Harbor to Lancaster (Engleside) which is owned by Pennsylvania Power and Light Company. The record for 1935 shows 4 tube failures and 16 trip-outs. A footnote states that "The cause for these failures has been determined and remedied."

Briefly, the remedies applied or changes made were first, the external gap was increased from 5 inches to 11 or 12 inches; second, a shielding ring was placed around the outside of each tube near the lower end; third, the horns were shortened; and fourth, an attachment was added to the mounting to prevent the turning of the tube mounting with respect to the insulator string and at the same time to allow the tube to swing with the insulator string.

There were no tube failures in 1936 and we thought the problem had been solved. However, on June 14, 1937 there was another tube failure. The circuit switches were reclosed 4 times but in each case there was another trip-out and the circuit was left out of service. It was several hours before the trouble could be located and remedied. It was found that on one of the tubes on a strain tower the fastening bolts had slipped in the slots provided for adjustment and that on this particular tube the horn had not been shortened sufficiently and the movement caused the horn to approach the conductor instead of increasing the external gap.

The failure shows the importance of carefully designed and ruggedly constructed mountings. Otherwise a device which is

intended to eliminate a large number of short time interruptions may actually cause a relatively long time interruption.

I do not want to introduce a note of discouragement since with any new device it is natural that all of the things that can happen cannot be foreseen. There were no tube failures in 1936 and naturally we hope that there will be no more in the future.

**L. G. Smith** (Consolidated Gas, Electric Light, and Power Company of Baltimore, Baltimore, Md.): The authors state as a requisite for the operation of these gaps that they have a lower flashover than the line insulation. While from a design standpoint this co-ordination is readily obtained, in actual installations care is necessary in that it is possible in the case of improper application to so distort the dielectric field that either co-ordination between the gap and the line insulation is destroyed or the co-ordination between internal and external flashover is lost. In tests it has been found that both of these are possible, namely, that external flashovers and insulation flashovers have resulted without an internal breakdown of the gap. The authors mention the possible use of these gaps on ungrounded neutral systems. Until more definite data are available on the ability of these gaps to clear the very low currents that would exist in the case of breakdown from phase to ground it is believed that such applications are questionable. In addition to this, should an arcing ground occur on one phase the voltage might rise to sufficiently high values on other phases to cause numerous tube flashovers.

The setting of the external gaps, particularly on lower-voltage tubes is quite important where the external gap is quite small. Our company, which has applied these tubes on 13.2-kv wood pole lines has had a few cases where expansion and contraction of the cross-arms due to alternate wetting and drying may account for as much as one-fourth inch change in dimension, thus causing the mountings to loosen and short the external gap. One case of tube failure attributed to this cause has actually been experienced. It is hoped that the possibility of trouble of this type has been eliminated by the change in the design of the mounting bracket, which includes 2 spurs which are forced into the crossarm. In addition to this some trouble has been experienced on strain poles where stranded line conductors were attached to the crossarm through strain insulators in which the the unwinding effect of the stranded conductor caused the strain insulators to rotate, moving the loop over the crossarm into the arcing rod, shorting the external gap. This trouble has been corrected by installing 2 pin-type insulators, one on each crossarm and relocating the tube so that the arcing rod points at the conductor between the pin type insulators, which carry the loop over the top of the crossarm.

While it is desirable to install expulsion protective gaps on every structure on high-voltage lines such a practice becomes quite expensive on low-voltage lines. If satisfactory operating results can be obtained a more economical installation would consist of installing these gaps on only a fraction of the total number of structures. In order to do this successfully it is necessary to have reasonably low ground resistance on those poles on which the gaps are installed and to maintain an insulation level as high as possible on those that do not have the gaps. As shown in table I in the paper we installed gaps on every second pole on one 2-circuit line and on every third pole on another line in 1935. In 1936 gaps were installed on another double circuit line on every fourth pole. No trip-outs due to lightning on any of these lines have been experienced. There was one trip-out due to tube failure resulting from shorting the external gap. There were 2 other cases of tube failure without trip-outs due to the shorting of the external gaps. In 1935 we installed a similar device of another manufacture on a single-circuit 13.2-kv line. In 2 years' operating experience no trip-outs due to lightning have occurred on this line. It is interesting to compare this operating experience with the operating experience prior to the installation of the gaps. On feeders number 87 and 88, the 3-year period prior to the installation of gaps in 1935, one feeder tripped out 5 times, 4 of which were due to burning down of the conductors and the other feeder tripped out 5 times, all 5 trip-outs, being due to conductor burn-downs. On feeders 60 and 61 which were equipped with gaps on every fourth pole in 1936, in the 4-year period prior to 1936, one circuit had 7 conductor burn-downs and the other circuit 5, all due to lightning. In the single-circuit lines, which were equipped with tubes of another manufacture in 1935, this line tripped out 3 times due to lightning in the 3-year period prior to 1935. We plan to install devices of this kind on another double-circuit line with the tubes installed on every sixth pole. In all of these installations we are raising the impulse level of the ungapped poles to 700 kv. We are attempting to determine the maximum spacing of devices of this kind for use on 13.2 kv consistent with a material reduction in trip-outs. Obviously the lower the cost per mile for such installations the more miles of line that can be equipped.

It is believed that if satisfactory weathering characteristics are obtained with devices of this kind they have a real future in increasing reliability of service.

**L. R. Ludwig** (Westinghouse Electric & Manufacturing Company, East Pittsburgh, Pa.): Messrs. Rudge and Wade presented in their paper a tabulation of operating companies who have utilized self-clearing protector tubes. The authors are correct in stating that the tubes have given very satisfactory results in the field. Attached is a list of further applications of these devices, which have been made during the past few years, also with satisfactory results.

The authors have stated that the problem of applying these protector devices is one of determining the short circuit currents and the recovery voltage. While it is relatively a simple matter to determine the short circuit current, the problem of determining the recovery rate is much more involved.

Mr. Evans and Mr. Montieth have made a very considerable contribution in this field by utilizing the calculating board in a novel manner for obtaining with the oscillograph an actual trace of the recovery voltage as it will occur on any given system.

Referring to the authors' figure 1, it is to be noted that the tube is of unsymmetrical design with respect to the electrodes. It would be expected that breakdown at the 2 polarities would be different on this account and the authors are requested to state if this is the case. Furthermore, since an inserted lower electrode has been omitted, it is conceivable that a certain amount of difficulty may be experienced with this design due to external flashover of the tube rather than internal flashover. It will be interesting to inquire if difficulties of this kind have been obtained.

**H. G. Brinton** (General Electric Company, Pittsfield, Mass.): In the case of oil circuit-breakers where the whole circuit is cut off, the value of capacitance may be quite small and the recovery rate very high but the device is capable of operating with very high recovery rates. On the other hand the safe operation of the expulsion gap calls for a less rapid recovery rate, but the recovery rates are lower because the circuit capacitance at interruption of the current is larger. Ordinarily the recovery rate on expulsion gaps is of the order of 100 to 300 volts per microsecond.

Figure 9 of the Rudge-Wade paper shows a sudden kick or rise in the arc voltage just before the arc broke, caused by a sudden increase of arc resistance. The arc voltage kicks up to about twice its previous value and the current drops to zero more rapidly. The voltage on the gap then reverses suddenly when the current comes to zero, be-

**Table I. Installations of Delon Protectors, Type L**

| Customer | Location | Voltage (Kv) | Quantity | Date |
|---|---|---|---|---|
| Amtorg Trading Company | Russia | 110 | 275 | 4/35 |
| Cleveland Electric Illuminating Company | Cleveland, Ohio | 34.5 | 244 | 5/33–10/35 |
| Consolidated Gas and Electric | Baltimore, Md. | 13.8 | 285 | 3/35 |
| Government of Puerto Rico (Water Resources) | Puerto Rico | 33 | 250 | 2/34 |
| Jersey Central Power and Light Company | Ashury Park, N. J. | 13.8 | 111 | 8/35 |
| Loop River Public Power District | Columbus, Nebr. | 34.5 | 426 | 10/36 |
| Management and Engineering Corporation | Dubuque, Ia. | 66 | 1,023 | 3/31 |
| Milwaukee Electric Railway and Light | Milwaukee, Wis. | 132 | 500 | 12/33 |
| Pennsylvania Power and Light Company | Allentown, Pa. | 69 | 385 | 3/35 |
| Peoples Power Company | Davenport, Ia. | 66 | 222 | 2/35 |
| Platte Valley Public Power and Irrigation District | Kearney, Neb. | 115 | 590 | 7/35 |
| Platte Valley Public Power and Irrigation District | Grand Island, Neb. | 115 | 360 | |
| Public Service Gas and Electric Company | Newark, N. J. | 33 | 850 | 1/34–2/35 |
| Southern Ohio Power Company | Chillicothe, Ohio | 69 | 150 | 2/36 |

cause the current was lagging and so the current and arc voltage were negative when the generated voltage was positive.

The voltage recovery rate in figure 9 is considerably steeper than that obtained in single gap line to ground operation where the current was smaller and more nearly in phase with the generated voltage. The more rapid recovery rates are usually associated with larger short circuit currents. It is an interesting characteristic of the expulsion gap that the larger currents and consequently greater evolution of exhaust gases enable it to clear with greater recovery voltages.

**W. J. Rudge, Jr., and E. J. Wade:** The discussions of our paper are particularly valuable in that they not only lay emphasis on the importance of many points mentioned in the paper, but add to the total operating experience which may be critically examined by those interested in the application of protector tubes.

Both Mr. Smith and Mr. Thomas have endorsed our statements as to the importance of properly mounting hardware for tubes. Mr. Smith's data on the comparative performance of feeders, both before and after they were equipped with tubes, is particularly helpful because it gives a better understanding of the improvement in line performance which can be obtained through their use. While from a theoretical point of view, tubes should be located on each structure to obtain best protection, Mr. Smith has shown that tubes located on every second, third, or fourth structure can effect a material improvement in line performance. This type of experience is needed by the industry, as it will enable an economic evaluation of the improvement in line performance which can be accomplished with different densities of installations. By employing such schemes it appears possible to effect a material improvement in line performance in a great many cases where economic considerations indicate that it is impractical to equip every structure.

Mr. Ludwig's discussion with the attached table is useful in that it gives an idea of the number of companies which are interested in the application of tubes. However, it is to be regretted that the data does not include the operating experience with the tubes, since tubes are comparatively new devices and it is necessary to build up a back log of experience which will be helpful in both the design and application of tubes.

The calculating-board methods described by Messrs. Evans and Monteith will no doubt be helpful in examining numerous circuit arrangements which cannot be easily obtained by field measurements. It must be realized, however, that before the calculating board results can be fully relied upon, that sufficient data from field tests on the actual circuits as they are in service must be obtained in order to establish the constants used on the calculating board. Experience in the past with models in the laboratory, particularly in the study of lightning, has shown that extreme care must be exercised when interrupting results obtained from studies on models rather than the full scale structures found in service. While we have made numerous calculations and studies of circuit recovery voltages, it is our feeling that greater confidence can be placed in the results by obtaining measurements on full scale models such as are found in service. It is for this reason that we have developed the equipment and pursued a program of making field tests to obtain this necessary fundamental information.

Mr. Ludwig has asked if the unsymmetrical design with respect to the tube electrodes caused by the omission of an inserted lower electrode is responsible for the external flashover of the tubes. Our tests to date have indicated that the insertion of a lower electrode alone does not carry with it the assurance that external flashovers will not obtain. It is truer, however, that the assembly and design do have an influence on the positive and negative impulse characteristics of the tube.

We wish to thank those who have taken part in the discussion of our paper and urge all operators who are obtaining experience with tubes to keep records on their performance so that they may be made available to the industry, as in this way a more complete picture may be had as to the relative merits of tubes and their ability to improve the performance of transmission circuits.

## Flashover Characteristics of Rod Gaps and Insulators

**Discussion of a report of the subcommittee on correlation of laboratory data of the EEI-NEMA joint committee on insulation coordination published in the June 1937 issue, pages 712–14, and presented for oral discussion at the lightning protective equipment session of the summer convention, Milwaukee, Wis., June 24, 1937.**

**C. S. Sprague** (Purdue University, Lafayette, Ind.): This report presents data which are evidently the result of a considerable amount of work by 5 of the larger high-voltage laboratories of the country. The calibration of such easily reproducible apparatus as the insulator string and the rod gap should be of considerable advantage in checking the satisfactory operation of equipment and testing technique. Even though the insulator string and rod gap are rapidly losing caste as protective devices due to their impulse characteristics at very short times and the data is subject to a tolerance of 8 per cent, this does not seriously affect its usefulness for the above purpose.

Tables I and II show some apparent minor inconsistencies. For instance in table I, for suspension insulators with the 1 × 5 wave, the negative wave values are higher than those for the positive wave over the range of 12 units shown. With the 1.5 × 40 wave, the negative values are lower up to 12 units, at which points the curves apparently cross, the negative values being higher from 13 to 20 units.

However in table II for the rod gap, with the 1 × 5 wave the negative values are considerably higher except in the range from 8 to 20 inches where the positive and negative values are essentially the same, but with one point at 15 inches showing the negative value to be lower. For the 1.5 × 40 wave the negative values are considerably higher over the whole range, which is in contrast to the 1.5 × 40 wave data on the suspension insulators.

There is admittedly a considerable physical difference between the insulator string and the rod gap, and perhaps, in view of the 8 per cent tolerance, the above inconsistencies are more apparent than real. However, the writer would ask if there is, as yet, any satisfactory explanation of the preceding trends of the data of tables I and II.

In further reference to table I, will the 8 per cent tolerance apply to the values as given, for all 10-inch disks at $5^{3}/_{4}$-inch spacing, regardless of size or type of insulator cap and other hardware?

From figure 1, it appears that we now have a much needed correction for the effect of humidity. Years ago we talked of the relative humidity. Then there was found to be a correlation between spark-over values and the absolute humidity, and the latter was expressed sometimes as grams per cubic meter, and sometimes as grains per cubic foot. Now we have the correction factor plotted against the absolute pressure of the water vapor. While the writer has no particular preference as to how the water content of the air is expressed, it is hoped that a unified terminology can be adopted.

**P. H. McAuley** (Westinghouse Electric & Manufacturing Company, East Pittsburgh, Pa.): A review at this time of the technical details leading to the satisfactory agreement in data from different laboratories seems appropriate. The outstanding items which contributed to this agreement are:

1. Use of cathode-ray oscillograph and resistance voltage divider as a method of voltage measurement.
2. Adoption of standard waves by all laboratories.
3. Determination of correction factors chiefly for humidity of the air.

Previous to 1929 the usual method of making high-voltage impulse tests was to set up a generator circuit, calculate the wave form by approximate methods and measure the peak voltage with a sphere gap. With the capacitors available, poor regulation naturally could not be avoided with changes in the capacity of the test piece. The importance of the oscillations due to generator inductance and stray capacity was not appreciated. These oscillations varied with load and resulted in inconsistent and abnormally high values. Fielder and Torok applied the cathode-

**Table I. Comparing Early Trafford Impulse Data on Suspension Insulators With Values From the Committee Report**

| Units | 1929 | 1937 |
|---|---|---|
| 4 | 425 | 440 |
| 6 | 605 | 610 |
| 8 | 780 | 780 |
| 10 | 945 | 945 |
| 12 | 1,105 | 1,105 |
| 14 | 1,260 | 1,265 |
| 16 | 1,425 | 1,425 |

ray oscillograph with a resistance voltage divider to a 2,000-kv impulse generator at Trafford in 1928. The practice of determining the volt-time characteristic curve of high-voltage insulation was adopted immediately and the sphere gap was practically discarded for impulse measurements. Our first field curve above 1,000 kv, dated November 1928, was on 10 suspension insulators and shows a minimum value of 920 kv and a one microsecond value of 1,510 kv. The most recently published data gives 945 and 1,500 kv for these points. However, this accuracy within 3 per cent in 1928 was partly due to compensating errors. The humidity was not even recorded but was probably around 0.15 inches of mercury. A 5 per cent positive error in the divider system was later discovered and probably compensated for most of the humidity correction. The wave form was far from smooth but the fundamental happened to be close to 1.5 × 40 and positive.

It is interesting to compare the values from the committee report with the time

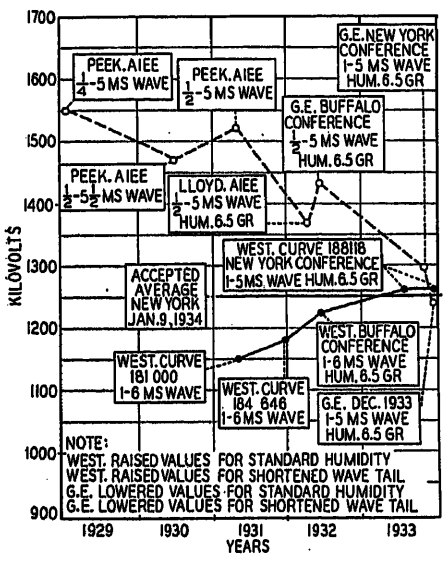



**Figure 1. History of laboratory co-ordination, 11 standard insulators, positive short waves**

log curves published in *Electrical World*, November 23, 1929 and in the AIEE TRANSACTIONS, July 1930. Insulators only are considered, as the present form of rod gap had not been adopted. The agreement in table I indicates the soundness of the measuring methods used at Trafford nearly 8 years ago.

A few years later this system of voltage measurement had benefited from a number of technical improvements chiefly on the cathode-ray oscillograph. Complete calibration curves for some of the sphere gaps based on measurements with the oscillograph were made and presented by Fielder (*Electrical World*, September 30, 1933). The effect of air conditions was realized and data on correction factors were collected. Standard waves were adopted in co-operation with other laboratories. Thus was made possible the correlation of laboratory data regardless of whether the sphere gap or the oscillograph was depended upon for voltage measurement. Many problems still remained and much time was required to collect and co-ordinate data on different apparatus. However, the technical obstacles had been solved experimentally. Then and not till then were reliable mathematical methods of impulse generator circuit analysis present.

The steps and progress in laboratory co-ordination are well illustrated by figure 1, showing different values obtained for minimum short wave flashover of 11 suspension insulators. Changes in wave form, humidity corrections, and measuring methods reduced a spread of 30 per cent to less than 2 per cent over a period of 3 years.

The trend at present to consider negative waves has introduced some more unknown factors and interesting problems. What seems to be needed now is fundamental research of the phenomena of breakdown.

## Lightning Currents in 132-Kv Lines

**Discussion of a paper by Philip Spom and I. W. Gross published in the February 1937 issue, pages 245–52, and presented for oral discussion at the opening session of the North Eastern District meeting, Buffalo, N. Y., May 5, 1937.**

**P. L. Bellaschi:** See discussion, this page.

**S. K. Waldorf** (Pennsylvania Water and Power Company, Baltimore, Md.): Analysis of a recent outage of the Holtwood-York 69-kv line has yielded information closely related to that presented by Messrs. Sporn and Gross. It has particular bearing on the questions of current distribution in transmission towers and the surge impedance of overhead ground wires.

One circuit of the double-circuit line tripped during a severe lightning storm. On patrolling the line, it was found that an arc had occurred between the top phase conductor and the structure of tower 63, and that the surge-crest ammeter links were strongly magnetized on towers 63 and 64. The links on towers 61 and 62 were found magnetized to a less extent. Brackets for the links were mounted on only one leg of each tower and indicated leg currents of 14,600 and 12,200 amperes in towers 63 and 64, respectively. As is customary when estimating the current in a tower equipped with only one pair of surge-crest ammeter links, the tower currents were taken as 4 times the leg currents, or 58,400 and 48,800 amperes in towers 63 and 64, respectively. The currents in the 2 towers being almost equal, it was concluded that lightning had probably struck one or both of the overhead ground wires between the towers.

With the footing resistance of tower 63 being 11 ohms, and the tower current 58,400 amperes, their product yielded a tower potential of approximately 640 kv. This was only about 60 per cent of the nominal flashover value of the line which indicated at first glance that the initial flashover should have occurred elsewhere than at the tower. Following this train of thought, the next possibility investigated was that of a flashover from a ground wire to the line conductor between towers, followed by flashover from the line conductor to tower 63. This seemed a likely sequence of events with the current of 58,400 amperes and the surge impedance of the overhead ground wire causing a potential difference of approximately 29,000 kv between the struck wire and the line conductor. Examination of lightning current observations made on 3 transmission lines since 1934 showed that this hypothesis also was probably incorrect. Numerous cases were found where heavy surge currents had travelled along overhead ground wires without flashover occurring. The circumstance has been repeated so often that the conclusion was inevitable that the surge impedance of an overhead ground wire is something appreciably less than 500 ohms at the point of contact of a lightning stroke.

Messrs. Sporn and Gross have shown that a relation exists between the length of a counterpoise conductor and its relative current-carrying capacity. At tower 63, 50 ohms was the ground resistance of the counterpoise connected to the leg in which the current of 14,600 amperes was measured, and the ground resistance of the other 3 counterpoise wires was 16, 20, and 55 ohms, respectively. The current in the tower was estimated on the assumption that the current carried by each leg varied inversely as the ground resistance of the buried conductor connected to that leg. On this basis, the current in the tower was calculated to be in the neighborhood of 110,000 amperes, which is more than enough to account for the flashover at the tower.

Measurements on towers having surge crest ammeter links on all four legs have shown that appreciable error in measurement can result if only one leg carries links, due to the unequal distribution of surge current between the legs of a tower. When all of the enumerated facts were considered, the conclusion was that the flashover was due to a very heavy surge current in tower 63.

In general, the analysis of this outage has led to an examination of the data collected by the Pennsylvania Water and Power Company from an additional point of view. At this time it is felt that Messrs. Sporn and Gross are correct in questioning the accepted value of 400 or 500 ohms as the surge impedence of a wire near the point of contact of a lightning stroke. Further investigation is being made to establish the effect of counterpoise ground resistance on the distribution of surge current in a tower.

## Probable Outages of Shielded Transmission Lines

**Discussion and author's closure of a paper by S. K. Waldorf published in the May 1937 issue, pages 597–600, and presented for oral discussion at the opening session of the North Eastern District meeting, Buffalo, N. Y., May 5, 1937.**

**P. L. Bellaschi** (Westinghouse Electric & Manufacturing Company, Sharon, Pa.): The considerable field data on lightning currents now available naturally suggest through correlation processes the best design technique to render transmission lines

practically free from lightning outages. A great deal of laboratory and analytical work has been done to establish this development along sound lines. All this is clearly set forth in these 2 papers, yet it is apparent also that new data suggest further analysis. It is with this viewpoint in mind that a method is suggested for evaluating the duration of the lightning stroke discharge from the crest currents measured at adjacent towers.

Thus, lightning upon striking directly a tower of footing resistance $R_1$, discharges a current $i_1$ through it. Consider a current $i_2$ through the adjacent tower of footing resistance $R_2$. The inductance of the overhead wire or wires between the 2 towers is designated as $L$. The corresponding crest values of the currents measured at the two towers are, respectively, $I_1$ and $I_2$.

It has been established from fundamental findings, here and abroad, that the more common type of lightning discharge rises abruptly to crest, receding to low values in a relatively longer time (microseconds). The discharge is apparently unidirectional or quasi-unidirectional in wave form, though there are indications that reversal of the polarity of the current discharge may occur. The exponential wave form, when all is considered, is sufficiently valid for the purpose here and serves well as a first approach in the analysis. That is, considering that the current is

$$i_1 = I_1 e^{-\frac{0.69t}{T}} \qquad (1)$$

it can be shown by relatively simple analysis that

$$i_2 = I_1 \left(\frac{R_1}{R_2}\right)\left(\frac{R_2/L}{R_2/L - \frac{0.69}{T}}\right) \times \left(e^{-\frac{0.69t}{T}} - e^{-\frac{R_2 t}{L}}\right) \qquad (2)$$

The maximum current $I_2$ occurs at $t_m$, i.e.

$$t_m = \frac{\ln \frac{R_2}{L} - \ln \frac{0.69}{T}}{R_2/L - \frac{0.69}{T}} \qquad (3)$$

Then

$$\frac{I_2}{I_1} \cdot \frac{R_2}{R_1} = \left(\frac{R_2/L}{R_2/L - \frac{0.69}{T}}\right) \times \left(e^{-\frac{0.69 t_m}{T}} - e^{-\frac{R_2}{L} t_m}\right) \qquad (4)$$

In applying relationship (4) it is essential that the crest currents should correspond to a lightning stroke directly to one of the towers. Considering values of transmission line constants encountered (such for example, $L = 400$ microhenries; $R_2 = 5$ to 20 or more), and since the ratio on the right hand of equation 4 would hardly or infrequently exceed 0.70 approximately, possible ranging down to 0.10, it appears from the equation that values of $T$ (duration of lightning discharge) range from 10 to 100 microseconds.

Though this preliminary analysis in calculating the duration of the lightning-stroke discharge is subject to a number of obvious criticisms, these hardly should detract from the possibilities new analytical methods of attack present in the study of field data.

**S. K. Waldorf:** Mr. Bellaschi's conclusion that lightning surges are slower in development than has been generally supposed, is borne out by experience. There has been a lack of flashovers on overhead ground wires carrying heavy surge currents, a behavior probably due to the surge impedance of the ground wires being low as a result of the surges not having steep wave fronts.

Since table IV of the paper was prepared, the initial flashover of the Holtwood-York 69-kv line has occurred, which changes the actual lightning outages per year for this line from 0 as given in the table to approximately 0.5. This is in agreement with the value of 0.38 probable outages per year which calculation shows can be expected for this line. The other figures given in table IV remain approximately the same as originally given.

## Heat Transfer Efficiency of Range Units

**Discussion and author's closure of a paper by W. James Walsh published in the August 1937 issue, pages 953–8.**

**W. N. Lindblad** (Pacific Gas and Electric Company, Emeryville, Calif.): Experience gained by the writer in making a number of tests such as Mr. Walsh describes has accentuated the importance of careful measurement and necessary compensation for errors in order that consistent results may be obtained. The use of a drop of oil to minimize evaporation is a unique and no doubt effective method of reducing this rather considerable error.

The over-all efficiency is greatly affected by the amount of water chosen. In a number of tests made by the writer on similar pots and units but with 5 pounds of water instead of 2.76 pounds, appreciably higher efficiencies were obtained. It would be of interest to know why Mr. Walsh selected 1,250 grams as the weight of water used.

The maximum instantaneous efficiencies were assumed by Mr. Walsh to be those coincident with the flat portion of the efficiency curves in figure 7 of Mr. Walsh's paper. It is to be noted that these efficiencies are occurring while the water and presumably the unit are increasing in temperature, possibly at the same rate. It has been the writer's experience that the unit continues to increase in temperature after the water reaches a constant temperature (boiling) and that, consequently, the heat transfer efficiency increases to a value somewhat higher than shown.

The increase in efficiency obtained with black-bottom pots, particularly on the more radiant units, coincides with the writer's experience. Other factors also have a bearing, particularly the concavity of the bottom. With a perfectly flat and bright-bottom pot, the writer has found that the unit $B$ (as labeled in Mr. Walsh's paper) invariably showed higher efficiencies than unit $A$. When the flat bottom was blackened by spraying with lacquer, the efficiency on unit $B$ was reduced considerably, showing that the heat conduction was reduced by the addition of the lacquer.

Tests with pots having a concavity of as little as $^1/_{32}$ inch gave results similar to those of Mr. Walsh's which leads the writer to believe that Mr. Walsh's pots were slightly concave.

It is interesting to note that with a perfectly flat top unit and a flat-bottom pot, over-all efficiencies of 67 per cent and instantaneous efficiencies of over 80 per cent were obtained with 5 pounds of water over a 75 degrees centigrade range of temperature.

**W. J. Walsh:** In regard to Mr. Lindblad's first remark, it may be stated that it was found quite possible to secure consistent results when a good oil film was formed over the water surface. However, there were times when, due to a slight surface contamination on the water, a film refused to form. This difficulty was remedied by taking greater pains in cleaning the equipment used in handling the water.

In connection with methods of minimizing evaporation, the device employed in similar tests performed recently at Oregon State College by Mr. W. G. Short may be of interest. In his tests, Mr. Short substituted a thin sheet of waxed paper (cut to fit the utensil at the water line) for the oil film, and secured even better results without the difficulties attending the use of oil.

In determining the amount of water to be used, the writer was guided principally by the apparent predominance of 2-quart utensils in ordinary cooking operations. In the writer's opinion, the use of larger quantities of water would result, in general, in slightly lower values of efficiency, supposing of course that the utensil diameter remained the same. Further, it appears to the writer that the efficiency values obtained with the larger quantities of water would depend to a great extent upon the ability of the temperature-indicating device employed to give truly representative average temperature values. To be more explicit, one would not use, say, a resistance thermometer with the resistance element spread out in only one plane, but one having the resistance element distributed in both horizontal and vertical planes. It seems reasonable to expect the latter device to give much more representative temperature values than the former when larger quantities of water are used. It would be of interest to know the method employed by Mr. Lindblad in determining his temperature values.

In his discussion, Mr. Lindblad further states that the writer assumed that the maximum instantaneous efficiency was coincident with the flat portion of the efficiency curves shown in figure 7 of the paper. This was not assumed, but definitely justified, as indicated in the paper under the heading "Discussion of Results" (page 957, ELECTRICAL ENGINEERING, Aug. 1937).

Mr. Lindblad also indicates that in his experiments the use of lacquer on the bottom of the utensil reduced the efficiency of heat transfer of the unit labeled $B$ in the

writer's paper. In this connection, it may be pointed out that the thickness of the lacquer layer and the condition of its surface would have a great deal to do with the results obtained. In the writer's experiments, results were obtained which indicated nearly a 3 per cent increase in the instantaneous efficiency of the unit *B* when it was used with the black-bottomed utensil. With a relatively thick layer of lacquer, it should be quite possible to effect a reduction in the efficiency of a unit such as *B*, but in the writer's opinion, a thin, dull-surfaced layer of lacquer would not result in an appreciable reduction in efficiency except on those units operating at a very low temperature.

Mr. Lindblad further points out that the concavity of the bottom of the utensil has a marked influence on the heat-transfer efficiency of surface units. It may also be pointed that a convex bottom has just as great, and probably a greater, effect. Since the utensils used by the writer were intended for actual kitchen use, they were purposely made slightly concave for obvious practical reasons.

In his closing statement, Mr. Lindblad cites certain efficiency values which he has obtained in his experiments. It would be very interesting to know the rating of the unit upon which the tests were performed, and the methods employed by Mr. Lindblad in determining the several necessary quantities involved. In short, a paper by Mr. Lindblad setting forth the results of his experience would be most welcome. The writer would like to take this opportunity to express his appreciation to Mr. Lindblad for his most instructive discussion.

The writer notes with considerable interest the presence of 2 letters to the editor in ELECTRICAL ENGINEERING for October 1937 commenting on the paper. Mr. Wiegand presents several interesting points which will undoubtedly be of value in future work along this line. Of course, the time and financial investment necessary for carrying out such tests as he proposes are practically beyond the range of any but a commercial organization.

The writer notes with particular interest the comments made by Professor Seeley in his letter. Essentially the same ideas were expressed to the writer by Professor F. O. McMillan of Oregon State College at the time that he suggested the subject to the writer.

## Relay Operation During System Oscillations

**Discussion of a paper by C. R. Mason published in the July 1937 issue, pages 823–32, and presented for oral discussion at the development of protective equipment session of the Pacific Coast convention, Spokane, Wash., August 31, 1937.**

L. F. Kennedy (General Electric Company, Philadelphia, Pa.): It is my hope that every relay engineer will thoroughly study Mr. Mason's paper, particularly figures 5 and 6. Familiarity, with the changing relations between current and voltage, is necessary to an understanding of relay performance when the system is in a disturbed condition. We have known that protective systems, with the exception of the differential types, are more or less prone to operation during system swings or oscillations. Mr. Mason has presented the information bearing on relay operation in compact form for the benefit of relay engineers in such a manner that it should be of very material assistance to all relay engineers.

Supplementing the fundamental data showing system performance, Mr. Mason has indicated in general terms the manner in which various types of relay elements may operate. As he states, such conclusions as may be drawn are thorougly obvious from the text.

The use of zero-phase-sequence or negative-phase-sequence relay devices would eliminate any tendency to operate on oscillations or swings. Such relays will not operate to clear simultaneous 3-phase faults. It is most important that 3-phase faults be quickly removed if severe and prolonged oscillations are to be avoided. I have recently reviewed a number of oscillograph records of disturbances on a large Eastern system. A surprising number of these started as balanced 3-phase faults. I am in agreement with most protective engineers who feel justified in demanding that the protective equipment operate with at least the same degree of promptness on these balanced faults as on any other type.

J. H. Neher (Philadelphia Electric Company, Philadelphia, Pa.): Mr. Mason is to be congratulated on his excellent presentation of the complicated factors involved in the analysis of relay performance during out-of-step conditions on a transmission system.

In presenting the operating characteristics of the various types of relays involved, Mr. Mason has employed a somewhat different method than I have used in my paper. I should like to emphasize the point, therefore, that whichever method you prefer to use, that method is equally applicable in determining the performance of the relay under either out-of-step or fault conditions. In other words, the operation of a relay under short circuit conditions may be determined by applying the currents and voltages given in table I of my paper to the characteristic figures in Mr. Mason's paper, and, conversely, the impedance presented to the relay under out of step conditions as determined by Mr. Mason may be plotted against the characteristic impedance circle for the relay as I have described.

In this connection it is necessary to point out that equation 7 in Mr. Mason's paper gives the impedance presented to the relay as a scalar quantity, whereas it must be employed as a vector quantity in the graphical method which I have described. Equation 6 may be readily transformed into a vector expression for impedance and may be written using polar notation as follows:

$$Z\angle\phi_z = = \frac{Z^1}{2}\angle\phi_z' \times \left[(2n-1) - ctn\frac{\theta}{2}\angle 90^\circ\right]$$

This equation when plotted for a given value of $Z'\angle\phi_z'$ and for all possible values of $\theta$ yields a series of parallel straight lines one for each value of $n$ assumed. This is shown in figure 1 of this discussion in which the constants employed are the same as those in Mr. Mason's paper. The plus sign only of the equation has been used and the equivalent effect of the minus sign has

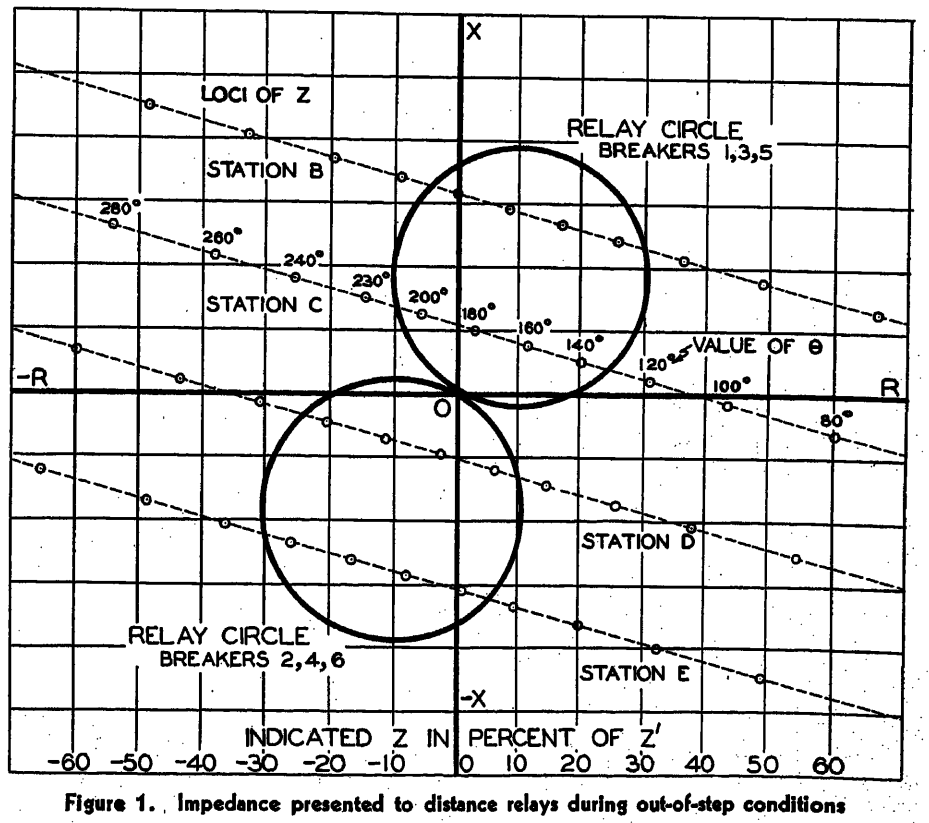



**Figure 1. Impedance presented to distance relays during out-of-step conditions**

been obtained by reversing the relay circle for breakers 2, 4, and 6. Considering the relay operation for breaker 3 at station *C*, as the system pulls out of step with source *A* leading source *F*, the impedance sweeps in from infinity on the right, passes through the relay circle shown (during which time the relay will operate) and then on to infinity on the left, very much in the manner of a comet. The relay operation at the other breakers may be illustrated in a similar manner.

The relay circles shown are those characteristic of directional elements with voltage restraint, but they may be drawn to fit the particular type of element and setting employed. The characteristic circle for a directional element without voltage restraint is a straight line passing through the origin drawn at a slope dependent upon its connections and its internal characteristic angle.

## Capacitance Control of Voltage Distribution in Multibreak Breakers

**Discussion of a paper by R. C. Van Sickle published in the August 1937 issue, pages 1018–24, and presented for oral discussion at the development of protective equipment session of the Pacific Coast convention, Spokane, Wash., August 31, 1937.**

**J. B. MacNeill** (Westinghouse Electric and Manufacturing Company, East Pittsburgh, Pa.): The uneven distribution of voltage between breaks of a metal-tank circuit breaker has been known for several years. This unbalance is caused primarily by the relatively large electrostatic capacitance of the grounded tank relative to the capacitance of the contact parts. The voltage balance depends on the type of short circuit, whether grounded or ungrounded, as well as the spacings and capacitances of the parts involved.

It has been claimed by some that the unbalance referred to could not be disposed of in a commercial structure of the conventional type, and therefore radically different structures eliminating the metal tank have been proposed. This is not necessary, however, and the safety and ruggedness of the grounded tank still may be used, as shown by Mr. Van Sickle.

In 1929 and 1930 the general idea of using capacitance to balance that of the tank was used when the deion grids on the Plymouth Meeting 220-kv breakers of the Philadelphia Electric Company were designed with plate condensers in the upper units. Several other applications of the same principle have been since made.

The 3-cycle Boulder Dam 287-kv breakers required a more intensive application of the shunt capacitance principle, since over-all operation at this voltage made necessary complete duration of arcing of not over $1^1/_2$ cycles.

A paper in the AIEE for June 1937 by Wilcox and Leeds discussed these breakers and showed the performance well within 3 cycles on a 60-cycle basis can be expected during short circuit duty. Mr. Van Sickle's paper covers the methods of securing voltage distribution used in that design. The fact of proper distribution has been proved by several types of test:

1. Low-voltage electrostatic tests
2. High-voltage electrostatic tests
3. High-voltage dynamic tests using high-power laboratory

All 3 methods have borne out very closely the results expected from simple calculations of the electrostatic factors involved. Such calculations on a pure capacitance basis are slightly pessimistic, as the natural resistance characteristic of arcs in the interrupting devices tend to better the distribution.

Where exceedingly short times for switching are required at very high voltages, it must be conceded that some device to secure adequate distribution of voltage must be used. Recent claims for high speed at high voltages for devices which have inherently bad unbalance between breaks must be discounted as probably due to low rates of restored voltage. This will be seen if we look at figure 3 of Mr. Van Sickle's paper. Notice that in the curve for 8 breaks, the line break must handle 30 per cent of the total voltage across the pole unit, while on the other hand the last 4 breaks near ground total only 22 per cent, or less than the first single break. The tendency of the first break to re-establish an arc after current zero on a difficult high-voltage circuit is obvious.

On the other hand, figure 4 shows for 8 breaks that when proper devices for voltage balance are used, the first break handles only 16 per cent of the voltage across the pole unit, and the last 4 breaks average 10 per cent each and total 40 per cent of the pole unit voltage.

The design factors involved in very high speed, high-voltage breakers make these differences in voltage distribution a major factor in the ability of a design to handle difficult circuits, which at 230,000 volts or higher may have restored voltage rates of 4,000 to 6,000 volts per microsecond.

**C. A. Powel** (Westinghouse Electric & Manufacturing Company, East Pittsburgh, Pa.): The multibreak circuit breaker is not new. Many years ago several manufacturers introduced various designs of such breakers but their performance was not strikingly better than that of ordinary 2-break breakers, in fact, generally not as good. In a paper presented to the first International Conference on High Voltage Systems in Paris in 1921, the writer pointed out that unless some means was found to reduce the total length of the arc, the volume of gas generated by a multiplicity of breaks was increased and arc interruption was made more difficult. A serious difficulty, which was not fully understood at the time, was the proper distribution, after current zero, of the voltage across the many breaks which tended to restrike and prevent extinction of the arcs. With the introduction of the "deion" grid, the arc energy and formation of gas was enormously reduced and the multibreak idea became interesting if an over-all opening time of less then 8 cycles, which had been reached with the conventional 2-break design, was required. The difficulty of proper distribution of the voltage over the various breaks, however, still remained, and how it was solved is admirably explained in Mr. Van Sickle's paper. In the great majority of cases stability is the factor which determines the selection of breaker opening time, and the conventional 8-cycle breaker economically meets most operating requirements. In some few cases, however, a shorter time of opening can be justified and it is a satisfaction to know that where such an application proves economical, a design of breaker is available which is not radically different from that used for years.

## The Ultrahigh-Speed Reclosing Expulsion Oil Circuit Breaker

**Discussion and author's closure of a paper by A. C. Schwager published in the August 1937 issue, pages 968–70, and presented for oral discussion at the development of protective equipment session of the Pacific Coast convention, Spokane, Wash., August 31, 1937.**

**W. F. Skeats** (General Electric Company, Philadelphia, Pa.): Mr. Schwager has developed a mechanism for making the complete opening and closing strokes of a 69-kv breaker within half a second. This will undoubtedly find an application in connection with interrupting devices which cannot be relied upon to clear appreciably before the end of the stroke and in cases where the shorter reclosing times which have been reported by other authors are not considered necessary. It appears, however, that this mechanism must complete its closing stroke before starting to open, so that the trip-free feature which is now applied very widely on large oil circuit breakers has been sacrificed.

In evaluating the tests which are listed, it would be interesting to know the interrupting capacity rating of the breakers tested. Without this information, it is not clear whether the tests were made on breakers of low interrupting capacity or whether the power available for testing was considerably less than the breaker rating. In the second case, while the tests no doubt establish the adequacy of the interrupting devices for the duty at which they are to be applied, it cannot be inferred without further proof that the interrupting capacity of the breaker is not modified by the short interval between interruptions.

It is noted that the duration of the second short circuit at figure 5 is approximately 14 cycles as against a little over 8 cycles for the first interruption. This is apparently due to the fact that in the second interruption was a closing-opening operation in which the breaker was delayed by the fact that the mechanism is not trip-free, but has to close all the way home before it can start to open.

**A. C. Schwager:** Mr. Skeats discusses the reclosing mechanism developed for 69-kv breakers and points out that the reclosing time of $^1/_2$ second is larger than that en-

countered on some more recently built mechanisms. The mechanism shown in figure 3 is the first motor-operated reclosing control installed in the United States and fully meets the requirements for which it was designed. It is believed that a control of this type will find application in a great many cases. However, in order to meet special requirements for still shorter reclosing times changes have been incorporated in more recent designs. These changes mainly consist of using a spring of smaller diameter, thereby reducing the moment of inertia and increasing the speed of operation. The duration of the second short circuit referred to in the third paragraph of Mr. Skeats' discussion (which in the case shown includes relay time) is thereby reduced to a value which is equal to or smaller than that obtained with any modern "trip free in any position" mechanism.

The short-circuiting tests described were performed on a 69-kv breaker which was equipped with expulsion contacts at the time of the installation of the control. The tests were not intended to be short-circuiting tests of the 1,000,000-kva breaker, but were to establish the performance of the breaker under fast reclosing service at maximum system load. The absence of carbonization and tank pressures indicate, however, that the breaker was stressed to a fraction of its full rating only.

The "trip free in any position " feature mentioned deserves a more detailed discussion. It is, of course, evident that the "electrically trip free" and "mechanically trip free" feature generally applied on breakers is retained in this mechanism. Mr. Skeats, in all probability, refers to the "trip free in any position of the closing stroke" feature.

This feature, in my opinion, has become of minor importance with the design of breakers using high-pressure contacts or butt-type contacts. Approximately one inch of travel is allowed in these breakers from the "contact touch" to the fully closed position. With the closing speeds used in present-day breakers, the blade cannot help but to go fully closed even if the breaker were tripped at the instant the contacts touch. With relays interposed it is even more impossible for these breakers not to go fully closed when closed into a short circuit. There are definite advantages in omitting the collapsible link which is normally identified with the term "trip free in any position" and which has been used on "modern" controls for the last 30 years. With its use the blade has to be accelerated by the opening spring exclusively whereas with the motor control described, the kinetic energy contained in the fast-moving spring is immediately and completely converted into opening speed.

Since modern arc-rupturing devices are dependent on operation above a definite minimum speed the use of this control gives assurance of fool-proof performance which cannot be expected of a breaker which has to be relied upon to accelerate in the part of the stroke where interruption should take place. In other words, the breaker cannot hang within the arc-rupturing devices.

It is believed that the intentional omission of the obsolete collapsible link mechanism is highly desirable from an operating standpoint alone, however, since it permits the design of such a mechanically simple and fool-proof control as described it seems to be doubly justified. Experience with this modern control will undoubtedly confirm this idea.

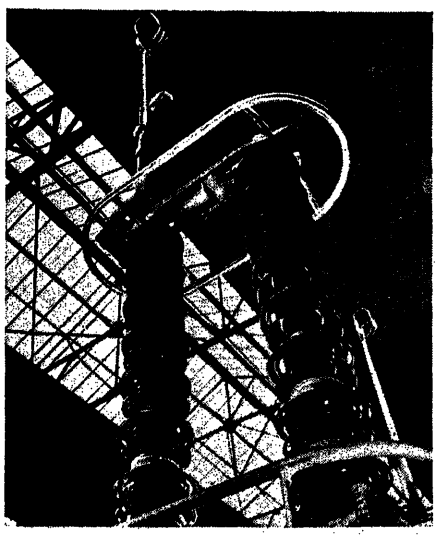
## A Comprehensive Method of Determining the Performance of Distance Relays

**Discussion and author's closure of a paper by J. H. Neher published in the July 1937 issue, pages 833–44, and presented for oral discussion at the development of protective equipment session of the Pacific Coast convention, Spokane, Wash., August 31, 1937.**

**L. F. Kennedy** (General Electric Company, Philadelphia, Pa.): Mr. Neher deserves the thanks of all protective engineers for the work he has put forth in preparing the formulas included in table II. I have some idea of the vast amount of time necessary for its preparation. Many are familiar with the changes of distance relay indications between 3-phase faults and phase-to-phase faults when star-connected current transformers are used. Few, however, know the indications under all the conditions covered by this paper.

I am afraid that the author's work will not be made use of by many relay engineers because of lack of time and facilities for the necessary calculations. I should like to suggest that the formulas in table II be supplemented by actual figures for an assumed typical system. Such an effort would not represent a great amount of work in addition to that already done and would certainly make the author's efforts of real value.

**C. R. Mason** (General Electric Company, Schenectady, N. Y.): Some of your best friends are those you take the longest to get acquainted with. If you should feel that Mr. Neher's paper is a reticent sort of neighbor, I suggest that you proceed carefully but studiously toward making its acquaintance. It is my feeling that it will then be numbered among your choicest possessions.



Supplementing the excellent treatments by Lewis and Tippet and by Calabrese, Mr. Neher's paper sheds new light on the subject. Perhaps I should say light at a different angle. For, in this paper the conception of impedance at an angle is skillfully handled. For example, the operating characteristic of a relay which functions according to 3 variables, such as most distance and directional relays, is very conveniently drawn to 2 dimensions without parameters to confuse the picture. Then all possible types of faults are expressed in the same manner, and conveniently tabulated. This in itself represents a creditable contribution.

This method of treatment is particularly valuable where one is confronted by the problem of determining a new shape for a relay characteristic to fit certain special requirements. The requirements can be plotted in the form of impedance at an angle and then a relay curve or portions of curves can be drawn to fit the requirements. The methods of this paper thus operate conveniently either way—to find out how a given relay will operate under prescribed conditions or to devise a relay or a combination of relays to operate in a desired manner.

If a fourth variable, time, should be involved, this can still be cared for by the use of parameters.

Mr. Neher's methods provide a very powerful analytical tool which is well worth having on your work bench.

**J. H. Neher:** I wish to thank Messrs. Kennedy and Mason for their very kind remarks about this paper. I feel obliged to point out the fact, which was displayed too inconspicuously as a footnote in the printed copy, that I am indebted to their associate, Mr. Warrington for a good deal for which they are giving me credit.

Mr. Kennedy has suggested that the formulas in table II be supplemented by actual figures for an assumed typical system. I hesitate to do this because, as I have endeavored to point out, in some cases the impedance presented to a relay under a given fault condition is only a function of the effective line impedance between the relay and the point of fault, and in other cases it is dependent upon the system set-up as well. This can be determined by inspection of table II by noting whether or not the expressions for the impedance presented to the relay involve factors dependent upon the system set-up. In cases where the effect of system capacity is manifest, any figures which might be included based on an assumed system, would apply only to the particular system set-up assumed and might lead to erroneous conclusions if one were to generalize from them.

In preparing a paper of this kind the elimination of errors in the mathematical text is difficult. On page 834 directly below equation number 3 a square root sign should appear over the numerator of the expression given in the text for the radius of the circle. In table II the factors $C$ and $C'$ have been incorrectly printed in small letters in columns 5 and 8, lines 8 and 10. Also, in the first 2 lines of the seventh column a small $z$ has been omitted in the denominators after the factor small $c$.

# News
## Of Institute and Related Activities

# AIEE Winter Convention to Feature Enlarged Program

TO PROVIDE added interest for the specialist as well as the average member, an enlarged program of 16 technical sessions and 1 general interest session has been tentatively arranged for the 1938 AIEE winter convention, which will be held in New York, N. Y., January 24–28. Sessions will be held both mornings and afternoons beginning on Monday and continuing through Thursday. Friday, the fifth day, will be devoted exclusively to inspection trips to places of interest in the city and its environs. The main social events will consist of the smoker and the dinner-dance, which will be held in the evenings. In view of the popularity of last year's cruise, another post-convention cruise to Bermuda will be arranged by Leon V. Arnold. More information regarding these features will be announced in the January issue.

TECHNICAL SESSIONS

Of the 16 technical sessions tentatively arranged, 5 sessions are symposia. The symposium on modern electric vehicles will be held in both the morning and afternoon of the same day with interim for luncheon; the papers will deal with modern developments and experience with electric vehicles used in urban transportation. Similarly, two electronics symposia will be held: The first will treat the speed control of motors, and operating experience; the second, electronic applications and the slide-

## Tentative Technical Program

**In this program page references are given for papers that have been or will be published in ELECTRICAL ENGINEERING up to and including January 1938.**

### Communication

COUPLING BETWEEN PARALLEL EARTH-RETURN CIRCUITS UNDER D-C TRANSIENT CONDITIONS, K. E. Gould, Bell Telephone Laboratories, Inc.
September issue, pages 1159–64

*PRINTING TELEGRAPH OPERATION OF WAY WIRES, G. S. Vernam, Postal Telegraph-Cable Company.

*ELECTRICAL REMOTE CONTROL ACCOUNTING, L. F. Woodruff, Massachusetts Institute of Technology.

A NEW SINGLE-CHANNEL CARRIER TELEPHONE SYSTEM, H. J. Fisher, M. L. Almquist, and R. H. Mills, Bell Telephone Laboratories, Inc.
Scheduled for January issue

### Symposium on Modern Electric Vehicles

APPLICATION OF MODERN ELECTRIC VEHICLES TO URBAN TRANSPORTATION, C. M. Davis, General Electric Company. Scheduled for January issue

ELECTRICAL EQUIPMENT FOR MODERN URBAN SURFACE TRANSIT, S. B. Cooper, Westinghouse Electric & Manufacturing Company.
Scheduled for January issue

*GENERAL FEATURES OF THE P.C.C. CAR, C. F. Hirshfeld, Transit Research Corporation.

*OPERATING EXPERIENCE WITH P.C.C. CAR, Thomas Fitzgerald, Pittsburgh Railways Company.

### Symposium on a New Carrier Telephone System for Toll Cable

Introductory Address: BROAD-BAND WIRE TRANSMISSION SYSTEMS, H. A. Affel, Bell Telephone Laboratories, Inc.

*A CARRIER TELEPHONE SYSTEM FOR TOLL CABLES, C. W. Green and E. I. Green, Bell Telephone Laboratories, Inc.

*CABLE CARRIER TELEPHONE TERMINALS, R. W. Chesnut, L. M. Ilgenfritz and A. Kenner, Bell Telephone Laboratories, Inc.

* Subject to approval for presentation, preprints of these papers will be made available. If ordered by mail, price 10¢ per copy. If purchased at headquarters, price 5¢ per copy.

*CRYSTAL CHANNEL FILTERS FOR THE CABLE CARRIER SYSTEM, C. E. Lane, Bell Telephone Laboratories, Inc.

*CROSS TALK AND NOISE FEATURES OF THE CABLE CARRIER SYSTEM, M. A. Weaver, R. S. Tucker, and P. S. Darnell, Bell Telephone Laboratories, Inc.

### Symposium on Modern Electric Vehicles—Continued

*MODERN CITY TRANSPORTATION, E. J. McIlraith, Chicago Surface Lines.

MODERN TROLLEY-COACH OPERATION, Edward Dana, Boston Elevated Railway.
December issue, pages 1461–63

MODERN TROLLEY-COACH OPERATION, J. H. Polhemus, Portland Electric Power Company.
December issue, pages 1483–86

*OPERATING EXPERIENCE WITH GAS-ELECTRIC AND DIESEL-ELECTRIC BUSSES, R. H. Stier, Philadelphia Rapid Transit Company.

*EXPERIENCE WITH DIESEL-ELECTRIC BUSSES AND ALL-SERVICE VEHICLES, M. R. Boylan, Public Service Coordinated Transport.

### Lightning Protection

CHARACTERISTICS OF THE NEW STATION-TYPE AUTOVALVE LIGHTNING ARRESTER, W. G. Roman, Westinghouse Electric & Manufacturing Company.
July issue, pages 819–22

*DISCHARGE CURRENTS IN DISTRIBUTION ARRESTERS—PART II, K. B. McEachron and W. A. McMorris, General Electric Company.

*DISTRIBUTION TRANSFORMER LIGHTNING PROTECTION PRACTICE, L. G. Smith, Consolidated Gas, Electric Light and Power Company.

SOME ENGINEERING FEATURES OF PETERSEN COILS AND THEIR APPLICATION, E. M. Hunter, General Electric Company.
Scheduled for January issue

*TEST AND OPERATION OF PETERSEN COIL ON 100-KV SYSTEM OF PUBLIC SERVICE COMPANY OF COLORADO, W. D. Hardaway, Public Service Company of Colorado, and W. W. Lewis, General Electric Company.

### Symposium on Electronics—I

*ELECTRONIC SPEED CONTROL OF MOTORS, E. F. W. Alexanderson, General Electric Company, C. H. Willis, Princeton University, and M. A. Edwards, General Electric Company.

OPERATING EXPERIENCE WITH THE THYRATRON MOTOR, A. H. Beiler, American Gas and Electric Company. Scheduled for January issue

*PHANOTRON RECTIFIERS AS A DIRECT CURRENT SUPPLY FOR ELEVATOR MOTORS, C. C. Clymer and R. G. Lorraine, General Electric Company.

*THYRATRON CONTROL OF DIRECT CURRENT MOTORS, G. W. Garman, General Electric Company.

### Relays and Reactors

A SYSTEM OUT OF STEP AND ITS RELAY REQUIREMENTS, L. C. Crichton, Westinghouse Electric & Manufacturing Company.
October issue, pages 1261–67

A HIGH-SPEED DISTANCE-TYPE CARRIER PILOT RELAY SYSTEM, E. L. Harder, B. E. Lenehan, and S. L. Goldsborough, Westinghouse Electric & Manufacturing Company.
Scheduled for January issue

*THE APPLICATION AND PERFORMANCE OF CARRIER CURRENT RELAYING, Philip Sporn and C. A. Muller, American Gas and Electric Company.

TEMPERATURE LIMITS FOR SHORT-TIME OVERLOADS FOR OIL-INSULATED NEUTRAL GROUNDING REACTORS AND TRANSFORMERS, V. M. Montsinger, General Electric Company.
Scheduled for January issue

*HARMONIC CURRENT RESTRAINED RELAYS FOR DIFFERENTIAL PROTECTION, L. F. Kennedy and C. D. Hayward, General Electric Company.

*SOME SCHEMES OF CURRENT-LIMITING REACTOR APPLICATIONS, F. H. Kierstead, General Electric Company.

back voltmeter, theater lighting, welding, and a new type of vacuum seal. The fifth symposium will deal with a new carrier telephone system for toll cable. Also in the communication field, there will be a general communication session and another session on the subject of television and broad band transmission. The remainder of the program is comprised of sessions on the subjects of lightning protection, relays and reactors, instruments and measurements, electric welding, basic sciences, power transmission, cables and research, and two sessions on electrical machinery. For the general session arrangements are being made to obtain a prominent speaker on a subject of broad interest to the engineering profession.

### Technical Conferences

During the convention, technical conferences will be held on the subjects of education, field problems, network analysis and synthesis, electrical units, sound and vibration. The technical conferences are intended to afford opportunity for groups of specialists to meet and discuss subjects informally, no provision being made for the publication of the papers or the discussions in the TRANSACTIONS.

### Rules on Presenting and Discussing Papers

At some of the technical sessions, a few papers may be presented only by title. This will permit the devotion of more time to discussion. At other sessions, papers will be presented in abstract, ten minutes being allowed for each paper unless otherwise arranged, or the presiding officer meets with the authors preceding the session to arrange the order of presentation and allotment of time for papers and discussion. Authors will be notified officially in each case about one month in advance.

Any member is free to discuss any paper when the meeting is opened for general discussion. Usually five minutes is allowed to each discusser for the discussion of a single paper or of several papers on the same general subject. When a member signifies his desire to discuss several papers not dealing with the same general subject, he may be permitted to have a somewhat longer time.

It is preferable that a member who wishes to discuss a paper give his name in advance to the presiding officer of the session at which the paper is to be presented. Each discusser should step to the front of the room and announce, so that all may hear, his name and professional affiliations. Three typewritten copies of discussion prepared in advance should be left with the presiding officer.

Other discussions to be considered for publication must be submitted, typed double spaced, in triplicate to C. S. Rich, secretary, technical program committee, AIEE headquarters, 33 West 39th St., New York, N. Y., on or before February 11, 1938. Discussion received after this date will not be accepted.

The personnel of the 1938 winter convention committee is as follows: T. F. Barton, *chairman*, C. R. Beardsley, O. B. Blackwell, G. E. Dean, A. F. Dixon, E. E. Dorting, H. S. Osborne, C. S. Purnell, George Sutherland, and F. P. West.

# Tentative Technical Program—Continued

## Symposium on Electronics—II

*SHARP CUT-OFF IN VACUUM TUBES, WITH APPLICATIONS TO THE SLIDE-BACK VOLTMETER, C. B. Aiken, Purdue University, and L. C. Birdsall, Glencoe, Ill.

*THYRATRON REACTOR LIGHTING CONTROL, E. D. Schneider, General Electric Company.

*AN ELECTRONIC ARC-LENGTH MONITOR, Walther Richter, A. O. Smith Corporation.

*A NEW TYPE VACUUM SEAL, W. E. Bahls, Westinghouse Electric & Manufacturing Company.

## Instruments and Measurements

*A NEW ALTERNATING-CURRENT NETWORK ANALYZER, H. P. Kuehni and R. G. Lorraine, General Electric Company.

*A STABILIZED AMPLIFIER FOR MEASUREMENT PURPOSES, H. A. Thompson, General Electric Company.

ELECTRICAL STUDIES OF LIVING TISSUE—II—CORRELATION BETWEEN TISSUE RESPONSE AND VOLTAGE DISTRIBUTION, A. G. Conrad, H. W. Haggard, and B. R. Teare, Yale University.
Scheduled for January issue

A NEW CORRELATION OF SPHERE GAP DATA, D. W. Ver Planck, Yale University.
Scheduled for January issue

## Electric Welding

RECENT ADVANCES IN RESISTANCE WELDING, AIEE Resistance Welding Subcommittee, C. L. Pfeiffer, chairman. Scheduled for January issue

MECHANICAL HIGH-SPEED RESISTANCE-WELDER CONTROL, F. H. Roby, Square D Company.
September issue, pages 1145–48

*INTERPRETATION OF OSCILLOGRAMS OF ARC-WELDING GENERATORS IN TERMS OF WELDING PERFORMANCE, K. L. Hansen, Harnischfeger Corporation.

*THE RATING OF RESISTANCE-WELDING TRANSFORMERS, C. E. Heitman, Edward G. Budd Manufacturing Company.

## Basic Sciences

MATRICES IN ENGINEERING, L. A. Pipes, The Rice Institute. September issue, pages 1177–90

*RESONANT NONLINEAR CONTROL CIRCUITS, W. T. Thomson, Alameda, Calif.

*SUBHARMONICS IN CIRCUITS CONTAINING IRON, I. A. Travis and C. N. Weygandt, University of Pennsylvania.

*THE PROPERTIES OF THREE-PHASE SYSTEMS DEDUCED WITH THE AID OF MATRICES, M. B. Reed, The University of Texas.

*CRITICAL CONDITIONS IN FERRO-RESONANCE, P. H. Odessey and Ernst Weber, The Polytechnic Institute of Brooklyn.

## Power Transmission

*TRANSMISSION LINE TRANSIENTS IN MOTION PICTURES, L. F. Woodruff, Massachusetts Institute of Technology.

*LIGHTNING STRENGTH OF WOOD IN TRANSMISSION STRUCTURES, Philip Sporn, American Gas and Electric Company, and J. T. Lusignan, Ohio Brass Company.

*RECOVERY-VOLTAGE CHARACTERISTICS OF TYPICAL TRANSMISSION SYSTEMS AND RELATION TO PROTECTOR-TUBE APPLICATION, R. D. Evans and A. C. Monteith, Westinghouse Electric & Manufacturing Company.

SWITCHING SURGES WITH TRANSFORMER LOAD-RATIO CONTROL CONTACTORS, L. F. Blume and L. V. Bewley, General Electric Company.
December issue, pages 1464–75.

*SAFETY FEATURES FOR THE JOINT USE OF WOOD POLES CARRYING COMMUNICATION CIRCUITS AND POWER DISTRIBUTION CIRCUITS ABOVE 5,000 VOLTS, J. O'R. Coleman, Edison Electric Institute, and A. H. Schirmer, Bell Telephone Laboratories, Inc.

## Electrical Machinery—I

CO-ORDINATION OF POWER TRANSFORMERS FOR STEEP-FRONT IMPULSE WAVES, V. M. Montsinger, General Electric Company.

CORONA VOLTAGES OF TYPICAL TRANSFORMER INSULATIONS UNDER OIL, F. J. Vogel, Westinghouse Electric & Manufacturing Company.
Scheduled for January issue

A FORMULA FOR THE REACTANCE OF THE INTERLEAVED COMPONENT, H. B. Dwight and L. S Dzung, Massachusetts Institute of Technology
November issue, pages 1368–71

*STABILITY CHARACTERISTICS OF TURBINE GENERATORS, C. Concordia, S. B. Crary, and J. M. Lyons, General Electric Company.

## Cables and Research

OIL OXIDATION IN IMPREGNATED PAPER, J. B. Whitehead, The Johns Hopkins University, and T. B. Jones, Bell Telephone Laboratories, Inc.
December issue, pages 1492–1502

*MECHANICAL UNIFORMITY OF PAPER-INSULATED CABLE, K. S. Wyatt, D. L. Smart, and J. M. Reynar, The Detroit Edison Company.

*THE CURRENT-CARRYING CAPACITY OF RUBBER-INSULATED CONDUCTORS, S. J. Rosch, Anaconda Wire & Cable Company.

SHORT-CIRCUIT PROTECTION OF DISTRIBUTION NETWORKS BY THE USE OF LIMITERS, C. P. Xenis, Consolidated Edison Company of New York, Inc.
September issue, pages 1191–96

## Television

Address:. CURRENT FIELD WORK IN TELEVISION Ralph R. Beal, Radio Corporation of America.

Address: NEW BROAD-BAND TELEPHONE SYSTEM H. A. Affel, Bell Telephone Laboratories, Inc.

## Electrical Machinery—II

STRAY-LOAD LOSSES OF D-C MACHINES, E. W. Schilling, Michigan College of Mining and Technology, and R. W. Koopman, University of Kansas.
December issue, pages 1487–91

D-C MACHINE STRAY-LOAD-LOSS TESTS, Victor Siegfried, Worcester Polytechnic Institute.
October issue, pages 1285–89

UNSYMMETRICAL SHORT-CIRCUITS ON WATER-WHEEL GENERATORS UNDER CAPACITIVE LOADING, C. F. Wagner, Westinghouse Electric & Manufacturing Company. November issue, pages 1385–95

ALTERNATOR SHORT-CIRCUIT CURRENTS UNDER UNSYMMETRICAL TERMINAL CONDITIONS, A. R. Miller and W. S. Weil, Jr., Lehigh University.
October issue, pages 1268–76

# AIEE Board of Directors Meets at Institute Headquarters

THE regular meeting of the board of directors of the American Institute of Electrical Engineers was held at Institute headquarters, New York, on October 28, 1937.

There were present: *President*—W. H. Harrison, New York, N. Y. *Past-Presidents*—A. M. MacCutcheon, Cleveland, Ohio; J. B. Whitehead, Baltimore, Md. *Vice-Presidents*—O. B. Blackwell, New York, N. Y.; C. Francis Harding, Lafayette, Ind.; M. J. McHenry, Toronto, Ont.; I. Melville Stein, Philadelphia, Pa.; A. C. Stevens, Schenectady, N. Y.; Edwin D. Wood, Louisville, Ky. *Directors*—C. R. Beardsley, Brooklyn, N. Y.; V. Bush, Cambridge, Mass.; N. E. Funk, Philadelphia, Pa.; F. Ellis Johnson, Columbia, Mo.; C. R. Jones, New York, N. Y.; W. B. Kouwenhoven, Baltimore, Md.; F. H. Lane, Chicago, Ill.; K. B. McEachron, Pittsfield, Mass.; C. A. Powel, East Pittsburgh, Pa.; R. W. Sorensen, Pasadena, Calif. *National Treasurer*—W. I. Slichter, New York, N. Y. *National Secretary*—H. H. Henline, New York, N. Y. Present by invitation: V. M. Montsinger, chairman, standards committee.

Minutes of the meeting of the board of directors held August 3, 1937, were approved.

Representatives and alternates of the Institute on other organizations were appointed as follows:

**United Engineering Trustees, Inc.**—for 4-year term beginning in October 1937: F. M. Farmer.

**American Engineering Council Assembly**—for calendar year 1938: C. O. Bickelhaupt, chairman, AIEE delegation; C. Francis Harding; William McClellan; C. E. Stephens; H. H. Henline, alternate. President W. H. Harrison is the fifth representative of the Institute, for the term August 1, 1937, to August 1, 1938.

**Standards Council, ASA**—for 3-year term beginning January 1, 1938: E. L. Moreland. Alternates for calendar year 1938: R. E. Hellmund; H. H. Henline; H. S. Osborne.

**Engineers' Council for Professional Development**—for 3-year term beginning in October 1937: F. Ellis Johnson.

The following were appointed for the year beginning August 1, 1937:

**Committee of Apparatus Makers and Users, National Research Council:** L. F. Adams.

**Electrical Standards Committee, ASA** (and, *ex-officio*, United States National Committee of the International Electrotechnical Commission): A. M. MacCutcheon; V. M. Montsinger; H. S. Osborne. Alternates: H. E. Farrer; R. E. Hellmund; E. L. Moreland.

**Committee on Heat Transmission, National Research Council:** T. S. Taylor.

**Committee on Low Voltage Hazards, ASSE Engineering Section, National Safety Council:** F. V. Magalhaes.

**Electrical Committee, National Fire Protection Association:** F. V. Magalhaes.

**National Fire Waste Council:** Wills Maclachlan, H. S. Warren.

It was decided to discontinue the appointment of representatives upon the following bodies, reports having been received of inactivity of the organization or of no further need for Institute representation: American Marine Standards Committee, and the Radio Advisory Committee of the National Bureau of Standards.

The following actions of the executive committee under date of September 20, 1937, were reported and confirmed: 4 applicants transferred to grade of Fellow; 20 applicants transferred and 7 elected to the grade of Member; 57 applicants elected to the grade of Associate; 32 Students enrolled.

Reports were presented and approved of meetings of the board of examiners held on September 16 and October 14, 1937. Upon recommendation of the board of examiners, the following actions were taken: 13 applicants were elected and one applicant was reinstated to the grade of Member; 50 applicants were elected to the grade of Associate; 843 Students were enrolled.

Monthly disbursements were reported by the finance committee and approved by the board of directors as follows: August, $24,804.67; September, $19,296.69; October, $35,234.32.

Upon the recommendation of the finance committee, the board authorized the transfer of the sum of $7,500 from last year's surplus in general funds to the reserve capital fund, and its investment in General Motors Acceptance Corporation bonds; and appropriated from last year's surplus the sum of $1,500 for the Institute's share of the cost of new book stacks for the Engineering Societies Library.

A budget, which had been prepared by the finance committee, was adopted for the appropriation year beginning October 1, 1937. Detailed budget information may be found on other pages in this issue.

The budget included provision for the reestablishment of cash prizes of $100 each for the national prize for initial paper and the national prize for Branch paper and of $25 each for the District prizes for initial papers, as recommended by the committee on award of Institute prizes if complete restoration this year of all cash prizes should not be considered practicable; also for the continuation of the cash prizes of $25 each for the District prizes for Branch papers.

A revised publication policy was adopted, as recommended by the publication committee. (Announcement was made in ELECTRICAL ENGINEERING for November 1937, page 1409.)

The chairman of the publication committee reported on the sales of the "Lightning Reference Book," which had been prepared by a subcommittee of the committee on power transmission and distribution and published by the AIEE. The sales indicate that the project will be self-sustaining.

Upon recommendation of the Section and District officers concerned, the board approved the dates, August 9–12, 1938, for the Pacific Coast convention to be held at Portland, Oregon.

Sections 81 and 68 of the by-laws were amended as follows, to bring them in accord with action of the board of directors, in June 1937, in approving certain recommendations of the committee on safety codes, which included a change in name of the committee to "committee on safety":

Section 81 changed to read:

**Sec. 81. The committee on safety shall consist of 15 members, and shall consider and investigate matters relating to the protection of persons and property against hazard due to or resultant upon the presence of electricity or the use of electrical apparatus, material, and appliances, and shall report to the board of directors such recommendations thereon as it shall deem desirable for action by the Institute. To this end it shall encourage and co-ordinate safety considerations by other Institute committees in their respective fields, and with the approval of the board of directors, may arrange for co-operative relations with other bodies in the consideration of electrical hazard.**

The first sentence of section 68 changed to read:

**Sec. 68. The technical program committee shall consist of 9 members; and the chairman of each technical committee, the chairman of the committee on co-ordination of Institute activities, and the chairman of the committee on safety, *ex-officio*.**

The following board members were selected to serve as members of the national nominating committee for the year 1937–1938: C. R. Beardsley, O. B. Blackwell, V. Bush, R. W. Sorensen, and A. C. Stevens. Mr. C. R. Jones was designated an alternate.

Upon recommendation of the standards committee, the board approved a revised edition of American Standard for Power Operated Radio Receiving Appliances, which had been submitted for approval by the Underwriters' Laboratories, proprietary sponsor for the project.

It was reported that, at the annual meeting of The Engineering Foundation on October 14, the budget for the fiscal year October 1, 1937, to September 30, 1938, was adopted, and it contained appropriations for research projects recommended by the AIEE, namely, stability of impregnated-paper insulation, and electric shock.

Other matters were discussed, reference to which may be found in this or future issues of ELECTRICAL ENGINEERING.

# Tulsa Section Holds Organization Meeting

Eighty-one members and guests attended the organization meeting of the AIEE Tulsa (Okla.) Section, October 18, 1937, which was authorized by the Institute's board of directors June 24. This is the Institute's 64th Section, the 63d having been organized recently at Wichita, Kans. Officers elected to take office immediately are: R. K. Lane (M'37) Public Service Company of Oklahoma, Tulsa, chairman; A. Naeter (A'23, M'30) Oklahoma Agricultural and Mechanical College, Stillwater, vice-chairman; and D. J. Tuepker (A'37) Public Service Company of Oklahoma, Tulsa, secretary.

H. L. Andrews (A'16, M'26) vice-president, General Electric Company, New York, N. Y., spoke on "Modern Transportation," a subject of wide interest as indicated by the discussion which followed.

**Electricity Production Record.** Production of electricity for public use in the United States reached a new high of 118,809,000,000 kilowatt-hours in the 12-month period ending September 30, 1937, the Federal Power Commission has reported. Total production in September was 9,985,000,000 kilowatt-hours as compared with 10,378,-

000,000 in August, which, on a comparable basis, is an increase of 7.2 per cent over September 1936. Average daily production in September was 332,833,000 kilowatt-hours, 0.2 per cent less than the average daily production in August. Production by water power in September was 32 per cent of the total. Considerable increases have been recorded every month this year over the same months in 1936. Electric-utility power plants consumed 4,030,059 net tons of coal in September 1937. Of this amount, 3,872,264 tons were bituminous coal and 157,795 tons were anthracite, decreases of 4.0 per cent and 1.6 per cent, respectively, when compared with consumption in the preceding month.

## John Fritz Medal for 1937 Awarded to P. D. Merica

Paul Dyer Merica, director of research of the International Nickel Company and vice-president of the International Nickel Company of Canada, has been awarded the 1938 John Fritz Gold Medal, highest of American engineering honors, for "important contributions to the development of alloys for industrial uses." The award is made annually for notable scientific or industrial achievement by a board composed of representatives of the 4 national engineering societies of civil, mining and metallurgical, mechanical, and electrical engineers.

Doctor Merica's extensive research in theoretical and practical metallurgy has increased scientific knowledge in both ferrous and nonferrous fields, the citation of the board points out. "He has contributed generously to the science of metals, his work having covered the magnetic mechanical properties of steel; railway materials; failure of brass; the constitution, manufacture, and application of light alloys of aluminum; heat treatment of cast aluminum alloys; the precipitation theory of hardening of metals; and nickel and nickel alloys," it is declared.

Doctor Merica was born at Warsaw, Ind., on March 17, 1889. He studied from 1904 to 1907 at De Pauw University, which in 1934 conferred upon him the degree of doctor of science. In 1909 he received the bachelor of arts degree from the University of Wisconsin, and in 1914 the degree of doctor of philosophy from the University of Berlin. Following 5 years of work as research physicist in the United States Bureau of Standards, Doctor Merica in 1919 became director of research of the International Nickel Company. His home is at Millwood, N. Y.

He is a fellow of the American Association for the Advancement of Science, and a member of the American Chemical Society, the Electrochemical Society, the American Society for Testing Materials, the American Physical Society, the American Institute of Mining and Metallurgical Engineers, the American Institute of Civil Engineers, the Washington Academy of Sciences, the Institute of Metals, the Iron and Steel Institute, the Canadian Institute of Mining and Metallurgy, and Deutsche Gesellschaft für Metallkunde. He is the author of many articles and monographs in scientific and technical publications, and in 1929 received the James Douglas Medal.

Representatives of the AIEE on the board of award were J. B. Whitehead (A'00, F'12, past-president, Life Member), A. W. Berresford (A'94, F'14, past-president, member for life), and A. M. MacCutcheon (A'12, F'26, past-president).

## Noble Prize Awarded to Institute Member

For his paper "Properties of Saturants for Paper-Insulated Cables," G. M. L. Sommerman (A'31, M'37) research engineer, American Steel and Wire Company, Worcester, Mass., has been awarded the Alfred Noble prize for 1937. This paper was published in the May 1937 issue of ELECTRICAL ENGINEERING, pages 566–76, and was presented for discussion at the AIEE 1937 summer convention held June 21–25 at Milwaukee, Wis. A biographical sketch of the recipient is included in the "Personal Items" section of this issue. Formal presentation of the award will take place at the AIEE 1938 winter convention to be held January 24–28 in New York, N. Y.

The Alfred Noble Prize was instituted in 1929 in honor of Alfred Noble, past-president of the American Society of Civil Engineers and the Western Society of Engineers, and consists of a $500 cash award and an engraved certificate. The award is made to a member of any grade of either the American Society of Civil Engineers, the American Institute of Mining and Metallurgical Engineers, The American Society of Mechanical Engineers, the American Institute of Electrical Engineers, or the Western Society of Engineers, for a technical paper of particular merit accepted by the publication committee of any of the foregoing societies for publication, in whole or in abstract, in any of their respective technical publications, provided the author, at the time the paper is accepted in practically its final form is not over 30 years of age. The recipient of the prize is selected by a committee of five members, consisting of one representative of each society, the award being based upon papers published by the societies within the 12 months preceding July 15 of each year. The first prize was awarded in 1931.

This is the third time that a member of the AIEE has been so honored, the 1932 award having gone to F. M. Starr (A'30, M'37) and the 1936 award to Abe Tilles (A'30, M'36).

## A T & T Commemorates Works of G. A. Campbell

A volume entitled "Collected Papers of George Ashley Campbell" has just been privately printed by the American Telephone and Telegraph Company "in appreciation of Doctor Campbell's long and distinguished service, and of his fundamental contributions to the development of electrical communication." Commemorating Doctor Campbell's brilliant services to telephony, this 548-page (seven- by ten-inch) cloth-bound volume also marks his retirement from active service in the Bell System (*EE Jan. '36 p. 122*). In addition to three early memoranda on loading, the full text of some 21 of his noteworthy contributions to technical literature on communication over a period of more than 30 years are included.

In a foreword to the volume, Doctor Vannevar Bush (A'15, F'24) vice-president and dean of engineering of Massachusetts Institute of Technology, says of Doctor Campbell: "...he stands out as the one to whom the telephone art owes the realization of the loaded line, the electrical filter, and the facile treatment of the transients which pulsate in its network, and as a modest, generous character who by his very nature has inspired others to broaden into a highway the trail which he brilliantly blazed into the vast reaches of science and engineering."

ELECTRICAL ENGINEERING appreciates being authorized to state that requests for copies of this commemorative volume will be entertained by the American Telephone and Telegraph Company, 195 Broadway, New York, N. Y., as long as the rather limited edition lasts.

**Scholarship Available.** The Elizabeth Clay Howald scholarship, which carries a stipend of $3,000 payable in 12 monthly installments, was endowed by the late Ferdinand Howald, an alumnus of The Ohio State University. Any person who has shown marked ability in some field of study and has in progress work, the results of which promise to constitute important additions to knowledge, shall be deemed eligible to appointment for this scholarship. The scholar will be expected to devote his time uninterruptedly to the pursuit of his investigation. If the scholar never has had any connection with The Ohio State University, he must carry on his investigations there; otherwise investigations may be carried on elsewhere. Applications must be filed with the dean of the graduate school of The Ohio State University, Columbus, before March 1, 1938. The appointment will be made on April 1, and the time of appointment will begin July 1.

### Future AIEE Meetings

**Winter Convention**
New York, N. Y., January 24–28, 1938

**North Eastern District Meeting**
Pittsfield, Mass., May 1938

**Summer Convention**
Washington, D. C., June 20–24, 1938

**Pacific Coast Convention**
Portland, Ore., August 9–12, 1938

**Southern District Meeting**
Miami, Fla., November 1938

# National Research Council Continues Discussion of Insulation at New York Meeting

THE tenth annual meeting of the National Research Council's committee on electrical insulation of the division of engineering and industrial research attracted 144 registered guests and members of the committee for a two-day program devoted to the subject of dielectric research, November 4–5, at the Consolidated Edison Company building, New York, N. Y. Devoted to the interchange of information relative to many phases of dielectric research, this annual meeting, as usual, was notable in its unbiased attention to both the theoretical and practical aspects of the subject. The first technical session, devoted to the chemistry and physics of insulation, indicated clearly the increasing participation of the chemist and the physicist and the importance of their contributions in the solution of problems vitally important to both the manufacturer and user of electrical equipment. The committee, realizing the importance of co-ordination of the efforts of the chemist, physicist, and electrical engineer, is effectively contributing to many important advances by providing for the frank presentation of new problems and free, noncommercial discussions of products, manufacturing methods, and operating difficulties.

Representing the Consolidated Edison Company as official host, Doctor John C. Parker (A'04, F'12) vice-president of the company, delivered an address of welcome, encouraging the committee in the conduct of its work, and outlining what he termed the "selfish" interest of the electric power company in the work being carried on by the committee. Co-founder of the committee and continuing chairman, Doctor J. B. Whitehead, dean of the school of engineering of The Johns Hopkins University and past-president of the AIEE (1933–34), presided at the 3 technical sessions. W. F. Davidson (A'14, F'26), secretary of the committee, was chairman of the local committee on arrangements.

Among other features of the program were several informal group meetings for the discussion and outlining of special problems; the annual dinner meeting held Thursday evening at the Hotel Gramercy Park; a luncheon Friday noon, tendered by the Consolidated Edison Company; and several inspection trips to important plants and research laboratories located in the metropolitan area.

### Atom Physics in Insulation Research

At the Thursday dinner meeting, a motion picture "Electrifying New York" was presented by the Consolidated Edison Company, and Professor A. von Hippel (M'37) Massachusetts Institute of Technology, delivered a lecture "What Can Atom Physics Contribute to Insulation Research?" Professor von Hippel's lecture revealed the importance of some of the fundamental investigations of the theoretical physicist in the domain of insulation research, and served to emphasize the value of a closer understanding between the physicist and others working in that field.

At the conclusion of the technical sessions a resolution to record in the minutes of the meeting the death (ELECTRICAL ENGINEERING for November 1937, pages 1427–28) of Henry Wright Fisher (A'95, M'01, F'12) former consulting engineer for the General Cable Corporation, and one of the pioneer cable engineers in the United States, was introduced by William A. Del Mar (A'06, M'20) and adopted unanimously by the committee.

### Full Technical Program

Characterized throughout by spontaneous enthusiasm, the 3 technical sessions included a total of 21 papers, representing the efforts of 28 authors, and related discussions. Both the presentation of the papers and their discussions were entirely informal. For those readers interested in pursuing some of the subjects further, a complete list of titles and authors is given here. Although the committee expects that many of these papers will be published in various technical journals, so far only Doctor Whitehead's annual report and a paper by Doctors Whitehead and T. B. Jones have been published in ELECTRICAL ENGINEERING. Some few of the papers presented were extensions or continuations of papers presented at the meeting of the subcommittee on chemistry of the committee on insulation held recently at Rochester, N. Y., and reported in the November 1937 issue, page 1420. Others represented continuations of studies reported at previous meetings.

#### First Technical Session—Chemistry and Physics

RECENT PROGRESS IN DIELECTRIC RESEARCH (Annual Report of Chairman), J. B. Whitehead (A'00, F'12, past-president), The Johns Hopkins University, Baltimore, Md. [*November 1937 issue, pages 1346–52.*]

ELECTRICAL AND CHEMICAL STUDIES OF OIL OXIDATION, J. C. Balsbaugh (A'23, M'25), R. G. Larsen, and J. L. Oncley, Massachusetts Institute of Technology, Cambridge.

A continuation of a paper presented by one of the authors at the Rochester meeting of the subcommittee on chemistry, this paper presents relations between oxidation stability, acid formation, power factor, colloidal content, Grignard test, oil source, and refining methods. Many phenomena of the chemical and electrical aspects of this problem are still without any satisfactory explanation.

THE DIELECTRIC BEHAVIOR OF POLYMERIC MOLECULES IN DILUTE SOLUTION, J. W. Williams, University of Wisconsin, Madison.

Admittedly a highly theoretical approach of the chemist to dielectric theory, this progress report of work being done at the University of Wisconsin contributes to the general theory by a discussion of polymeric substances of high molecular weight, and shows evidence of dielectric polarization of such substances, principally in dilute solutions.

SOME RECENT STUDIES OF DIELECTRIC BEHAVIOR AND MOLECULAR ROTATION IN SOLIDS, C. P. Smyth, Princeton University, Princeton, N. J.

A correlation of dipole rotation in long-chain molecules with molecular size and with the dielectric constant of the material. This progress report of chemical research at Princeton University shows that solids consist of rod-like molecules with perpendicular axes; increased temperature causes rotation (change from the alpha to the beta form of the substance) and change of dielectric constant. For most substances the dipole moment is independent of frequency. "Small molecules,


## Membership—

Mr. Institute Member:

The advantages of membership in the Institute have been emphasized in several excellent papers in ELECTRICAL ENGINEERING. The steady progress of the Institute is material testimony of its value. The services and opportunities it affords are numerous and varied. Some are attracted by its tangible benefits and direct services. Others are more interested in its general activities and opportunities for technical association and advancement of the electrical engineering profession.

You no doubt had definite reasons for joining the Institute. Why not tell one of your nonmember associates what they were and which of its services and opportunities you have found most valuable? You may give him an idea or viewpoint he has not previously considered which will induce him to join, and thereby receive the benefits he rightfully deserves as one connected with a branch of the electrical industry.

M. W. Smith

Vice-Chairman, District No. 2
National Membership Committee

because of their greater symmetry, are more likely to rotate in a crystal than are large molecules, but a large number of the latter have been found to give a high dielectric constant to the solid by their rotation."

DIELECTRIC PROPERTIES OF CHLORINATED NAPHTHALENES, W. A. Yager, Bell Telephone Laboratories, Incorporated, New York, N. Y.

Investigation of the dielectric behavior of a commercial polar compound, a chlorine derivative of naphthalene.

ABSORPTION OF WATER BY PAPER AT HIGH TEMPERATURES, C. C. Houtz and D. A. McLean, Bell Telephone Laboratories, Incorporated, New York, N. Y.

Deals with the adsorption of water by insulating paper, instead of absorption indicated by the title. Aimed toward a better understanding of the fundamental nature of paper structure, the researches described produced adsorption data for various types of paper at various water-vapor pressures.

FURTHER STUDIES OF DETERIORATION IN INSULATING OILS, R. N. Evans, Consolidated Edison Company of New York, Inc., New York, N. Y.

Describing the methods of analysis of insulation deterioration as divisible into 3 classes (1) water evolution, (2) gas evolution and (3) miscellaneous, including electrical tests, this paper presents the results of studies based upon the second method, for predicting and analyzing cable failures caused by deterioration.

Second Technical Session—
Materials and Measurements

THE EFFECT OF FILLERS ON THE ELECTRICAL PROPERTIES OF RUBBER-SULPHUR COMPOUNDS, A. H. Scott, National Bureau of Standards, Washington, D. C.

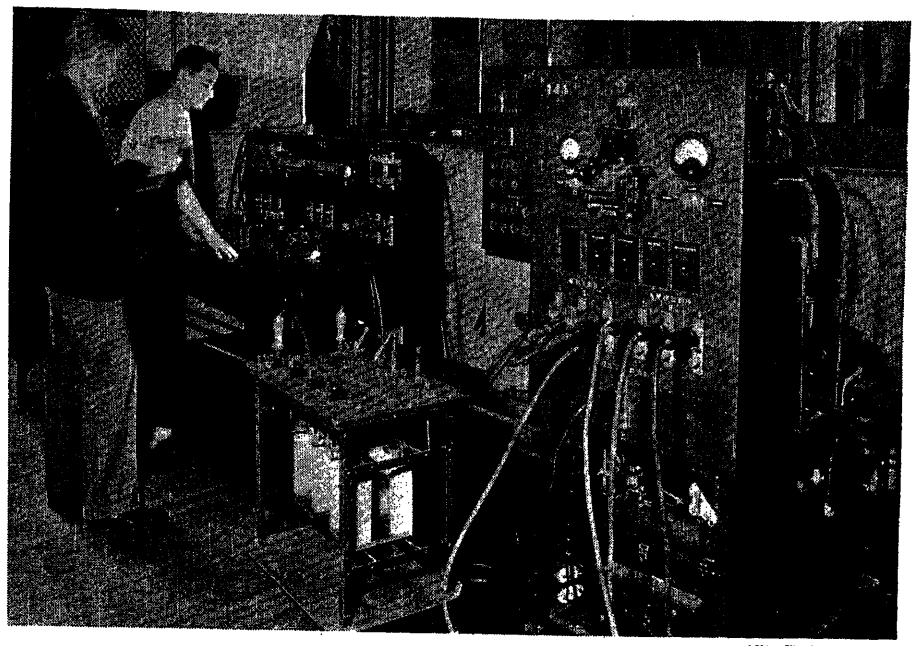
In a continuation of previous studies undertaken by the National Bureau of Standards, methods of improving the preparation of specimens and of testing have been described. "The study of the effect of fillers on the electrical properties of rubber has so far been concerned only with spherulized "kaolin" (kaolin in the form of tiny spheres). With no kaolin the power factor was 0.0026 and the dielectric constant was 2.61. With 26.5 per cent of kaolin (by volume), the power factor was 0.0047 and the dielectric constant was 3.23. The d-c conductivity did not appear to be affected by kaolin. The dielectric constant decreased linearly with the logarithm of frequency and the power factor passed through a minimum as the frequency was increased."

RUBBER AS A DIELECTRIC, A. R. Kemp, Bell Telephone Laboratories, Incorporated, New York, N. Y.

Dealing entirely with soft rubber compounds, "this report shows the extreme effect of moisture distributed heterogeneously in rubber in association with conducting substances on the dielectric properties. The loss in the insulating value of crude rubber upon exposure to water is explained on the basis of its latex particle structure with the impurities and moisture located in the particle interface forming a continuous phase . . . milling and vulcanizing crude rubber results in stabilizing its dielectric properties when the rubber is exposed to water. Rubber and gutta percha are shown to be nonpolar substances which are not appreciably affected by large contents of moisture." The effect of fillers and pigments on dielectric properties of soft vulcanized rubber are described.

SURFACE CHARACTERISTICS OF FIBROUS INSULATION, K. S. Wyatt (A'32), The Detroit Edison Company, Detroit, Mich., and W. F. Davidson (A'14, F'26), Consolidated Edison Company of New York, Inc., New York, N. Y.

Outlining some of the problems concerning utility operating companies in determining the characteristics contributing to failure of fiber insulation, the methods of failure are described, and several practical tests for analyzing and predetermining such failures are indicated. Following the formal presentation of the paper by Mr. Davidson, co-author Wyatt spoke briefly about the correlation between the amount of gas involved and the life of paper impregnated with oil, describing some of the European studies of the subject. Quoting Van Dycke, a research engineer at The Hague, Netherlands, Mr. Wyatt pointed out that "there is a correlation between life and gas generation as determined by the method with hydrogen pressure; in proportion as the gas generation of the oil is greater, the life of the paper impregnated with it is shorter. This correlation does not exist with the methods at low pressure."



Allis-Chalmers Photo

**A demountable metal-tank mercury-arc rectifier embodying the characteristics of commercial-size equipment is used in the study of electronics in the laboratories of Massachusetts Institute of Technology, Cambridge; similar equipment is said to have been installed at Cornell, Harvard, Columbia, and other colleges**

THE EFFECT OF THE SURFACES OF THE ELECTRODES ON POWER FACTOR OF AN AIR CAPACITOR, A. V. Astin, National Bureau of Standards, Washington, D. C.

An extension of the National Bureau of Standards research work described at the 1936 meeting. Although no solid is included between the plates of an air capacitor, the capacitor has an appreciable power factor, because of surface characteristics of the plate. The 1936 report included investigations of only 4 materials for plates; the present paper, including a description of the effect of relative humidity on power factors, gives results for 10 materials. With aluminum plates a negative phase-defect angle at high humidity was observed, and was found to be more marked for large plate spacing than for smaller spacing.

THE POWER FACTOR OF AIR CAPACITORS, W. B. Kouwenhoven (A'06, F'34) and E. L. Lotz (Enrolled Student), The Johns Hopkins University, Baltimore, Md.

Although describing independent research work done at The Johns Hopkins University, scope is almost identical with preceding paper.

THERMAL BREAKDOWN OF PLASTIC INSULATING MATERIALS, R. M. Fuoss, General Electric Company, Schenectady, N. Y.

A continuation of investigations described at the recent Rochester meeting of the subcommittee on chemistry, this investigation embraced changes of resistance with changes in voltage caused by thermal variation. The thermal failures observed were caused by passage of current alone, not by puncture, and were found to be independent of thickness of the sample.

STUDIES OF BREAKDOWN IN COMPRESSED GASES, Alvin Howell (A'35) Massachusetts Institute of Technology, Cambridge.

Describing the breakdown of compressed air at voltages up to 500 kv and at high pressures, using direct current exclusively. The breakdown characteristics of gaps having various surface configurations have been studied, the characteristics of a gap consisting of a needle point opposite a plane being especially important, because such gaps are used in the Van de Graaf generators constructed at MIT. Present investigations indicate that such generators will not work well in compressed air at pressures above 200 pounds per square inch. In general, generators using compressed air may be made much smaller than the open-air type.

Third Technical Session—High-Voltage Insulation

MEASURING RATES OF OIL FLOW THROUGH PAPER, H. H. Race (A'24, M'31), General Electric Company, Schenectady, N. Y.

A description of the methods of measuring the rate of oil flow through flat sheets of paper in vacuum, to avoid inclusion of gas flow in the measurements. The method was extended to predict oil-flow characteristics by means of air-flow data.

PAPER-TO-OIL RATIO IN CABLES, E. W. Greenfield (A'34) Anaconda Wire and Cable Company, Hastings-on-Hudson, N. Y.

Because the ionization of power cables takes place in the voids in the insulation, the accurate determination of the most effective ratio of paper to voids is very important. Approaching these problems from a fundamental point of view, mathematical and experimental methods of determining the most effective arrangements of oil and paper layers are described.

STABILITY OF CABLE OILS EXPOSED TO ELECTRICAL DISCHARGE IN VACUUM, W. A. Del Mar (A'06, F'20), John H. Palmer (A'29), and E. J. Merrill, Habirshaw Cable and Wire Corporation, Yonkers, N. Y.

A description of oil-stability characteristics during accelerated life tests as used on power cables. Oils having stable gassing characteristics usually have somewhat unstable power-factor characteristics under electrical discharge in vacuum.

OIL OXIDATION IN IMPREGNATED PAPER, J. B. Whitehead, The Johns Hopkins University, Baltimore, Md., and T. B. Jones, Bell Telephone Laboratories, Incorporated, New York, N. Y.

A report of a series of studies of the oxidation process in cable paper impregnated with oil containing different amounts of oxygen, as indicated by changes in well-known electrical quantities. Separate studies of the effect of equal amounts of air and of nitrogen, of the behavior of the oil alone, and as affected by paper and metal, show something about the nature of the progressive changes found in the electrical characteristics. [*See pages 1492–1502, this issue.*]

STABILITY OF OIL-TREATED INSULATION, H. W. Bousman (A'25, M'36), General Electric Company, Schenectady, N. Y.

A long life test may not be the most important factor in judging an oil for use in a cable, for the

"specific optical dispersion of oil is known to be related to the life of oil-impregnated paper."

ELECTRICAL CHARACTERISTICS OF IONIZED GAS FILMS, C. L. Dawes (A'12, F'35), Harvard University, Cambridge, Mass.

Describes methods of measuring characteristics of ionized gas films. A capacitance method was used instead of a mechanical method for determining thickness of the gas films.

MECHANICAL UNIFORMITY OF CABLE INSULATION AND METHODS FOR ITS MEASUREMENT, K. S. Wyatt, The Detroit Edison Company, Detroit, Mich.

Ionization at the low stresses used in cables must take place between the layers. This report describes a method of examining these interstices without mechanical deformation of the layers. The specimen is "embalmed" in styrene, and wafer-like samples sawed from the specimen are translucent, being easily examined without complex equipment. "The uniformity of most electrical characteristics is dependent upon mechanical uniformity of the cable."

# The Institute Budget for the Year 1937-38

ALTHOUGH the members are familiar with the financial condition of the Institute, having seen the annual directors' report in the July issue of ELECTRICAL ENGINEERING, it is felt that many would appreciate a more detailed accounting of the $299,500 budget for the year ending September 30, 1938.

Accordingly, the following tabulation of estimated income and disbursements, adopted by the board of directors on October 28, 1937, is presented with comments which it is hoped will adequately explain the scope and purpose of those appropriations in which the membership is most vitally interested.

## PUBLICATIONS

*Electrical Engineering — Transactions.* The budget provides for the publication of an increased number of technical-program papers and general-interest articles. During the last appropriation year, 1,594 pages were used and 1,785 pages are planned for the current year—an increase of about 12 per cent. The appropriation for this purpose is approximately $83,300 as compared with an expense of approximately $77,800 for the preceding year—an increase of about 7 per cent. Roughly two-thirds of the increased cost results from the increased number of pages, the remaining third resulting from increased circulation and higher material costs.

The study of publication policy undertaken by the publication committee about a year ago, has been completed, with the co-operation of the technical program committee, and the recommendations were acted upon at the October meeting of the board of directors. The budget as adopted is based on the recommended revisions in publication policy and includes an appropriation of $7,900 to provide preprints of the accepted manuscripts of all papers for national meetings and papers approved by the technical program committee for District meeting programs. A limited number of these preprints will be provided without charge for the use of authors and the technical committees. Others may purchase them for five cents each at headquarters and at the registration desk at meetings, or for ten cents each by mail. There will be published regularly in ELECTRICAL ENGINEERING a list of preprints available.

Other provisions of the revised publication policy and the budget call for the publication in full in ELECTRICAL ENGINEERING of two-thirds of all technical-program papers and for the publication in ELECTRICAL ENGINEERING of the other third in "rewrite" or "abstract" form. TRANSACTIONS will include all formal technical-program papers in full and correlated with the approved discussions. Notwithstanding the increased number of pages and the increased material costs, the subscription price of TRANSACTIONS will be $4.00 as it has been in the recent past.

Additional information concerning the revised publication policy will be found in the November 1937 issue of ELECTRICAL ENGINEERING, page 1409.

*Yearbook.* An up-to-date revision of the YEARBOOK will be issued again this year and the budget includes approximately $6,800 for this purpose. Copies of the YEARBOOK are available without charge to members on request. An announcement will appear in the news columns of ELECTRICAL ENGINEERING when the book is ready for distribution.

## INSTITUTE MEETINGS

In conjunction with the publication of technical papers and discussions, the national and District meetings of the Institute, as well as the meetings of Sections, provide the greatest opportunity for the realization of Institute objectives. In organization work—whether it be social, political, trade, or the work of a professional group similar to the Institute—effectiveness of operation is measured to a great extent by the membership contact provided.

The appropriation for meetings' activities for the coming year is intended to cover particularly the routine printing and supplies expenses of the Middle Eastern District meeting, which was held in Akron, Ohio, October 13–15, 1937, the winter convention in New York City, January 24–28, 1938, the North Eastern District meeting to be held in Pittsfield, Mass., in May, the summer convention in Washington, D. C., June 20–24, 1938, and the Pacific Coast convention which will be held in Portland, Oregon, August 9–12, 1938. In addition, the appropriation takes care of those expenses of the 1937 Pacific Coast convention which were not reimbursed until after accounts were closed for the 1936–37 year, as well as routine expenses incurred at Institute headquarters and chargeable directly to meetings' activities.

In considering the amount appropriated for Institute meetings, attention must also be given to the provision for traveling expenses of Section and Branch delegates (see paragraph dealing with traveling expenses) who, together with the officers and members in attendance at the summer convention, hold an annual conference for the interchange of ideas and experiences. Of late years the scope of these conferences has broadened so that a considerable part of the discussion deals with topics of interest not only to members residing within Section territory but to the entire membership—in many cases the recommendations of the conference leading to the adoption of policies which are expected to enhance the benefits of membership and the usefulness of the organization.

## INSTITUTE SECTIONS

The major portion of the appropriation for Institute Sections is intended to cover the expenses of meetings as held during the year by 64 Section organizations. The By-Laws provide for a flat appropriation of $175 for each Section, plus an allowance of $1 for each active member residing within the territory of the Section on August 1.

As shown in the tabulation, other expenditures, charged directly to Institute Sections, comprise the cost of printing and supplies furnished by headquarters throughout the year, and that proportion of the headquarters' staff payroll which is allocated to Section activities.

## INSTITUTE BRANCHES

One hundred twenty Branches of the Institute are now established in schools of recognized standing throughout the country, where students hold regular meetings, as do the members in Institute Sections. The budget provides for the reimbursement of purely meeting expenses, the cost of necessary supplies for carrying on routine Branch work, and that portion of salary expense at headquarters which represents the time entirely devoted to Branch activities.

The appropriation for Institute Branches also provides for the reimbursemnt of miscellaneous expenses which develop incidental to Student conferences and conventions. Payments are not made to the individual Branches but to the committee in charge of a conference and cover the actual expenditures within a limitation of an appropriation of $5 for each Branch participating in the meeting.

## COMMITTEES

In view of the official record of Institute activities, as contained in the monthly journal, ELECTRICAL ENGINEERING, it is probably unnecessary to dwell upon the scope of the appropriations for the different committees of the organization. Nevertheless, a few comments regarding the larger appropriations may be of interest, as follows:

*Finance Committee.* For the third consecutive year the budget provides for the

engagement of investment counsel services, in an effort to insure the stability and security of Institute investments for the reserve capital fund, as well as for the special funds for which the Institute has accepted the responsibility of trusteeship. In addition, the appropriation takes care of the expense of the annual audit of Institute accounts for the fiscal year ending April 30, a report of which appears in ELECTRICAL ENGINEERING for July 1937.

*Membership Committee.* The work of this committee in bringing the advantages of membership to the attention of desirable candidates continues along much the same lines each year; therefore, a considerable portion of the committee's appropriation is devoted to the printing of necessary application forms and other membership literature describing the aims of the Institute. The distribution of this literature is handled almost entirely by the 64 local Section membership committees under the general direction of the national committee.

As shown in the annual report of the board of directors, 1,756 new applications were received during the last fiscal year, many from persons whose names were proposed for membership as a result of the communications addressed by the national committee to the general membership. The expense of the clerical work at headquarters in handling these applications, as well as the routine correspondence with Section membership committees, with members concerning the status of their affiliations, with Enrolled Students eligible for advancement to the Associate grade, etc., constitutes a charge to the appropriation. One other item is worthy of mention, i.e., the special payment of a portion of the entrance fee to the Section in which a new member is located, estimated to require this year at least $1,400 of the committee's appropriation.

*Standards Committee.* The activities of the standards committee for the past year have been so fully related in the annual report of the board of directors published in the July issue of ELECTRICAL ENGINEERING that further comment should perhaps be confined to the plans of the committee for the revision and printing of new editions of 11 standards, as mentioned below:

Measurement of Test Voltages in Dielectric Tests
Industrial Control Apparatus
Graphical Symbols
Automatic Stations
Electrical Measuring Instruments
Insulators
Indicating Instruments
Electrical Recording Instruments
Electrical Installations on Shipboard
Test Code for D-C Machines
Test Code for Apparatus Noise Measurement

The preliminary expense for composition and other printing expenses on account of the above-mentioned revisions will be charged to the appropriation of the standards committee, in addition to any miscellaneous charges and that portion of the headquarters' payroll which reflects the time devoted to the work of the committee.

*Technical Committees.* It has not been necessary to make separate appropriations for the technical committees inasmuch as all of the expenses of printing technical papers, under existing publication policies, has been chargeable to the publication committee. A nominal appropriation of $250, therefore, covers principally the expense of providing committee stationery and also minor expenses which will arise during the year. However, with the inauguration of the plan to reproduce authors' manuscripts, already mentioned, it is probable that $1,000 of the appropriation of $7,900 for such preprints will be transferred to the appropriation for technical committees, for use in reproducing those papers which are not intended for publication in the annual TRANSACTIONS.

### TRAVELING EXPENSES

The budget again provides for reimbursement of substantially all the expense incurred for railroad fare, Pullman accommodations and meals en route, in the traveling allowance to District, Section, and Branch representatives, to members of the board of directors, and to members of the national nominating committee. The traveling allowances are reimbursed on a uniform rate of 7 1/2 cents per mile, one way, mileage being obtained from the Official Table of Distances compiled by the United States War Department. The authorized traveling expense appropriations are as follows:

1. For each vice-president of the Institute to one meeting each year of each Section and each Student Branch within his geographical District, it being understood that joint meetings of Sections and Branches will be arranged as far as may be expedient.

2. For the vice-president, the District secretary, the vice-chairman of the national membership committee located in the District, the chairman of the District committee on Student activities, and the chairman and secretary of each Section within a District (or, if neither can attend, an alternate chosen by the executive committee of the Section) to one meeting each year of the District executive committee held within the District.

3. For the vice-president and secretary of each District, the counselor and the incoming Student chairman of each Branch within the District, and the appointed member of the committee on Student Branches located in the District to one conference on Student activities within the District each year under the auspices of the committee on Student activities of the District. Alternates for counselors not authorized. The allowance is available to alternates for Branch chairmen only upon advance approval by the vice-president of the District in each case.

4. For one delegate from each Section to the annual summer convention.

5. For all District secretaries to the annual summer convention.

6. For one Student Branch counselor from each District, to represent the committee on Student activities of the District, to the annual summer convention.

7. For all members of the national nominating committee to the annual meeting of the committee, held during the winter convention.

**Table I. Institute Income and Expenses for Year Ending September 30, 1937, and Budget for Year Ending September 30, 1938**

| | Actual Income and Expenses, Year Ending 9-30-37 | Budget for Year Ending 9-30-38 |
|---|---|---|
| **Income** | | |
| Dues | $195,963.61 | $207,300.00 |
| Students' fees | 11,028.00 | 11,000.00 |
| Entrance fees | 7,468.15 | 7,000.00 |
| Transfer fees | 855.25 | 1,000.00 |
| Advertising | 33,602.31 | 35,000.00 |
| ELEC. ENGG.—non-mem. subscriptions | 13,700.56 | 14,000.00 |
| TRANS. subscriptions | 6,058.52 | 5,750.00 |
| Miscellaneous sales | 9,977.01 | 7,000.00 |
| Badge sales | 1,752.21 | 1,750.00 |
| Interest on securities | 9,109.52 | 9,700.00 |
| Total | $289,515.14 | $299,500.00 |
| **Expenses** | | |
| **Publications** | | |
| Text matter (ELEC. ENGG. & TRANS.) | $77,803.40 | $83,320.00 |
| Preprints | | 7,900.00 |
| Advertising section | 14,146.94 | 15,600.00 |
| Year book | 6,195.93 | 6,760.00 |
| Institute meetings | 12,020.41 | 13,960.00 |
| **Institute Sections** | | |
| Appropriations | 21,051.68 | 25,000.00 |
| Other expenses | 5,477.32 | 6,050.00 |
| **Institute Branches** | | |
| Meetings expenses | 897.62 | 1,000.00 |
| Other expenses | 2,001.15 | 2,300.00 |
| **Committees** | | |
| Finance | 1,600.00 | 1,600.00 |
| Membership | 8,000.46 | 8,300.00 |
| Standards | 6,475.58 | 7,700.00 |
| Technical | 201.44 | 250.00 |
| Others | 198.53 | 1,175.00 |
| **Traveling Expenses** | | |
| Geo. Dist. exec. committees | 1,620.48 | 3,000.00 |
| Section delegates to summer conv. | 3,861.14 | 5,000.00 |
| Counselor del. to summer conv. | 760.21 | 750.00 |
| Dist. secys. to summer conv. | 574.96 | 900.00 |
| District Student conferences | 6,407.15 | 6,500.00 |
| President's appropriation | 2,312.82 | 1,500.00 |
| Vice-presidents | 227.60 | 750.00 |
| Board of directors | 4,690.60 | 6,000.00 |
| National nominating com. | 907.38 | 1,000.00 |
| Institute representatives | | 100.00 |
| **Administration** | | |
| Headquarters' salaries | 32,994.72 | 36,990.00 |
| Postage | 3,294.66 | 3,500.00 |
| Stationery&printing | 3,427.24 | 3,600.00 |
| Office equipment | 181.03 | 250.00 |
| Trav. expense, insurance, misc. supplies & services | 2,933.40 | 2,950.00 |
| Paper prizes | 140.00 | 600.00 |
| **Joint activities** | | |
| Amer. Engg. Council | 12,000.00 | 12,000.00 |
| Amer. Standards Assn. | 1,375.00 | 1,500.00 |
| Engrs. Council Prof. Dev. | 450.00 | 850.00 |
| Engg. Soc. Employment Serv. | 1,964.40 | 1,162.00 |
| Engg. Societies Library | 8,788.20 | 9,700.00 |
| United Engg. Trustees building assessment | 9,740.13 | 10,882.00 |
| U. S. Natl. Com. I.C.I. | 300.00 | 300.00 |
| Miscellaneous printing, etc. | | 3,500.00 |
| Authors' reprints | 1,628.70 | ..... |
| Reprints of standards | 815.11 | ..... |
| Lightning Reference Book | 4,964.88 | ..... |
| Miscellaneous | 223.24 | ..... |
| **Other expenses** | | |
| Membership badges | 1,709.71 | 1,750.00 |
| Text paper & env. in storage | 1,251.10 | ..... |
| Retirement salary | 2,700.00 | 2,700.00 |
| Miscellaneous | 416.18 | 310.00 |
| Total | $268,730.50 | $298,959.00 |

8. For members of the board of directors and the executive committee to meetings of the respective bodies.

It will be noted that the traveling expense allowance has been restored for both the chairman and secretary of each Section within a District in attendance at the annual meeting of the District executive committee, whereas the budget allowance during recent years provided for the attendance of but one representative from each Section. In addition, an allowance for traveling expense has been provided to the vice-chairman of the national membership committee, who is now a member of the executive committee in his respective geographical District.

### Administration

The duties of the headquarters staff being closely interwoven with the activities of the 24 standing administrative committees and 18 technical committees, it is easy to understand the allocation to this appropriation of approximately 41 per cent of the total of salaries paid to those members of the staff whose compensation is not chargeable elsewhere in the budget. This item also absorbs the full salaries of the national secretary and office manager, and temporarily includes an appropriation of $2,500 for authorized additions to the staff required by extra duties to be performed for Institute committees and to relieve a congestion of work which develops in some departments at certain seasons of the year; as this expense is incurred later it will be reallocated to the committee or other activity involved. The Institute still maintains the smallest staff per 1,000 members of any of the Founder Societies.

The work of general administration, joint activities, secretarial, and other duties for committees is so broad as to make it difficult to describe the specific services required of the staff within the limitations of space for this article.

### Prizes for Papers

On account of the severe effects of the depression upon Institute finances, the board of directors discontinued in the fall of 1932 all cash payments in connection with prizes for papers except those accompanying District Branch paper prizes. Upon the recommendation of the committee on Institute prizes, the board has restored in this year's budget the cash awards of $100 each for the national prize for initial paper and the national prize for Branch paper, as well as the award of $25 for the District prize for initial paper in each district. The budget again provides for the cash award of $25 for the District prize for Branch paper in each District, and for the issuance of certificates of award to the recipients of all other prizes.

### Joint Activities

The activities in which the Institute is engaged jointly with other engineering organizations are many and varied and have been so frequently brought to the attention of the membership through the news columns of the monthly journal that it is probably unnecessary to comment on the provisions of the budget for such activities beyond a statement of the amount expended last year and the anticipated expense for the present year. It will be noted that the Institute will contribute toward the support of American Engineering Council the same sum as during the preceding year. With respect to the joint activities which are internal in nature, it will be observed that the appropriation for the support of the Engineering Societies Library has increased in proportion to the higher membership figures as of the present year, and also that the assessment paid to United Engineering Trustees is calculated upon a basis which permits of the desired annual reserve for the depreciation and renewal fund.

### Other Appropriations

The remaining items in the budget are self-explanatory in nature, and for the present appropriation year beginning October 1, 1937, involve but a small percentage of the estimated total disbursements.

In closing these comments regarding the proposed expenditure of Institute income, mention should be made that during the year ending September 30, 1937, the board of directors authorized the transfer of $7,500 from general funds to the reserve capital fund, for investment purposes; a similar transfer was authorized at the meeting of the board held on October 28, 1937.

As stated in the budget message of President Harrison, printed elsewhere in this issue, the board of directors has adopted a budget of expenditures for the coming year which appropriates practically all of the estimated income for the corresponding period, and which is substantially in excess of the amount expended last year. It is the expectation of the board, however, that the resultant benefits to the entire membership will fully justify the increased expenditures. Each year the board of directors and finance committee endeavor to adopt a budget that places the proper emphasis on the different phases of Institute activities and which limits the annual expenditures to the total of anticipated yearly income. Membership dues, of course, comprise the principal source of Institute revenue, so that the success of all work planned for in the budget virtually depends upon the prompt collection of dues. It is gratifying to know that this situation is realized by the membership, as evidenced by the fact that the number who are in arrears for dues as of this date is at the lowest figure for several years.

**Civil Engineer Honored.** Arthur S. Tuttle, former head of the engineering force of the city of New York, N. Y., recently was awarded a certificate of distinguished service. The award was made by Mayor F. H. Laguardia before a large group of engineers and city officials assembled in the chambers of the Board of Estimate and Apportionment, the body that Mr. Tuttle had served as principal assistant engineer, deputy chief engineer, chief engineer, and consulting engineer for over 30 years. In presenting the certificate, the mayor stated that this is an age in which special training is an essential qualification for public office and that Mr. Tuttle's distinguished service to the city stands out as an example of what can be accomplished by obtaining the right men for such service. Mr. Tuttle is a life member of the American Society of Civil Engineers, and has served that society as treasurer, 1919–1920, vice-president, 1932–33: and president, 1935.

## More Hydro Power Scheduled for Texas

Preliminary plans incident to the proposed rehabilitation of the Austin Dam located on the Colorado River (of Texas) at Austin contemplate reconstruction of the dam to a height of 63 feet and the construction of a new power house on the west side of the river with an initial hydroelectric generating capacity of some 6,250 kw. Another 6,250 kw installation is planned for the Marshall Ford Dam, some 12 miles upstream from Austin, when that dam shall have been completed and adequate water becomes available.

Under the terms of a proposed agreement between the City of Austin and the Colorado River authority, the Austin Dam rehabilitation will be undertaken by the authority at a cost of about $1,800,000 financed by a PWA loan and grant. The authority is to lease the dam from the city for a 30 year period, furnishing $20,000 worth of free power to the city as rental. The original Austin Dam was finished in 1893, and destroyed by flood in 1900; it was reconstructed in 1911 but never accepted by the city. Through a court decree the city obtained the title in 1934.

**Annual Science Exhibition.** In concurrence with the annual meetings of several scientific organizations, the annual science exhibit of the American Association for the Advancement of Science is to be held at the Murat Theater, Indianapolis, Ind., December 27–30, 1937. Besides the product displays of various companies the exhibition will feature the recent scientific discoveries of individual investigators and noncommercial research organizations. Among these exhibits will be specimens of equipment used for the measurement of cosmic rays, samples of "heavy" water, and a series of photographs of a recent solar eclipse made by means of new and improved cameras built especially for the purpose.

**Poems by Prominent Member.** A collection of poems written during the past 25 years by Vladimir Karapetoff (A'03, F'12, Life Member) professor of electrical engineering at Cornell University, has been published under the title of "Rhythmical Tales of Stormy Years." The poems are classified under Lyrical, The Immigrant's Fun, A Crazy Quilt, Religious, Philosophy of Life, and Translations from the Russian. Some of the poems have appeared in various periodicals or been recited at conventions. Copies may be obtained from the Cornell Co-operative Society, Ithaca, N. Y.

# Effective Joint Action Among Technical Groups in Cincinnati

By dealing only with the broadest interests of its participating societies, the Technical Scientific Societies Council of Cincinnati, Ohio, has achieved notable success in the promotion of joint activities among technical and scientific groups in that city. The effectiveness of the carefully mapped plan of organization, which brings together in this co-operative effort ten organizations comprising a total of some 1,500 members, is evidenced by the fact that in the two years since the council was organized no serious difficulties have developed, growth and progress alone being noted. With the thought that the experience of the Cincinnati Council might be of assistance elsewhere, L. R. Culver, chairman of the AIEE Cincinnati Section (one of the participating bodies) has prepared the accompanying article which describes not only the final arrangements and results, but also the more difficult preliminary steps that were necessary to assure smooth sailing during the organization period.

The idea of closer contact and mutual support among groups of the Institute type was not new, even locally. There were or had been, in Cincinnati as well as in other large centers, more or less satisfactory local affiliations; it was considered desirable to analyze their difficulties and accomplishments as the preliminary step, before approaching all the groups whose co-operation was desired. Particular attention was given to the reasons for the collapse of previous aggregations of societies. Two elements appeared to be responsible for most of the bickering on the one hand, and lack of interest on the other, with eventual disbandment in either event: (1) too much centralization of authority in one of the participating societies, especially in financial matters; and (2) too few points of contact through which to maintain mutual interest. To forestall these troubles, the organizers in Cincinnati set as their guiding principles that no participating society would suffer any loss of autonomy, that the idea of joint progress and support would be kept actively alive by having several operating committees with definite duties and full representation, and finally that the whole structure would be explicitly subservient to its component parts.

By adhering strictly to the principles laid down, the organizers encountered little or no difficulty in convincing the principal members of the technical community that everything was to be gained by the formation of a technical council among them to promote their joint interests. Included in the program were publishing of notices, sponsoring of joint meetings, reducing of duplication of services, stressing of mutual aims, exchanging of information in overlapping fields of interest and, in general, eliminating sources of conflict while promoting friendly intercourse.

Changing conditions bring changing need no less in the scientific world than elsewhere. With this premise, the organizing committee conducted its work throughout the summer of 1935, laying down a code in which the societies defined their mutual relationships and established their council, restricting their pronouncements to stating their aims and the duties of the several operating committees. By-laws were not framed; in their place the salient actions of the governing committees are preserved for ready reference, as guides but not as mandates for the future. That the organization was carefully mapped out may be realized from the fact that two whole years of operation have disclosed no "sore spots," growth and progress alone being noted. In fact, the code has been revised only once and then only in very minor respects, principally in clarifying the wording.

It may be debatable that the experience of some 1,500 members of ten co-operating societies in Cincinnati may be used elsewhere, perhaps nationally, as a guide to effective group effort. The societies, however, feel that they have dealt only with the broadest interests in establishing their council. They offer the following code for study and, if found suitable, adoption by other technical and scientific groups. No attempt is made to analyze its parts, to point out its restricting clauses or to show how the committees are interrelated; if it requires such interpretation, it fails in its purpose.

### Section I—Name

1.01 The co-operative body of the technical societies of Cincinnati shall be known as the Technical and Scientific Societies Council of Cincinnati, hereinafter designated the Council.

### Section II—Purpose

2.01 The purpose of the Council shall be to bring together for co-operative effort in rendering more and better service and in furthering scientific and technical activities, the technical societies of the Cincinnati district, which have as their purpose the maintenance of a high professional standing.

2.02 The Council shall have no jurisdiction over the meetings or actions of the constituent societies individually or jointly, its purpose being limited to the co-ordination of the societies' activities.

### Section III—Participating Societies

3.01 The following societies are member organizations of the Council:

| | |
|---|---|
| ACS | American Chemical Society |
| AIEE | American Institute of Electrical Engineers |
| ASCE | American Society of Civil Engineers |
| ASHVE | American Society of Heating and Ventilating Engineers |
| ASM | American Society for Metals |
| ASME | American Society of Mechanical Engineers |
| ECC | Engineers' Club of Cincinnati |
| IES | Illuminating Engineering Society |
| IRE | Institute of Radio Engineers |
| SAME | Society of American Military Engineers |

3.02 The governing committee of the Council shall be empowered to approve requests of other qualified societies for participation in the Council. This committee shall also be empowered to accept the withdrawal of any society or for just cause to request the withdrawal of any society.

### Section IV—Administration

4.01 The administrative affairs of the Council shall be executed by the following committees:

A. Policy committee
B. Program co-ordination committee
C. Publication committee
D. Executive committee

4.02 The policy committee shall be the governing committee of the Council and shall consist of the presiding officers of the participating societies, the chairman of the Council's program co-ordination committee, the chairman of the Council's publication committee, secretary-treasurer of the Council, and two members-at-large.

4.03 The program co-ordination committee shall consist of representatives—one from each society—qualified to act upon their respective program and meeting-arrangement matters. It shall be the duty of this committee so to arrange the programs of the several societies as to reduce conflicts in dates, to encourage joint meetings of two or more societies and generally to promote effective co-ordination of their activities.

4.04 The publication committee shall consist of representatives—one from each society—qualified to act upon publication matters, and the editor of the Council's publication whenever such officer is appointed by the policy committee. It shall be the duty of this committee to prepare and distribute suitable publication material, including the announcements of the meetings of the constituent societies and such other items as the Council may devise.

4.05 The executive committee shall consist of the president of the Council who shall act as chairman, chairman of the program co-ordination committee who shall act as vice-chairman, chairman of the publication committee, secretary-treasurer of the Council, two members of the policy committee selected by that committee, and the junior past-president of the Council. It shall be the duty of this committee to supervise, initiate, and direct in detail the affairs of the Council on behalf, and subject to the approval, of the policy committee. In the event that a member of the executive committee is unable to perform his duties, the policy committee shall appoint a substitute to serve out his term, at the request of the president.

4.06 The chairmen of the several committees and the secretary-treasurer shall serve for a period of one year without re-election. However, each shall serve until his successor has taken office. All positions shall be honorary excepting that of editor.

4.07 Each society shall name, and report to the secretary of the Council, its representatives on the committees before September 1 of each year. Then an organization meeting shall be held by each committee not later than the 20th of September. Each committee meeting shall be called to order by its retiring chairman who first shall present a report of his committee work and make such recommendations as he desires. The retiring chairmen of the program co-ordination and publication committees then shall conduct secret ballot elections of their successors. The new chairmen of these two committees then shall take charge of their meetings and conduct their business, including elections of secretaries if the committees so desire.

4.08 At the organization meeting of the policy committee, after making his report and recommendations, the retiring chairmen shall conduct secret ballot elections of the following officers in the order given:

A. Two members-at-large of the policy committee, to be chosen from the membership in good standing in the constituent societies.

B. President of the Council (who serves as chairman of the policy and executive committees).

C. Secretary-treasurer of the Council (who serves as secretary of the policy and executive committees) to be chosen from the membership in good standing in the constituent societies and not necessarily otherwise a member of the policy committee.

D. One member of the policy committee to serve as member-at-large on the executive committee for a term of two years.

4.09 Each committee shall hold throughout the year such further meetings as may be required, or called by its chairman, but meetings in January and May at least are mandatory.

4.10 The secretary-treasurer of the Council shall perform the customary duties pertaining to his office, but shall be required to submit a financial report at the May meeting of the policy committee. Also, he shall be required to maintain an up-to-date digest of the important actions of the policy and executive committees, including those of earlier years, and to convey this digest to his successor at the organization meeting of the policy committee.

### Section V—Finances

5.01 The stated expenses of the Council shall be limited to expense in connection with the publication. They shall be apportioned equitably on

the basis of the services rendered. Each organization's proportionate share of the publication expenses shall be determined on an annual basis.

5.02 Any other expenditure must be approved by the policy committee.

SECTION VI—CODE REVISION

6.01 Code revisions involving financial considerations may be enacted or adopted by a three-fourths vote of the policy committee.

6.02 Such other regulations as may be necessary for the conduct of the business of the Council may be enacted or approved by majority vote of those present at any policy committee meeting.

In conclusion, it should be pointed out that the council started with a four-page monthly publication; this is now expanded to 24 pages and it reaches the membership at less cost than the four-page original. This publication, *The Cincinnati Engineer and Scientist*, supports a part-time editor and prints items of common interest in addition to the notices concerning the societies individually. For the present the publication schedule includes ten monthly issues from September through June, and a directory issue released during the summer interval. The 1937 directory includes a dual, alphabetical listing of the entire membership which required a 72-page issue. An innovation recently introduced consists of a gummed strip bound into the center of the publication and divided into sections by perforations; in these sections are printed the emblems of the various societies with associated current meeting dates and places, so that those who wish may detach the sections containing notices of meetings they plan to attend and stick them, in stamp fashion, to their appointment calendars as final reminders.

In addition to publication and other routine duties, the Council has arranged annual joint meetings of all societies at which the average attendance has been over 2,500. These concrete examples of the growth of the movement in Cincinnati are offered as an indication of its merits. It is believed that the general plan can be employed usefully elsewhere.

**ASHVE to Hold Meeting.** The 44th annual meeting of the American Society of Heating and Ventilating Engineers will be held at New York, N. Y., during the week of January 24, 1938. Joint sessions are planned with the American Society of Refrigerating Engineers and the National Warm Air Heating and Air Conditioning Association. The fifth International Heating and Ventilating Exposition also will be held concurrently at Grand Central Palace.

# Current Items From American Engineering Council

## A Public Works Department

Definite recommendations for a public works department to be created in the process of government reorganization which is still before Congress are to have consideration during the eighteenth annual meeting of the American Engineering Council's assembly in Washington, D. C., January 13–15, 1938. Special studies by the staff and a comprehensive report of the AEC public works committee regarding the structure of a public works department are to be ready for discussion at that time.

Engineers have advocated a public works department for many years and now that the President's committee on administrative management has also recommended the creation of a public works department, engineers are encouraged to believe that the proposal may be due for serious consideration by this next session of Congress. It is not likely to be without opposition, however, because even the Brookings Institution which made a study for Senator Byrd's committee, failed to support the idea although they did recommend many changes in public works and engineering functions.

One of the major problems is to determine what is public works and to name those bureaus or activities among federal government agencies which should be included in the initial structure of a public works department. The President's committee came to the conclusion that such a department should "advise the President with regard to public works" and that it should be prepared to serve other government agencies as indicated in the following quotation:

"To design, construct and maintain large-scale public works, which are not incidental to the normal work of other departments, except as their agent on request; to administer federal grants, if any, to state and local governments or other agencies for construction purposes, and to gather information with regard to public works standard throughout the nation."

The complexity of the problem is indicated by the fact that neither one of the more recent studies undertook to name those engineering or public works agencies or functions which should be drawn together into a public works department. The President's committee concluded its suggestion, as follows: "The committee does not assign to the new department particular agencies and bureaus, but leaves this assignment to the Executive when, and if, the Congress enacts a law setting up the general departmental structure."

Conditions with reference to "public works" have changed materially in recent years, and engineers in both public and private life have made many observations and acquired a vast amount of actual experience with public works programs. Recognizing that fact, American Engineering Council is anxious to help to unite engineers in their public responsibility with reference to public works activities undertaken by the federal government, the several states, and local committees. To that end, engineers and engineering organizations are invited to express themselves to the AEC public works committee.

## Scientific Research Legislation

The American Engineering Council has appointed a special committee to consider the ramifications of Congressman Randolph's H.R. 7939 for the promotion and coordination of scientific research activities as a means for the prevention of unemployment in the future. Congressman Randolph seems to be leading a school of thought which publicly subscribes to the philosophy that an even greater application of technology to industry and business is necessary to insure that expansion of capital outlets which guarantees an increasing volume of employment.

Although the Randolph bill has not come up for action in Congress and is still subject to change, it has aroused much interest among members of the engineering profession. A number of engineers have already filed criticisms and suggestions, and Randolph informs us that he is anxious to have reactions representing all fields of technology. Council has not formulated an official policy with reference to this legislation but the following observations are made available for the convenience of those engineers and engineering organizations who may be concerned about either federal government support or control of research in both pure and applied science.

In essence, Congressman Randolph proposes that instead of having a variety of research projects carried on by government bureaus and special research agencies seeking government funds in an unplanned way for their particular projects, these various efforts be co-ordinated through the establishment of an advisory board made up of representatives of the government, of scientists, and of industry. That approach to the problem has appealed to this organization.

Last year the land-grant colleges introduced a bill proposing the establishment of engineering experiment stations in each state paralleling in general the agricultural experiment station idea. Since the land-grant act is administered through the Agricultural Department, the land-grant colleges believe that any development of such experiment stations should be so administered. Meanwhile the state colleges in 19 states—in some of which there are also land-grant colleges—sought to have this bill modified so that money could be spent at state colleges as well as at land-grant colleges in particular states. In this proposal, the administrative machinery would be located in the Bureau of Standards of the United States Department of Commerce.

A third bill confused the issue further by proposing a plan for government expenditures in the field of business research, this one to be headed in the Department of Commerce. Each of these bills has had the active support in Congress of the particular group of representatives of educational associations, the land-grant colleges having a committee and the state colleges another, the business schools having a third. Mean-

while, of course, certain government bureaus, like the Bureau of Standards and the Bureau of Mines, seek money for fundamental research, and sometimes the regular functions of the government in their research efforts are confused with the proposals outlined above. So far, it has been impossible to secure a meeting of minds between the college groups. Within certain states, there is a feeling of sharp competition, and as a result in earlier years none of the bills have succeeded in passing largely because there has been no meeting of minds in the state by which the Congressman in that state could be induced to take action.

It seems that Congressman Randolph is approaching this matter in a way in which some order might be brought out of this chaos. While the American Engineering council has not committed itself to any detail of the bills, we have been assisting Mr. Randolph in securing all the information he can from all the sources, so he will have before him as complete a picture of the problem as possible before he revises his bill. Our understanding is that Congressman Randolph has the friendly support of the President in his efforts, and this seemed to be an added reason, if anything was to be done in this matter, for working with Mr. Randolph in perfecting his legislation.

## Accurate Maps and Public Works

In response to an invitation from the Federal Board of Surveys and Maps, the American Engineering Council, through its committee on surveys and maps, has prepared the following statement to be used by a special committee in an effort to have the "mapping agencies" seek additional appropriations from Congress for the acceleration of "basic mapping" under the Temple Act during the fiscal year ending June 30, 1939.

"American Engineering Council has for many years vigorously supported, in the public interest, the requests of our member engineering organizations that the basic map of the United States be completed at the earliest possible date. As a move in the right direction, American Engineering Council has accepted, in principle, the recommendations made by Secretary Ickes in response to Senate Resolution 281 which requested a program for expediting the topographic mapping of the United States. The recommendations involve a 20-year program and the expenditure of $100,000,000. They would give the Geological Survey $4,000,000 for topographic surveys and maps, and the Coast and Geodetic Survey $1,000,000 for first and second order control surveys in 1938 under such items as the directors of the surveys may designate.

"The committee on surveys and maps of American Engineering Council earnestly hopes that steps will be taken by the Bureau of the Budget and the Congress to appropriate the minimum of $5,000,000 that is called for in this program. They believe that in the interest of public economy, of present immediate need, and of the future conservation of our national resources, this step should be taken.

"Earlier communications from American Engineering Council to the President, to the committees of the House and Senate, and to the various federal and state agencies involved, have pointed out that the fulfilment of original Temple Act passed in February 1925 and supported uuanimously by map makers and map users alike, is long overdue. We can think of no more practical contribution to both national economy in a broad sense of planning and national economy in a strict budgetary sense than can be made by the administration and by the Congress at this time. . . .

"The committee, in supporting this first step toward an adequate mapping program, perceives it as only the beginning of a long desired objective and earnestly hopes that every effort be made to carry out the complete plan with additional appropriations annually of such size as will complete a basic map for the United States at the earliest possible date. The committee on surveys and maps of American Engineering Council wishes to record itself as willing to help forward this program in every proper way consistent with the great public desirability for fulfilment of a very real social and economic need for accurate knowledge of both horizontal locations and topography in all sections of this country."

# United Engineering Trustees, Inc.

## The Joint Engineering Organizations

United Engineering Trustees, Inc., was organized in 1904 as an instrumentality of the Founder Societies, the 4 national societies of civil, mining and metallurgical, mechanical, and electrical engineers. Its purpose is the managing of property and funds in which these societies have joint interests, and it is governed by trustees duly appointed by the societies as their representatives. It maintains 2 departments: (1) the Engineering Societies Library, and (2) The Engineering Foundation.

The corporation (UET, Inc.) manages the Engineering Societies Building and all trust funds placed in the hands of the United Engineering Trustees, Inc.

The Engineering Foundation, founded by the late Ambrose Swasey (HM'28) in 1914, is entrusted with the expenditure of income from endowment and other funds. The ultimate objective of Foundation is stated to be: "for the furtherance of research in science and engineering, or for the advancement in any other manner of the profession of engineering and the good of mankind."

The Engineering Societies Library is a free public engineering library, which, is operated for users at a distance, as well as for those who visit its rooms in the Engineering Societies Building.

In the accompanying articles may be found announcements of the elections recently held by UET and The Engineering Foundation, and abstracts of the annual reports of these organizations and of the Engineering Societies Library.

## Election of Officers of United Engineering Trustees, Inc.

Officers to serve the United Engineering Trustees, Inc., for the year 1937–38, were elected at the annual meeting of UET held in the Engineering Societies Building, New York, N. Y., October 28, 1937. D. Robert Yarnall, chief engineer of the Yarnall-Waring Company, manufacturers of power-plant specialties, Philadelphia, Pa., was elected president, and Albert Roberts and H. A. Lardner (A'94, F'13) were chosen vice-presidents. H. R. Woodrow (A'12, F'23) becomes treasurer, and J. P. H. Perry, assistant treasurer. John H. R. Arms, general manager, was re-elected secretary.

The names of all members of the board of trustees of UET for the year 1937–38, including both new and hold-over members, are as follows:

*Terms expiring October 1938*

| | |
|---|---|
| J. P. H. Perry | ASCE representative |
| H. A. Lardner | ASME representative |

*Terms expiring October 1939*

| | |
|---|---|
| J. P. Hogan | ASCE representative |
| Albert Roberts | AIME representative |
| D. Robert Yarnall | ASME representative |
| H. P. Charlesworth (M'22, F'28, past-president) | AIEE representative |

*Terms expiring October 1940*

| | |
|---|---|
| O. E. Hovey | ASCE representative |
| W. D. B. Motter, Jr. | AIME representative |
| K. H. Condit | ASME representative |
| H. R. Woodrow (A'12, F'23) | AIEE representative |

*Terms expiring October 1941*

| | |
|---|---|
| A. L. J. Queneau | AIME representative |
| F. M. Farmer (A'02, F'13, director) | AIEE representative |

Of these, O. E. Hovey, A. L. J. Queneau, and K. H. Condit became reappointed members at the annual meeting, upon presentation of credentials from the Founder Societies. W. D. B. Motter, Jr., fills the unexpired term of H. G. Moulton and H. A. Lardner fills the unexpired term of H. V. Coes. The following committees were appointed:

**Finance:** Albert Roberts, *chairman;* J. P. Hogan, H. A. Lardner, H. R. Woodrow, D. Robert Yarnall, *ex-officio.*

**Real Estate:** J. P. H. Perry, *chairman;* A. L. J. Queneau, K. H. Condit, H. P. Charlesworth, D. Robert Yarnall, *ex-officio.*

## Engineering Foundation Elects Officers

The annual meeting of The Engineering Foundation was held October 14, 1937, in the Engineering Societies Building, New York, N. Y. F. M. Farmer (A'02, F'13, director) was re-elected chairman, and D. Robert Yarnall was re-elected vice-chairman.

The executive committee is composed of these two, together with George E. Beggs, A. L. Queneau, and W. I. Slichter (A'00, F'12, national treasurer, member for life.)

O. E. Hovey was elected director, and John H. R. Arms was elected secretary.

These officers and the executive committee of The Engineering Foundation are elected by the Foundation board, from among its own members. The Engineering Foundation board is itself elected by the board of trustees of the United Engineering Trustees, Inc. The complete membership of the Engineering Foundation board for the year 1937–38 is as follows:

| Name | | Term Expires |
|---|---|---|
| *Four Trustees of U.E.T., Inc.* | | |
| A. L. Queneau | AIME | 1938 |
| D. Robert Yarnall | ASME | 1939 |
| H. P. Charlesworth | AIEE | 1939 |
| O. E. Hovey | ASCE | 1941 |
| *Eight Members Nominated by Founder Societies* | | |
| G. D. Barron | AIME | 1940 |
| G. E. Beggs | ASCE | 1939 |
| F. F. Colcord | AIME | 1938 |
| F. M. Farmer | AIEE | 1939 |
| W. H. Fulweiler | ASME | 1940 |
| Langdon Pearse | ASCE | 1938 |
| W. I. Slichter | AIEE | 1940 |
| A. E. White | ASME | 1939 |
| *Three Members-at-Large* | | |
| F. M. Becket | AIME | 1938 |
| J. V. N. Dorr | AIME | 1939 |
| E. R. Fish | ASME | 1939 |
| *Ex-officio, President, U.E.T., Inc.* | | |
| D. Robert Yarnall | | |

At the annual meeting members of the research procedure committee were appointed or re-appointed as follows:

D. R. Yarnall, *chairman*, representing The Engineering Foundation.

L. W. Chubb (A'09, F'21) director, Westinghouse Research Laboratories, Westinghouse Electric & Manufacturing Company, East Pittsburgh, Pa., representing AIEE.

F. F. Colcord, representing The Engineering Foundation.

W. H. Fulweiler, Wallingford, Pa., representing The American Society of Mechanical Engineers.

F. O. Scobey, senior irrigating engineer, United States Department of Agriculture, Berkeley, Calif., representing the American Society of Civil Engineers.

Sam Tour, Lucius Pitkin, Inc., New York, N. Y., representing American Institute of Mining and Metallurgical Engineers.

F. M. Farmer (A'02, F'13, director) *ex-officio.*

The personnel of other committees as appointed or re-appointed at this meeting is as follows:

IRON ALLOYS

G. B. Waterhouse, *chairman and director;* professor of metallurgy, Massachusetts Institute of Technology, Cambridge, Mass., representing American Institute of Mining and Metallurgical Engineers.

Director, National Bureau of Standards, Lyman J. Briggs, represented by Doctor J. G. Thompson, chief of section on chemical metallurgy, National Bureau of Standards, Washington, D. C.

Director, United States Bureau of Mines, J. W. Finch, represented by R. S. Dean, chief engineer, Metallurgical Division, Washington, D. C.

J. T. MacKenzie, metallurgist and chief chemist, American Cast Iron Pipe Company, Birmingham, Ala., representing American Foundrymen's Association.

John Johnston, director of research, United States Steel Corporation, Kearny, N. J., representing American Iron and Steel Institute.

Bradley Stoughton, dean of engineering, Lehigh University, Bethlehem, Pa., representing American Society for Metals.

Jerome Strauss, vice-president, Vanadium Corporation of America, Bridgeville, Pa., representing American Society for Testing Materials.

T. H. Wickenden, metallurgical engineer, International Nickel Company, New York, N. Y., representing The Society of Automotive Engineers.

J. H. Critchett, vice-president, Union Carbide and Carbon Research Laboratories, Inc., New York, N. Y., representing American Electrochemical Society.

Wilfred Sykes (A'09, F'14) assistant to the president, Inland Steel Company, Chicago, Ill., and a director; member-at-large.

F. T. Sisco, *editor.*

WELDING RESEARCH

C. A. Adams, (A'94, F'13, past-president, member for life) *chairman;* consulting engineer, Edward G. Budd Manufacturing Company, Philadelphia, Pa.

Everett Chapman, president, Lukenweld, Inc., Coatesville, Pa.

J. H. Critchett, vice-president, Union Carbide and Carbon Research Laboratories, Inc., New York, N. Y.

J. J. Crowe, engineer-in-charge of apparatus, research, and development department of Air Reduction Company, Jersey City, N. J.

## Table I. Summary of Annual Report of Finance Committee of U.E.T.

### Operation of Building

| | | |
|---|---|---|
| Operating revenue | | $ 159,636.82 |
| Less operating expenditures | | 135,291.79 |
| Net operating income before transfers to reserves | | 24,345.03 |
| Operating credit previous years | | 8,151.89 |
| Credit balance September 30, 1937 | | 32,496.92 |
| Transferred to general reserve fund | | 8,000.00 |
| | | 24,496.92 |
| Transferred to depreciation and renewal fund | | 15,000.00 |
| Net balance September 30, 1937 | | $ 9,496.92 |

### Operation of Library

| | | | |
|---|---|---|---|
| Maintenance revenue | $43,344.13 | | |
| Maintenance expenditures | 42,944.15 | | |
| Credit balance for year 1937 | 399.98 | | |
| Credit balance from previous year | 6,178.69 | | |
| Credit balance September 30, 1937 | | $ | 6,578.67 |
| Service Bureau revenue | 7,887.08 | | |
| Service Bureau expenditures and adjustments | 6,597.30 | | |
| Credit balance for year 1937 | 1,289.78 | | |
| Credit balance from previous year | 4,571.96 | | |
| Credit balance September 30, 1937 | | | 5,861.74 |
| Total net operating credit balance cumulated to September 30, 1937 | | $ | 12,440.41 |

### Funds and Property

*Combined Fund: Summary of Investments, September 30, 1937

| | Legal | Nonlegal | Book Value | Market Value |
|---|---|---|---|---|
| Funds included: | | | | |
| Engineering Foundation fund | $494,311.38 | $283,226.19 | $ 777,537.57 | |
| Edward Dean Adams fund | | 90,873.03 | 90,873.03 | |
| Library endowment fund | 92,728.21 | 75,210.25 | 167,938.46 | |
| Depreciation and renewal fund | | 352,411.96 | 352,411.96 | |
| General reserve fund | | 9,170.68 | 9,170.68 | |
| Total | $587,039.59 | $810,892.11 | $1,397,931.70 | |
| Investments: Legal | | | $ 656,654.72 | |
| Nonlegal | | | 737,309.33 | |
| Total investment, September 30, 1937 | | | 1,393,964.05 | $1,311,690.72 |
| Cash uninvested | | | 3,967.65 | |
| | | | $1,397,931.70 | |
| Real estate, cost of—September 30, 1937 | | | $1,987,793.92 | |
| Operating cash | | | 19,280.65 | |
| Accounts receivable, gross | | | 4,196.10 | |
| The Engineering Foundation—unexpended income | | | 18,375.11 | |
| The Engineering Foundation—temporary investments | | | 6,180.00 | $ 6,885.00 |
| Alloys of iron research—unexpended income | | | 5,259.75 | |
| The Engineering Foundation custodian fund assets | | | 500.00 | |
| Welding research—unexpended income | | | 6,299.89 | |
| Henry R. Towne engineering fund | | | 50,544.18 | $ 36,676.97 |
| Total | | | $3,496,361.30 | |
| **Moneys Held for Special Purposes** | | | | |
| Endowment committee (Adams expense fund) | | | $702.57 | |
| Special Library binding fund (W. S. Barstow) | | | 430.33 | |
| **U.E.T., Inc., Custodian of John Fritz Medal Fund** | | | | |
| Securities held September 30, 1937 | | | $3,500.00 | $ 3,535.00 |
| Cash on hand September 30, 1937 | | | 225.38 | |

*A group of funds managed as one for convenience and economy in investment transactions.

A. S. Douglass, construction engineer, Detroit Edison Company, Detroit, Mich.

C. L. Eksergian, chief engineer, Budd Wheel Company, Detroit, Mich.

A. J. Ely, mechanical engineer, Standard Oil Development Company, Elizabeth, N. J.

H. M. Hobart (A'94, F'12, member for life) consulting engineer, General Electric Company, Schenectady, N. Y.

D. S. Jacobus (A'08, member for life) advisory engineer, The Babcock and Wilcox Company, New York, N. Y.

G. F. Jenks, colonel, Ordnance Department, United States Army, Washington, D. C.

Jonathan Jones, chief engineer, fabricated steel construction, Bethlehem Steel Company, Bethlehem, Pa.

P. G. Lang, Jr., engineer of bridges, Baltimore and Ohio Railroad, Baltimore, Md.

F. T. Llewellyn, research engineer, United States Steel Corporation, New York, N. Y.

Aubrey Weymouth, vice-president and chief engineer, Post and McCord, Inc., New York, N. Y. (Alternate for Jonathan Jones.)

William Spraragen (A'17, M'20) *secretary*, technical secretary and editor, New York, N. Y.

BARODYNAMIC RESEARCH: ADVISORY COMMITTEE

H. N. Eavenson, mining engineer, Pittsburgh, Pa.

H. G. Moulton, consulting mining engineer, New York, N. Y.

J. W. Finch, director, United States Bureau of Mines, Washington, D. C.

Chairman Farmer is Foundation's representative on the executive committee of National Research Council.

## Annual Report Issued by United Engineering Trustees, Inc.

The annual report of United Engineering Trustees, Inc., for the year ending September 30, 1937, has been submitted by G. L. Knight (A'11, F'17), president. The year showed reasonable stability in finances, full occupancy of the Engineering Societies Building, an increasing use of meeting halls, and improvement in the protection of property including resumption of contributions to the depreciation and renewal fund which had by necessity been withheld since 1932. Engineering Societies Building in its thirty-first year of activity remains in good physical condition with a minimum of repairs and maintenance expense. Minor improvements have been made in certain meeting-hall facilities. The American Institute of Chemical Engineers now has made its headquarters in the Engineering Societies Building.

The depreciation and renewal fund additions of $12,000 a year ceased in 1932 in order to lighten the building operating assessment against the societies at a time when the societies' income suffered from lowered volume of membership fees. During the year just closed, $15,000 has been added to the fund, the value of which is shown to be $352,411.96 against a building held at $1,447,793.92. A summary of the report of the U.E.T. finance committee is given in table I.

A new edition of history, charter, and by-laws of the corporation, the first since 1931, was issued just prior to the close of the fiscal year, and gives much of historical and legal interest not only to trustees and members of the Founder Societies, but also to any person who may wish to make a gift or bequest to the corporation or its departments for the advancement of science and engineering.

## Annual Report Issued by Engineering Foundation

The annual report of the Engineering Foundation for the year ending September 30, 1937, has been submitted by F. M. Farmer (A'02, F'13, director) chairman of the Foundation board. Chairman Farmer conducted the affairs of the Foundation during the year with the assistance of John H. R. Arms, secretary of United Engineering Trustees, Inc., following the death on March 14, 1937, of Doctor Alfred D. Flinn, secretary and director of the Foundation since 1917.

A summary of the capital fund of the Engineering Foundation and a condensed financial statement follows:

**Capital Funds**

| | |
|---|---|
| Endowment, total book value on September 30, 1937 | $872,000 |
| E. H. McHenry bequest, in hands of executors until decease of 2 life beneficiaries, appraised at probate of will in 1931, approximately | 400,000 |
| Fifth Swasey gift | 89,102 |

The capital funds are held and administered by United Engineering Trustees, Inc. The net income from endowment was $36,596.78 for the fiscal year ended September 30, 1937. The Foundation board has discretion in use of income. For many of the enterprises which the Foundation has aided, large contributions of money, services, and materials have been obtained from others.

**Expendable Resources**

| | | |
|---|---|---|
| Balance on October 1, 1936 | | $17,798.93 |
| Receipts | | |
| Income from endowment | $36,596.78 | |
| Income from minor items | 666.44 | 37,263.22 |
| Total resources | | $55,062.15 |
| **Disbursements** | | |
| Research projects | $22,134.28 | |
| Promotion of research and administrative expenses | 8,572.76 | |
| Total for furtherance and support of research | | 30,707.04 |
| Balance on October 1, 1937 | | $24,355.11 |

Money "contributions" from organizations and individuals, for specific activities, passed through the Foundation's accounts from its organization to September 30, 1937, totaled $282,851.60.

During the year ending September 30, 1937, the Foundation aided the following activities:

**Soil Mechanics and Foundations Division** (ASCE, $2,000). The following studies have been completed, or are under way:

(*a*) Settlement of structures. Progress report in the September 1937 ASCE *Proceedings*.

(*b*) Internal earth pressures. Studies have been made principally in New York City and Detroit. Report prepared and now before the publications committee of ASCE.

(*c*) Observed settlement of structures in Egypt. A report is being prepared.

(*d*) Properties of clay-type soils. Many thousands of tests have made made during the year but the program is not yet completed.

(*e*) Lateral stability of sheeting and piles. Some preliminary results have been published.

(*f*) Properties of "quick sands." Investigation just being started.

(*g*) Stability of earth dams subject to seepage. A series of tests is now under way.

(*h*) Problem of sand boils in connection with upward flow of water through soils. A series of tests is under way.

(*i*) Stability of earth banks subject to seepage. Data are being collected.

**Hydraulic Researches** (ASCE, $1,500). The following projects have been actively pursued during the year:

(*a*) Traveling waves on steep slopes. Studies of waves on a traveling belt through a glass-sided flume; 2 graduate theses have been written.

(*b*) Curves in open channels. Studies including motion pictures have been made with channels set up in Pyralin with the flow around a 180-degree bend.

(*c*) Phenomena of intersecting streams. After preliminary work with small metal flumes, square flumes have been constructed of Pyralin, experiments have been run with branch circuits at various angles, and studies made with water flowing in both directions. A thesis and a report have been prepared on the data obtained to date.

(*d*) Conversion of kinetic to potential energy. Library research and laboratory experiments being simultaneously conducted.

(*e*) Sedimentation at the confluence of rivers. A channel 12 by 24 inches and 65 feet long has been set up with a tributary channel and facilities have been provided for feeding sand to both flumes independently, and for varying the angle of convergence and the slope of the flumes.

**Alloys of Iron** (AIME, $5,000). This project, a critical compilation of the existing information on the alloys of iron, has been under way for several years. During this year 2 additional monographs were published, the total to date now being 9. Five chapters have been prepared for the tenth volume "The Alloys of Iron and Nickel—Volume I." A refinancing campaign carried on by the director of this project has resulted in subscriptions which with continued support by the Foundation at the present rate, will apparently finance this project to completion.

**Barodynamic Researches** (AIME, $2,500). Studies have been made of the following:

(*a*) Stress distribution in mine pillars and roofs. These studies are being made with the aid of the centrifugal photoelastic process previously developed in connection with this project.

(*b*) Methods of overcoming rock burst in deep mines.

(*c*) Development of artificial mine supports.

(*d*) The development of apparatus for the determination of pressure in loose materials.

A paper entitled "Modern Methods of Attacking Mining Problems," a direct result of the work on this project, was presented at the February 1937 annual meeting of AIME. It is expected that publication of information resulting from the above activities will be made during the coming year.

**Cutting Fluids** (ASME, $750). Experimental work completed on monel metal and reported in a paper in the November 1936 issue of ASME *Transactions*. Work being conducted on SAE 2345 steel.

**Critical Pressure Steam Boilers** (ASME, $850). This project has been under way for some time, the present program being the reaction between steam and metals at high temperatures. Apparatus is being built to test simultaneously 7 different tube materials.

**Fluid Meters** (ASME, $900). The present experimental program is on flow nozzles, an investigation which has been under way for some time, and is expected to require 3 years to complete. Articles concerning

this study have appeared in several technical journals.

**Strength of Gear Teeth** (ASME, $700). Twelve test runs have been made on a special surface fatigue testing machine. A series of reports on these tests of surface fatigue being prepared for publication.

**Lubrication** (ASME, $400). This project under a special research committee has included the compilation of a bibliography on lubrication started some time ago, a study of the problem of viscosity of lubricants under pressure, and investigation of increased viscosity under high pressure in bearing oil films. Two papers have been presented by members of the committee during the year. An extensive survey of lubrication research throughout the United States is being made.

**Effect of Temperature on the Properties of Metals** (ASME, $500). This extensive project, which has been under way for some years under the direction of a joint committee, the Foundation's contribution to which is a very small amount, was reorganized during the year, but a total of 9 research projects, either new or already under way, were prosecuted during the year.

**Stability of Impregnated Paper Insulation** (AIEE, $2,000). This project only got under way in 1936 under a supervisory committee designated by AIEE. Some time was spent in overhauling and improving equipment utilized on previous work. Certain preliminary test experiments involving a comparative study of a new procedure and the procedure previously used are nearly completed. Upon completion, the normal program, namely, the determination of the influence of the density and other physical properties of the paper on the electrical properties, the stability, and the life of impregnated paper insulation, will be started and will progress at a steady rate.

**Welding Research** (AIEE and AWS, $5,939). This project is very active under a large representative committee. The work is being carried on in 3 subdivisions, namely, fundamental research, industrial research, and literature. Each division has a record of important accomplishments during the year. A total of 32 reports comprising 368 printed pages were published during the year. These reports appeared in a supplement of the *Welding Journal*.

**Engineers Council for Professional Development** ($3,450). The death of General R. I. Rees has interfered with the carrying on of the work at rate contemplated; nevertheless much progress has been made under the chairmanship of Professor Chas. F. Scott (A'92, F'25, HM'29, past-president). The "accrediting schools" project has been highly successful so that during the year the perplexing problem of accrediting engineering education has been definitely solved. The total degree-granting schools that have been inspected to date is 134. Some of the Foundation funds were used for the general overhead expenses of this project but the cost of activity itself is self-liquidating from the fees paid by the schools, which to date have been something like $30,000. A study of the "evaluation of professional qualifications" is still under way. A study has been made of certain "aptitude tests" in 12 institutions which has confirmed previous reports that lack of schooling essential to engineering can be detected by these tests.

**Personnel Research Federation** ($1,200). A study of "Problems Incident to Engineering Advances" was made during the year and the results published in the *Personnel Journal*. The Federation considers that the extensive responses to these reports fully justify the investigation.

**Plastic Flow of Concrete** (University of California, $900). This investigation has been under way since 1926, and numerous reports have been issued to date, the most recent being a paper entitled "Plastic Flow and Volume Changes of Concrete" presented at the 1937 annual meeting of the American Society for Testing Materials. These later investigations included the studies to determine

(1) Effect of water-cement ratio and aggregate-cement ratio upon plastic flow.

(2) Effect of fineness and composition of cement upon plastic flow.

(3) Plastic flow of concrete in tension and in compression.

(4) Fiber strains in plain concrete beams under constant sustained bending moment.

(5) Stresses developed in large concrete cylinders under conditions simulating those occurring in mass concrete.

Detailed reports on the foregoing various projects are on file in the Foundation office, and show a large number of specific problems over a wide range, rather than a small number of elaborate problems. Further information on the Foundation and its activities may be obtained from the Foundation office, 29 West 39th Street, New York, N. Y.

## Annual Report Issued by Engineering Societies' Library

The annual report of the Engineering Societies' Library, containing information on the use of the library, its finances, and acquisitions, for the year ending September 30, 1937, has been submitted by Doctor Harrison W. Craver, director.

The number of readers was 26,750. In addition, 10,227 nonvisitors were supplied with information and material in various ways: 82 by the loan of 90 books, 112 by special bibliographies, 113 by translations, 2,374 by making 19,535 photocopies, 2,962 by letters, and 4,584 by telephone. Through all these methods, 36,977 persons used the library. In the previous year the library was used by 37,586 persons; 26,784 visitors and 10,812 nonvisitors. The number of users has thus remained practically constant, and the ratio of nonvisitors to visitors (2 to 5) has also remained the same.

Gifts and purchases during the year amounted to 11,003 pieces, of which 6,623 were new to the collection and were added to it. Sixty-seven volumes were added to the loan collection to meet requests from members, and the remaining items were given to other institutions or placed in the duplicate collection for sale or exchange. The sales of duplicates amounted to $431.50. Current issues of 1,416 periodicals were received, and 571 books, worth approximately $2,000, were received for review.

The gifts numbered 9,641 items; among them was that of Colonel W. J. Wilgus who presented his valuable library to the societies' library and the New York Public Library. Under an arrangement for the division of the collection planned by Colonel Wilgus and the directors of the 2 libraries, the societies' library received about 950 volumes and 255 cases of manuscript reports, etc., including all of the collection that dealt with engineering and that was not already on its shelves. A valuable collection of pamphlets by the late Frank J. Sprague (A'87, F'12, past-president) was presented by Mrs. Sprague. Other gifts were received from the *Engineering News Record*, the Perth Amboy Public Library, W. C. Huber, C. T. Hutchinson, Mrs. I. A. Ettlinger, Interborough Rapid Transit Company, Ralph Modjeski, J. L. Nicholson, George Orrok, F. F. Sharpless, and Mygren Werner, Inc.

A continuation of his gift by W. F. Barstow (A'94, F'12, Life Member) has made possible the restoration and rebinding of additional items in the collection of rare books.

On October 1, 1936, the library contained 138,742 volumes, 7,246 maps, and 4,298 manuscript bibliographies. During the year 184 volumes and 40 maps were withdrawn, and 2,734 volumes, 124 maps, and 64 bibliographies were added, bringing the total at the end to 141,292 volumes, 7,330 maps, and 4,362 searches. In addition, 3,701 pamphlets were added to volumes previously counted. The lending collection contained 660 volumes at the end of the year, and approximately 10,000 duplicate volumes and pamphlets were in stock. All new publications have been catalogued when received and made available at once. Cataloging is well abreast of receipts and there is no uncatalogued material except some recent gifts, which are being handled as rapidly as possible.

Substantial progress has been made on the periodical index, which is intended to provide a minutely classified guide to the important periodical literature of engineering. Over 20,000 references were added to the file, which now contains 187,000 references to material published during the past 10 years. The index is becoming increasingly popular with readers, and it is a matter of regret that funds are not available for its extension. More indexers are needed, as the present staff cannot cope with all that is being published.

Early in 1937, a microfilm copy of the library catalogue was made and deposited in a bank vault for safekeeping. From this film, duplicate card catalogues can be made at any time by a simple photographic process. Possession of the film has made possible an important reduction in the amount of insurance carried and so effected a continual annual saving of expense.

The budget for general operations was $46,700. Of this sum, $33,000 was appropriated by the Founder Societies, as follows:

| | |
|---|---|
| American Society of Civil Engineers | $8,890.90 |
| American Institute of Mining and Metallurgical Engineers | 6,921.40 |
| American Society of Mechanical Engineers | 8,399.50 |
| American Institute of Electrical Engineers | 8,788.20 |

Expenditures from the appropriation amounted to $42,944.15 of which $8,578.86 was spent for books and other equipment which increased the assets of the library. The service bureau received $7,887.08 and expended $6,581.87.

# Letters to the Editor

CONTRIBUTIONS to these columns are invited from Institute members and subscribers. They should be concise and may deal with technical papers, articles published in previous issues, or other subjects of some general interest and professional importance. ELECTRICAL ENGINEERING will endeavor to publish as many letters as possible, but of necessity reserves the right to publish them in whole or in part, or reject them entirely.

ALL letters submitted for consideration should be the original typewritten copy, double spaced. Any illustrations submitted should be in duplicate, one copy to be an inked drawing but without lettering, and other to be lettered. Captions should be furnished for all illustrations.

STATEMENTS in these letters are expressly understood to be made by the writers; publication here in no wise constitutes endorsement or recognition by the American Institute of Electrical Engineers.

## Rotor Flux Locus Concept of Single-Phase Induction Motor

*To the Editor:*

In the discussion (*EE, Aug. 1937, p. 1028–30*), of C. T. Button's paper "A Suggested Rotor Flux Locus Concept of Single-Phase Induction-Motor Operation," there was no intention of disagreement and any seeming disagreement is doubtless due to the inability of clearly expressing thoughts in words.

Mr. Button is correct in saying that the condition wherein the rotor flux may be considered as substantially constant along a diameter of the rotor is at or near synchronism. However, this condition was mentioned in the second paragraph and included throughout the comments.

He also states that the "pulsating component in the quadrature rotor axis" is neglected. While this statement is indefinite, it is assumed that it refers to the quadrature flux component. A careful reading of the comments will show that the quadrature flux is accounted for by the double-frequency flux-sustaining currents and the rotation of the rotor. In the assumed case where the rotor is held stationary and the field excited by rectified single-phase current, the factor of field rotation is eliminated and the flux acts only in one fixed direction, so that in this case there is no quadrature space relation, but the flux that is sustained by the double-frequency rotor currents while the primary magnetizing force goes through zero is the quadrature time flux.

The expression "after the rotor flux is once established" was merely intended to exclude the transient conditions as the rotor comes up to speed.

Considering the single-phase motor in the form of a stationary squirrel cage in a field excited by rectified single-phase current is the same method as used in considering a polyphase motor in the form of a squirrel cage in a d-c or constant field. It eliminates the factor of field rotation in both cases.

Mr. Button states that the conditions of coils *A* and *B* are transitory. This is true under slip conditions. However, this assumption of the two coils at right angles was used only in connection with synchronous conditions where they are not transitory. The comments clearly stated that in the practical motor under slip conditions these two sets of currents, the slip or torque currents of slip frequency and the flux sustaining currents of double frequency, less slip, are superimposed, and that the positions of the rotor conductors are constantly shifting from the transformer to the speed condition and vice versa. This action produces the characteristic single-phase rotor current form of one wave of slip frequency with another of double frequency less slip superimposed.

The expression "tendency to keep in synchronism" may be somewhat misleading. However, it does not indicate that the rotor actually attains synchronism, but that there is a tendency in that direction, a well-known characteristic of squirrel-cage motors.

The term "torque" was used in the sense of the torque produced by the electrical reactions between the field and rotor. Unless we eliminate mechanical rotation and reduce to stationary conditions as outlined by holding the rotor stationary and rectifying the single-phase exciting current, there is a negative torque due to friction, windage, etc., but this torque is not pulsating. Pulsating negative torque is only produced above synchronism.

The terms "speed voltage" and "transformer voltage" were used to indicate their source. A speed voltage involves a transformation between electrical and mechanical forces while a transformer voltage involves a transformation between electrical forces.

As Mr. Button states, the reactions under slip conditions are rather complex. It was intended to confine the argument more particularly to synchronous conditions and show how at synchronism, the double-frequency rotor currents maintain the flux approximately constant along a fixed rotor diameter, so that a rotary field is developed by the mechanical rotation of the sustained rotor flux. Other characteristics of the single-phase squirrel-cage motor that are explained by this method were mentioned, but space would not permit taking them up in detail.

Very truly yours,
EDWARD BRETCH (M'19)
President, The Advance Electric Company, St. Louis, Mo.

# Personal Items

A. P-T. SAH (A'35, M'36) professor of physics, Tsing Hua University, Peiping, China, recently was appointed president of the National University of Amoy, Amoy, China. Doctor Sah, who formerly served as visiting professor on the electrical engineering faculties of both The Ohio State University and the Massachusetts Institute of Technology, was born July 24, 1902, at Foochow, China, and after receiving the degree of bachelor of arts at Stanford University in 1924, enrolled in the electrical engineering school of Worcester Polytechnic Institute, where he received the degree of electrical engineer (1925) and doctor of science (1927). For one year after his graduation in 1927 he was affiliated with the Westinghouse Electric & Manufacturing Company, Pittsburgh, Pa., following which be became chief engineer of the China Radio Corporation, Tientsin. In 1928 he was appointed assistant professor of electrical engineering and physics at Tsing Hua University and in the following year he received his full professorship. In 1936 Doctor Sah returned to the United States as visiting professor of electrical engineering at The Ohio State University and Massachusetts Institute of Technology, and during his stay presented 2 papers on the engineering application of dyadics at the Institute's 1937 winter convention. Since 1935 Doctor Sah has served as a member of the Chinese National Electrotechnical Committee, affiliated with the International Electrotechnical Commission. He is a member of the Chinese Engineering Society, Chinese Science Society, Chinese Physical Society, and the Chinese Institute of Electrical Engineering.



A. P-T. SAH

G. M. L. SOMMERMAN (A'31, M'37) research engineer for the American Steel & Wire Company, Worcester, Mass., has been awarded the Alfred Noble Prize for 1937, as reported elsewhere in this issue. The award was made for his paper "Properties of Saturants for Paper-Insulated Cables," which was published in the May 1937 issue of ELECTRICAL ENGINEERING, pages 566–76, and presented at the AIEE 1937 summer

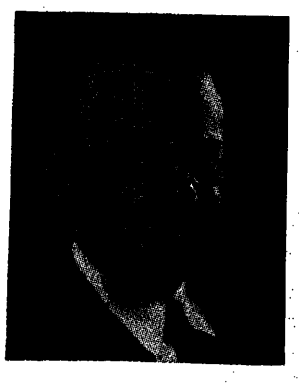
convention, Milwaukee, Wis., June 21–25. Doctor Sommerman was born July 2, 1909, at Baltimore, Md., and received the degrees of bachelor of engineering (1929) and doctor of engineering (1933) at The Johns Hopkins University. Following his graduation in 1929 he became a research assistant at that institution, devoting his attention to investigations sponsored by the former National Electric Light Association, and in the following year enrolled in the graduate school of electrical engineering. In 1931 he became an assistant physicist for the Consolidated Gas, Electric Light, and Power Company of Baltimore, and in 1934 joined the research engineering staff of the American Steel & Wire Company, where he has been in charge of fundamental researches on properties of materials for use in high-voltage cables. Doctor Sommerman is a member of the Institute's committee on research and was a member of the committee on instruments and measurements from 1934 until 1937. He has made many contributions to the technical literature on dielectrics, and has been an active member of the committee on electrical insulation of the division of engineering and industrial research of the National Research Council. He is a member of the American Physical Society, American Association for the Advancement of Science, American Society for Testing Materials, Sigma Xi, and Tau Beta Pi.

S. A. TUCKER (A'28) division engineer, Brooklyn Edison Company, Inc., Brooklyn, N. Y., recently became associate editor of *Power* a periodical published by the McGraw-Hill Publishing Company, New York, N. Y. Mr. Tucker was born October 11, 1905, at New Britain, Conn., and is an electrical engineering graduate of Yale University. Soon after his graduation he became associated with the Brooklyn Edison Company as a cadet engineer, and was associated with that company for more than 10 years.

A. J. ALLEN (M'27) operating vice-president of the Ohio Bell Telephone Company, Cleveland, recently was made president of the Cincinnati and Suburban Bell Telephone Company, Cincinnati, Ohio. Mr. Allen was born April 27, 1881, at Peoria, N. Y., and attended Geneseo State Normal School and Williams College. In 1907 he became associated with the Central District Telegraph Company, Pittsburgh, Pa., as a traffic assistant, later becoming division supervisor of traffic before leaving that company to join the engineering department of the American Telephone and Telegraph Company, New York, N. Y., in 1910. For several years his work with the American Telephone and Telegraph Company was concerned with local operating and engineering problems, but later he became a traffic engineer and in 1929 was made an assistant vice-president of the company. In the following year he was transferred to Cleveland as operating vice-president of the Ohio Bell Telephone Company.

T. H. HOGG (M'31) chief hydraulic engineer of the Hydro-Electric Power Commission of Ontario, Toronto, has been appointed chairman of the Commission. Mr. Hogg was born April 20, 1884, at Chippawa, Ontario, and received the degrees of bachelor of applied science, civil engineer, and doctor of engineering at Toronto University. In 1908 he became a member of the designing department of the Ontario Power Company, remaining there until 1911, when he became editor of *Canadian Engineer*. His affiliation with the Hydro-Electric Power Commission began in 1913, when he was appointed assistant hydraulic engineer. Doctor Hogg held that position until he was appointed chief hydraulic engineer in 1921. Since 1926 he has served as a consulting engineer for the government of the Dominion of Canada, the Province of Ontario, and for several local power companies.

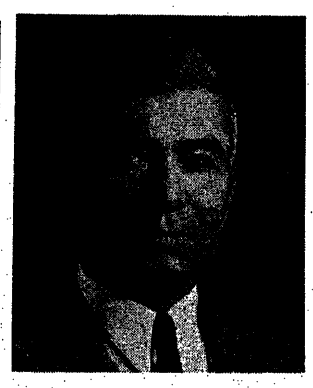
S. A. CANARIIS (A'25, M'27) assistant power engineer, Bureau of Water, Department of Public Works of the City of Pittsburgh, Pa., recently was appointed water works electrification engineer for the industrial department of the Westinghouse Electric & Manufacturing Company, East Pittsburgh, Pa. Born in Odense, Denmark, in 1893, Mr. Canariis received his formal technical education at the Polytechnical School of Odense, graduating in 1915. In 1922 he came to the United States, and was employed by several companies in various capacities before being appointed senior engineer of the commercial engineering division of the Duquesne Light Company, Pittsburgh, Pa., in 1926. Mr. Canariis became assistant power engineer for the Bureau of Water of the City of Pittsburgh in 1931.



A. J. ALLEN



G. M. L. SOMMERMAN



T. H. HOGG

R. M. BAKER (A'35) research engineer, Westinghouse Electric & Manufacturing Company, East Pittsburgh, Pa., has been appointed to the faculty of the Kansas State College of Agriculture and Applied Science, as an instructor in electrical engineering. Mr. Baker, a native (1903) of College Station, Texas, received the degree of bachelor of science in electrical engineering at the University of Texas in 1926, and the degree of master of science in electrical engineering at the University of Pittsburgh in 1931. Since 1928 he has been employed continuously in the research laboratories of the Westinghouse company, where he has been occupied chiefly in a study of electrical sliding contacts and related problems. During 1932–33 he studied in the Technische Hochschule of Charlottenburg, Germany, and was associated with the Siemens Research Laboratories in Berlin. Mr. Baker has presented several papers before the Institute.

ARTHUR SIMON (A'03, F'13) consulting electrical engineer for the Cutler-Hammer Co., Milwaukee, Wis., has established his own consulting engineering firm, with offices in Milwaukee. Doctor Simon was born in Ebersheim, Germany, May 21, 1881, was educated in the public schools of Germany, and later attended the Technical University of Darmstadt, from which he received a diploma of engineering in 1902. He came to the United States in 1903 when he entered the employ of Cutler-Hammer Company as an electrical engineer. In 1905 he was placed in charge of a-c engineering, and in 1921 was appointed consulting engineer to the company. He served as a member of the Institute's committee on power transmission and distribution, from 1923 until 1925. Doctor Simon will retain his connection with the Cutler-Hammer Company.

J. H. MANNING (M'14) president, Stone and Webster Engineering Corporation, New York, N. Y., has retired from active service. Born October 1, 1883 at Fall River, Mass., Mr. Manning was graduated from Worcester Polytechnic Institute with the degree of bachelor of science in civil engineering in 1906 before becoming associated with the consulting engineering firm of Hugh L. Cooper, New York, N. Y., as a draftsman. He remained with that organization until 1910, when he joined the staff of the Stone and Webster Engineering Corporation at Boston, Mass. He was superintendent of construction on many of the Stone and Webster projects throughout the United States, and has been associated with the engineering activities of that organization continuously for 27 years. Mr. Manning is a member of the American Society of Civil Engineers.

S. L. HENDERSON (A'12, M'34) section engineer for the Westinghouse Electric & Manufacturing Company, East Pittsburgh, Pa., has been promoted to the position of district engineer, with offices at New York, N. Y. A native of Boston, Mass. (1883), Mr. Henderson received the degree of bache-

lor of science in electrical engineering at Massachusetts Institute of Technology in 1910, following which he entered the test course of the Westinghouse Company. In 1913 he was appointed design engineer and successively became division engineer and section engineer. He was a member of the Institute's committee on electrical machinery from 1928 until 1935 (chairman 1932–34) and a member of the technical program committee from 1932 until 1934. At present Mr. Henderson is a member of the sectional committee on rotating machinery of the American Standards Association.

R. C. MASON (A'26) who has been for several years a research engineer for the Westinghouse Electric & Manufacturing Company, East Pittsburgh, Pa., recently has become associated with the Physisch Laboratorium, Utrecht, Netherlands. Mr. Mason is a native (1903) of Bentonville, Arkansas, and an electrical engineering graduate of the University of Arkansas (1924). After graduating from the student training course of the Westinghouse Company, he became an engineer in the materials and process engineering department in 1925, but later was transferred to the research laboratories. Mr. Mason was a member of the electrophysics (now basic sciences) committee from 1933 until 1937 (chairman 1936–37).

W. A. NICHOLS (A'37) since 1931 an engineer in the special products department of the Northern Electric Company, Ltd. Montreal, Que., Canada, recently became associated with the Canadian Broadcasting Corporation as chief engineer of radio station CBL at Hornby, Ontario. Mr. Nichols, a graduate (1928) of the University of Toronto, formerly was associated with Canadian National Telegraphs, and with the Northern Electric Company, where much of his work was concerned with sound equipment.

J. H. IRWIN (A'20) who has been a cable specialty salesman in the Chicago (Ill.) office of the Aluminum Company of America for the last 13 years recently was made manager of the company's Atlanta Ga. office. Mr. Irwin was born December 12, 1892, at Philadelphia, Pa., and was graduated from the University of Pennsylvania in 1915 with the degree of bachelor of science, immediately following which he joined the engineering sales staff of the Aluminum Company of America, with offices at Philadelphia, Pa.

E. W. CONROY (M'32) superintendent of light and power, Puget Sound Power and Light Company, Bremerton, Wash., has been transferred to the central district offices of the company at Seattle, Wash., and has been made assistant to the general superintendent of light and power. Mr. Conroy, a native of Helena, Mont., and an electrical engineering graduate of the University of Washington, has been associated with the Puget Sound Power and Light Company continuously since 1922.

G. W. THAXTON (M'36) formerly division engineering supervisor of the Rural Electrification Administration, Washington, D. C., has become electrical engineer for the Chase Brass and Copper Company, Inc., and the Kennecott Wire and Cable Company, New Orleans, La. Prior to his affiliation with the Rural Electrification Commission, Mr. Thaxton was division engineer of the Tennessee Valley Authority at Tupelo, Miss.

E. L. MORELAND (A'11, F'21) partner in the firm of Jackson and Moreland, Boston, Mass., and head of the department of electrical engineering of Massachusetts Institute of Technology, Cambridge, has been appointed to represent the Institute as alternate on the electrical standards committee of the American Standards Association. Professor Moreland is also Institute representative on the standards council of the American Standards Association.

FREDERICK BEDELL (A'91, F'26, past vice-president, member for life) recently retired from his position as professor of physics at Cornell University, Ithaca, N. Y., and will become professor emeritus. Doctor Bedell will continue to do research work at the University and in the R. C. Burt Scientific Laboratories, Pasadena, Calif., where he expects to spend the next few months.

H. S. DIXON (A'35) who has been an assistant engineer, Reclamation District No. 108, Knights Landing, Calif., recently became a member of the electrical engineering staff of Purdue University, Lafayette, Ind. A native (1910) of Woodland, Calif., Mr. Dixon received the degree of bachelor of arts (1931) and the degree of electrical engineer (1935) at Stanford University. He is a member of Tau Beta Pi.

W. M. LEEDS (A'32) electrical engineer for the Westinghouse Electric & Manufacturing Company, East Pittsburgh, Pa., recently awarded a B. G. Lamme scholarship by the Westinghouse company, has been granted a year's leave of absence to pursue graduate work at Massachusetts Institute of Technology, following which he will return to the switchgear engineering department of the company.

F. V. MAGALHAES (A'07, F'19) executive assistant to the president, Consolidated Edison Company of New York, Inc., New York, N. Y., has been appointed to serve as the Institute's representative on the committee on low-voltage hazards of the National Safety Council, and on the electrical committee of the National Fire Protection Association. Mr. Magalhaes is chairman of the Institute's board of examiners.

J. D. ROSS (A'08, F'12) superintendent of lighting, City of Seattle, Wash., and a former member of the United States Securities and Exchange Commission, has been appointed administrator of the Bonneville power project. Mr. Ross has been associated with the city lighting department of Seattle for 30 years, 26 of which have been as superintendent.

E. A. BALDWIN (A'07) vice-president and general European manager of the International General Electric Company, Paris, France, recently was made an officer of the Legion of Honor in recognition of his many services to France. Mr. Baldwin has been associated with the General Electric Company since 1896, and has been in the foreign department of the company since 1899.

O. F. ALLEN (A'10, F'24) consulting engineer, New York, N. Y., recently resigned from his position with the Public Works Administration in New York, to devote his entire time to his consulting engineering practice. He continues as managing director of Martin Motors, Inc., and as secretary and director of American Rezo, Inc.

C. F. HARDING (A'06, F'14, vice-president) head of the school of electrical engineering and director of the electrical laboratories of Purdue University, Lafayette, Ind., has been appointed to serve as the Institute's representative on the American Engineering Council assembly for the calendar year 1938.

W. H. BLISS (A'30) formerly an instructor in electrical engineering at the University of Maine, Orono, recently became a communications engineer for RCA Communications, Inc., New York, N. Y., where he is doing experimental work on radio facsimile transmissions.

R. A. SCHLEGEL (A'36) who has been colliery electrician for the Philadelphia and Reading Coal and Iron Company, Mahanoy City, Pa., recently became a service engineer with the Brown Instrument Company Industrial Division of the Minneapolis Honeywell Regulator Company, Philadelphia, Pa.

V. M. MONTSINGER (A'14, F'29) research engineer, General Electric Company, Pittsfield, Mass., has been appointed to serve as the Institute's representative on the electrical standards committee of the American Standards Association. Mr. Montsinger is chairman of the Institute's committee on standards.

W. M. BAUER (A'29, M'36) since 1929 an instructor in electrical engineering at Northwestern University, Evanston, Ill., now is a part-time assistant in electrical engineering at Harvard University, Cambridge, Mass., where he is enrolled in the graduate school as a candidate for a doctorate degree.

H. M. WITHEROW (A'28, M'36) designing engineer General Electric Company, Fort Wayne, Ind., has been transferred to the design department of the General Electric Company, Lynn, Mass. Mr. Witherow is a past chairman (1935–36) of the AIEE Fort Wayne Section.

MACKLEN KLEIMAN (A'37) assistant engineer, Thompson Gibb Electric Welding Company, Lynn, Mass., recently became welding engineer for the Lycoming Division of the Aviation Manufacturing Corporation,

Williamsport, Pa. Mr. Kleiman is a member of the American Welding Society.

F. E. JOHNSON (A'13, F'31, director) dean of the college of engineering, University of Missouri, Columbia, has been appointed to serve as the Institute's representative on the Engineer's Council for Professional Development for the term 1937–40.

F. J. SAFFORD (A'35) who has been an assistant in the electrical engineering department of Columbia University, New York, N. Y., recently was appointed a research assistant in the department of electrical engineering at Massachusetts Institute of Technology, Cambridge.

L. F. MOREHOUSE (A'16, F'20) has been elected to full membership in the British Institution of Electrical Engineers. Doctor Morehouse is technical representative in Europe of the American Telephone and Telegraph Company and of Bell Telephone Laboratories, Inc., with offices in London.

F. M. FARMER (A'02, F'13, director) vice-president and chief engineer of the Electrical Testing Laboratories, New York, N. Y., has been appointed to serve the Institute as representative on the United Engineering Trustees, Inc., for the 4-year term beginning October 1937.

H. A. LARDNER (A'94, F'13, member for life) vice-president, The J. G. White Engineering Corporation, New York, N. Y., has been elected a vice-president of United Engineering Trustees, and also a trustee of that agency, representing the American Society of Mechanical Engineers.

WILLS MACLACHLAN (A'08, F'21, past vice-president) consulting electrical engineer, Toronto, Ont., Canada, has been appointed to serve the Institute as representative on the National Fire Waste Council. Mr. Maclachlan is chairman of the Institute's committee on safety.

DOUGLAS MONTGOMERY (A'26) has resigned from the Westinghouse Electric & Manufacturing Company, New York, N. Y., with which company he was a field engineer, to become an electrical draftsman for The Detroit Edison Company, Detroit, Michigan.

J. E. ZIPOND (A'23) who has been an assistant electrical engineer for the public works branch, United States Treasury Department, Washington, D. C., recently became associated with the Duquesne Light Company, Pittsburgh, Pa., as an electrical engineer.

J. W. GRAY (A'36) formerly a teaching fellow in the physics department of the University of Washington, Seattle, now is an instructor in the electrical engineering department of the University of Idaho, Moscow.

G. H. BLIESNER (A'35) until recently farm electrification agent for the Puget Sound Power and Light Company, Mount Vernon, Wash., now has become agricultural electrical engineer for the Yam Hill Electric Company, Newburg, Ore.

R. F. HAYS, JR. (A'36) formerly an instructor in the department of physics, Mississippi State College, State College, now is employed as a vapor lamp engineer by the Westinghouse Lamp Division at Bloomfield, N. J.

E. R. PAIGE (A'35) until recently an electrical engineering instructor at Cornell University, Ithaca, N. Y., has become affiliated with the engineering department of the Niagara Hudson Power Corporation, Buffalo, N. Y.

H. H. HENLINE (A'19, M'26, national secretary) has been appointed to serve as the Institute's representative on the standards council of the American Standards Association for the 3-year term beginning January 1, 1938.

ROY WILKINS (A'16, F'29) who has been an engineer for the K-P-F Electric Company, San Francisco, Calif., now is associated with the firm of George E. Honn, San Francisco. Mr. Wilkins has been a consulting engineer in that city for several years.

FRANK WOREL (A'29) who has been chief toll testman of the Michigan Bell Telephone Company, Ann Arbor, has been transferred to the Grand Rapids office of that company as an exchange repairman.

H. L. COLLINS (A'35) has resigned his position as chief engineer of the Invincible Vacuum Cleaner Manufacturing Co., Dover, Ohio, to become production engineer with the Knapp-Monarch Company, St. Louis, Mo.

GEORG KEINATH (M'37) director of the laboratories of Siemens and Halske, Berlin, Germany, recently came to the United States to establish consulting engineering offices at New York, N. Y.

K. H. BLACK (A'37) second lieutenant, U.S. Army Corps of Engineers, Fort Lawton, Seattle, Wash., now is employed in the meter department of the Puget Sound Power and Light Company, Seattle.

K. E. V. HALLAR (A'31) formerly assistant operating and maintenance engineer with the Husqvarna Vapenfabriks, Huskvarna, Sweden, now is with the Stone and Webster Engineering Corporation, Boston, Mass.

H. E. REED (A'32) formerly an electrical operator for the Maine Seaboard Paper Company, Bucksport, now is employed as an electrical tester for the Westinghouse Electric & Manufacturing Company, East Pittsburgh, Pa.

C. V. POLING (A'27) formerly an electrical engineer in the Hawthorne works of the Western Electric Company, Inc., Chicago, Ill., has been appointed an assistant electrical engineer for the Tennessee Valley Authority, Knoxville, Tenn.

A. M. FLUKE (A'37) who has been a test engineer for the General Electric Company, Schenectady, N. Y., has been transferred to the Bridgeport, Conn., works of that company in the resistance welding engineering department.

R. A. TYLER (A'36) who has been assistant superintendent in the electric department of the Oklahoma Gas and Electric Company, Enid, has been transferred to the Oklahoma City offices of that company as service foreman.

J. R. EATON (A'27, M'35) until recently an engineer for the Consumer Power Company, Jackson, Mich., has enrolled in the graduate school of electrical engineering at the University of Wisconsin, Madison.

H. D. LARRABEE (A'06) operating superintendent of the Connecticut Light and Power Company, Norwich, Conn., has been transferred to the Willimantic offices of that company.

F. B. WESTON (A'33) who has been a draftsman for the General Electric Company, Bridgeport, Conn., now is a junior design engineer for M. H. Rhodes, Hartford, Conn.

G. K. WILLIAMS (A'34) until recently an electrical engineer at Cornell University, Ithaca, N. Y., now is employed in the inspection development laboratory of the Western Electric Company, Baltimore, Md.

H. R. WOODROW (A'12, F'23, past-director) vice-president of the consolidated Edison Company of New York, Inc., New York, N. Y., has been elected a vice-president of United Engineering Trustees.

## Obituary

ROBERT CALTHROP BROWN (A'03, member for life) vice-president of the Brazilian Tramway, Light, and Power Company, Barcelona Tramway, Light, and Power Company, Mexican Light and Power Company, Mexico Tramway Company, and Canadian and General Finance Company, Ltd., Toronto, Ont., Canada, died October 30, 1937. Mr. Brown, born June 1, 1866, at Medford, Mass., was graduated from Tufts College with the degree of bachelor of arts in 1888, and received the degree of electrical engineer in 1894. In 1889 he was employed by the Somerville Electric Light Company as lineman, but later in the same year entered the employ of the West End Street Railway Company, Boston, Mass., in its engineering department. In 1890 he was appointed assistant superintendent of electric power in the same company, which position he held for one year before resigning to take charge of the electrical work of the Brooklyn City Railroad, Brooklyn, N. Y., in 1891. In 1894 Mr. Brown became affiliated with the Montreal Street Railway Company as an electrical engineer, and from 1895 to 1898 was employed by the Halifax Tramway, Light, and Power Company as general manager. In 1899 he went to Brazil, where he remained until 1901 as general manager of the Sao Paulo Tramway, Light, and Power Company. From 1902 until 1905 he served as electrical engineer

with the Toronto and the Niagara River Power Company; in 1906 he was appointed managing director of the Mexican Tramways Company, Mexico City, and subsequently held numerous offices in Mexican and South American companies.

PHILIP PRICE BARTON (A'00, M'01, F'12, member for life) retired electrical engineer, Hartford, Conn., died September 3, 1937. Mr. Barton was born May 5, 1865, at Lock Haven, Pa., and was graduated from Cornell University with the degree of bachelor of philosophy in 1886; he then enrolled in the graduate school and was granted the degree of master of science in 1888, following which he was employed in the electrical department of the Cambria Iron Company, Johnstown, Pa. In the same year he became associated with the Allegheny County Light Company, Pittsburgh, Pa., but remained there only for a brief period before becoming a test engineer for the Westinghouse Electric & Manufacturing Company, East Pittsburgh, Pa., in 1889. Later he was transferred to the Chicago (Ill.) offices of that company as a construction engineer, and remained there until 1891, when he was employed in the office of the special agent of the Brush Electric Company, Pittsburgh, Pa., as engineer and salesman. After serving in a similar capacity in the Pittsburgh offices of the General Electric Company for a brief period, Mr. Barton was appointed assistant electrical superintendent of the Niagara Falls Power Company in 1899. Successively he became superintendent of operation, general manager, vice-president and general manager, serving concurrently as general manager of the Canadian Niagara Power Company, vice-president and general manager of the Niagara Junction Railway Company and the Niagara Development Company, and as director of the Bank of Niagara.

JAMES AQUILLA CORRELL (A'08, M'29) professor of electrical engineering, University of Texas, Austin, died October 30, 1937. Professor Correll was born in Wayne County, Ohio, May 4, 1883, and received the degrees of bachelor of science in mechanical engineering (1903) at Kansas State Agricultural College, bachelor of science in electrical engineering (1907) at Massachusetts Institute of Technology, and master of science in electrical engineering (1925) at the University of Texas. Following his graduation in 1903 he was appointed refrigeration engineer for the Louisiana Purchase Exposition at St. Louis, Mo., and following the close of the exposition, became assistant engineer for the Zeigler Coal Company, Zeigler, Ill. In 1907 he was apopinted to the faculty of the University of Texas as an instructor in electrical engineering, later becoming adjunct professor (1915), associate professor (1918), and professor of electrical engineering (1927). During the World War he was head of the engine division of the United States Government school of military aeronautics at the University of Texas. Professor Correll was co-author of a textbook on a-c circuits, and was a member of the Society for the Promotion of Engineering Education and the former National Electric Light Association.

ALBERT BENTON JUNKINS (M'24) contracting electrical engineer, Baltimore, Md., died in July 1937, according to word just received at Institute headquarters. Mr. Junkins was born in Baltimore February 12, 1894, attended Baltimore City College, and received the degree of bachelor of science in electrical engineering at The Johns Hopkins University in 1917. Following his graduation he became assistant to the power plant engineer of the Chesapeake and Potomac Telephone Company, Baltimore, but in the following year received a commission in the communication branch of the United States Army Air Corps, serving as an instructor in radio and telephone communication. In 1919 he returned to his former position with the Chesapeake and Potomac Telephone Co., but remained for only one year before becoming electrical engineer for the Union Ship Building Company, Baltimore. In 1921 Mr. Junkins became affiliated with Stone and Webster, Inc., as assistant to the electrical superintendent on the construction of the American Sugar Refinery, Baltimore, and upon completion of that project became electrical engineer for the newly organized company. After serving briefly as a construction engineer for the Electromechanical Company, Baltimore, he established his own electrical contracting business, and pursued it without interruption for more than 10 years.

# Membership

## Recommended for Transfer

The board of examiners at its meeting on November 18, 1937, recommended the following members for transfer to the grade of membership indicated. Any objection to these transfers should be filed at once with the national secretary.

**To Grade of Fellow**

Case, H. M., chief engineer, Long Island Lighting Company, New York, N. Y.
Hunt, L. F., protection engineer, Southern California Edison Company, Ltd., Los Angeles, Calif.
McKearin, J. P., chief engineer, Western Massachusetts Companies, Springfield, Mass.
Wooldridge, William J., manager, electric sheet sales, Allegheny Steel Company, Brackenridge, Pa.

4 to Grade of Fellow

**To Grade of Member**

Baker, T. S., chief engineer, communications division, Hearst Radio, Inc., New York, N. Y.
Bellows, K. F., division engineer, Consolidated Edison Company of New York, Inc., New York, N. Y.
Blakeslee, T. M., electrical engineer, Bureau of Power and Light, Los Angeles, Calif.
Burke, J. H., electrical engineer, The Scranton Electric Company, Scranton, Pa.
Craton, F. H., commercial engineer, General Electric Company, Erie, Pa.
Hapgood, K. E., assistant engineer of design and construction, Tennessee Valley Authority, Chattanooga, Tenn.
Hough, E. L., electrical engineer, Union Electric Company, St. Louis, Mo.
Keene, C. L., supervising engineer, Ocean Accident and Guarantee Corporation, New York, N. Y.
Leihy, C. W., editor, *Electric Light and Power*, Chicago, Ill.
Love, N. R., chief engineer, Denver Tramway Corporation, Denver, Colo.
McLean, C., assistant engineer, Northwestern Electric Company, Portland, Ore.
Scheering, W. S., substation engineer, Western Mass. Companies, Springfield, Mass.
Schlup, E. G., electrical engineer, The American Rolling Mill Co., Middletown, Ohio.

13 to Grade of Member

## Applications for Election

Applications have been received at headquarters from the following candidates for election to membership in the Institute. If the applicant has applied for direct admission to a grade higher than Associate, the grade follows immediately after the name. Any member objecting to the election of any of these candidates should so inform the national secretary before December 31, 1937, or February 28, 1938, if the applicant resides outside of the United States or Canada.

Anderson, J. W., Metropolitan Water District of Southern California, Los Angeles, Calif.
Bagnall, V. B. (Member) American Telegraph and Telephone Company, New York, N. Y.
Bain, J. R., Dominion Sound Equipments, Ltd., Vancouver, B. C., Canada.
Baker, B. P., Westinghouse Electric & Manufacturing Company, East Pittsburgh, Pa.
Bloodworth, E. W., Wilson Dam, Ala.
Bloxam, E. L., Duke Power Company, Salisbury, N. C.
Borland, E. E., Smith Milligan Electric Company, Tulsa, Okla.
Breon, K. H., Pennsylvania Power & Light Company, Williamsport, Pa.
Brown, F. H., Copperweld Steel Company, New York, N. Y.
Browne, A. A., Westinghouse Electric & Manufacturing Company, Portland, Ore.
Bulliet, L. J., W. F., and John Barnes Company, Rockford, Ill.
Cain, D. E., General Electric Company, St. Louis, Mo.
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Cook, V. M., Consolidated Edison Company of New York, Inc., New York, N. Y.
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Dillon, H. W., Southern Pacific Lines, Houston, Texas.
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Martin, E. L., Tennessee Valley Authority, Chattanooga, Tenn.
McKinley, W. W., Commonwealth and Southern Corporation, Jackson, Mich.
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Wane, D., Canada Wire and Cable Company, Ltd., Leaside, Ont., Canada.
Weiser, L. G., Westinghouse Electric and Manufacturing Company, Louisville, Ky.
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Wilkoff, H. M. (Member) American Steel & Wire Company, Worcester, Mass.
Williamson, R. L., Aluminum Company of America, Atlanta, Ga.
Wright, F. T., Underwriters' Laboratories, Inc., New York, N. Y.
Zurcher, L. A., Case School of Applied Science, Cleveland, Ohio.

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**Foreign**

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MacLean, L. R., Bolivian Power Company, Oruro, Bolivia.
Maissi, E., 39, rue Dulong, Paris 17e, France.
Megwinoff, I., Power Electric Company, San Juan, Puerto Rico.
Rama Rao Naidu, D. V., Madanapalle Electric Supply Corporation, Ltd., Madanapalle, South India.
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8 Foreign

## Addresses Wanted

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Dadashev, Musa, 32 Zamkovaja, Ulitsa, Baku, U.S.S.R.
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Gregory, G. A., 1217 Jefferson Street, Olympia, Wash.
Hall, John R., 1464 S. 74th St., West Allis, Wis.
Herr, Melvin D., South 228 Lincoln St., Spokane, Wash.
Kirk, W. C., 216 E. 22nd St., Owensboro, Ky.
Koziol, Roman Joseph, 174 Farmington Ave., Hartford, Conn.
Macomber, George S., Federal Power Commission, Washington, D. C.
McLean, Lee Vance, 1926 North Blvd., Baton Rouge, La.
Rizk, Kaleel S., Co. 418, C.C.C., Olustee, Fla.
Roberts, William N., 4175 Springle, Detroit, Mich.
Tribble, William Harry, 303 Park Place, Brooklyn, N. Y.

15 Addresses Wanted

# Engineering Literature

Among the new books received at the Engineering Societies Library, New York, recently are the following which have been selected because of their possible interest to the electrical engineer. Unless otherwise specified, books listed have been presented gratis by the publishers. The Institute assumes no responsibility for statements made in the following outlines, information for which is taken from the preface of the book in question.

ENGINEERING MECHANICS, DYNAMICS. By S. Timoshenko and D. H. Young. New York and London, McGraw-Hill Book Company, 1937. 323 pages, illustrated, 9 by 6 inches, cloth, $2.75. An elementary textbook on dynamics intended to give the student a thorough grounding in fundamentals. Contains discussions of 3 phases of the subject not usually contained in elementary books: vibration, elliptic harmonic motion, and relative motion.

ENGINEERING PROBLEMS MANUAL. By F. C. Dana and E. H. Willmarth. Third edition. New York and London, McGraw-Hill Book Company, 1937. 313 pages, illustrated, 8 by 5 inches, cloth, $2.25. A textbook for courses in engineering problems with the object of training the engineering student in good habits of work and study. The first 7 chapters furnish a ground work for this training; chapter 8 presents some 300 review problems; and chapter 9 contains miscellaneous tables.

MECHANICS and HEAT. (Physics for Technical Students). By W. B. Anderson. Third edition. New York and London, McGraw-Hill Book Company, 1937. 378 pages, illustrated, 9 by 6 inches, cloth, $2.50. This first volume of a set covers only mechanics and heat; sound, light, electricity, and magnetism are covered in a second volume. Intended as an elementary textbook.

TEXTBOOK of PHYSICS. By L. B. Spinney. Fifth edition. New York, Macmillan Company, 1937. 721 pages, illustrated, 9 by 6 inches, cloth $3.75. A textbook for university and college students emphasizing the practical applications of physics and illustrates the laws by reference to familiar phenomena.

THERMODYNAMICS. By H. A. Everett. New York, D. Van Nostrand Company, 1937. 430 pages, illustrated, 9 by 6 inches, cloth, $3.75. A textbook for a college course. Covers fundamentals and discusses various phases in the light of modern developments.

WIRELESS SERVICING MANUAL. By W. T. Cocking. Third revised edition. London, *Wireless World*, Iliffe & Sons, Ltd., 1937. 241 pages, illustrated, 8 by 5 inches, cloth, 5s. Covers the principles and practice of the repair and adjustment of wireless receivers. Deals in detail with methods of fault finding and describes the use of test apparatus.

THÉORIE et PRATIQUE des CIRCUITS FONDAMENTAUX de la T.S.F. By J. Quinet. Paris, Dunod, 1937. 431 pages, illustrated, 10 by 7 inches, paper, 120 frs. (140 frs., bound). An elementary study of the use of the calculus of imaginaries in the field of wireless telephony. Divided into 3 parts: the first deals with applications of the method to radio; the second shows its application to electricity; the third, application to the theory and construction of fundamental circuits in wireless telephony.

STROM- und SPANNUNGSWANDLER. By M. Walter. Munich and Berlin, R. Oldenbourg, 1937. 159 pages, illustrated, linen, 8.80 rm. Describes current and voltage transformers for switching installations. Covers current and voltage transformers as to method of operation, construction, safety precautions, connections, selection, and test procedures.

SCIENCE of SEEING. By M. Luckiesh and F. K. Moss. New York, D. Van Nostrand Company, 1937. 548 pages, illustrated, 9 by 6 inches, cloth, $6.00. A treatment of aspects not primarily considered in the various sciences with which seeing is connected. Discussions deal largely with controllable factors—physiological, typographical, illuminative.

SAGA of the SEAS. By P. B. McDonald. New York, Wilson-Erickson, 1937. 288 pages, illustrated 10 by 6 inches, cloth, $3.00. A biography of Cyrus W. Field, of which the greater part is devoted to his greatest achievement, the laying of the first Atlantic cable. Illustrated with contemporary prints and portraits.

RICHARD COCKBURN MACLAURIN. By H. G. Pearson. New York, Macmillan Company, 1937. 302 pages, illustrated, 9 by 6 inches, cloth, $3.00. A biography of the president of the Massachusetts Institute of Technology, 1909–1920. Chiefly concerned with his work in that capacity.

RADIO ENGINEERING. By F. E. Terman. Second edition. New York and London, McGraw-Hill Book Company, 1937. 813 pages illustrated, 9 by 6 inches, cloth, $5.50. Revised edition of a comprehensive engineering treatment of the more important vacuum-tube and radio phenomena.

PSYCHOLOGY of SELECTING EMPLOYEES. By D. A. Laird. Third edition. New York and London, McGraw-Hill Book Co., 1937. 316 pages, illustrated, 9 by 6 inches, cloth, $4.00. A practical treatment of the fundamental considerations in selecting men. Discusses psychological means and methods of selecting employees, and shows the employer how to find efficient employees in his own establishment, as well as in his employment office.

PREPARATION for SEEKING EMPLOYMENT. By H. L. Davis. New York, John Wiley & Sons, 1937. 39 pages, tables, 8 by 6 inches, paper, $0.25. A pamphlet for the guidance of those who seek employment for themselves or others.

PHYSICS for STUDENTS of APPLIED SCIENCE. By J. E. Shrader. New York and London, McGraw-Hill Book Company, 1937. 638 pages, illustrated, 9 by 6 inches, cloth, $4.00. Presents fundamentals necessary to give the technical student a working knowledge of physics.

MODERN THEORIES of INTEGRATION. By H. Kestelman. Oxford, England, Clarendon Press; New York, Oxford University Press, 1937. 252 pages, tables, 10 by 7 inches, cloth, $5.50. Concerned primarily with the theory of Lebesgue integration as simplified by C. Carathéodory. Designed as to be intelligible to one having a knowledge of elementary analysis. Includes discussion of Riemann integration, extensions of the Lebesgue integral, and Fourier series.

MANUAL of MATHEMATICS and MECHANICS. By G. R. Clements and L. T. Wilson. New York and London, McGraw-Hill Book Company, 1937. 266 pages, illustrated, 9 by 6 inches, leather $3.75. Contains facts and formulas useful in courses in mathematics and mechanics, also for general reference work.

LABOR'S SEARCH for MORE. By M. Keir. New York, Ronald Press Company, 1937. 527 pages, 9 by 6 inches, cloth, $3.50. Endeavors to present a record of the struggles, in recent times, of ordinary persons to improve their lot. Intended to furnish an insight as to why workers have been and are seeking more security, more income, more leisure. Strikes, trials, political campaigns, and mechanization are considered along with general economic data.


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# Fundamental Concepts of
# Synchronous Machine Reactances

By B. R. PRENTICE
ASSOCIATE AIEE

## Synopsis

This educational paper presents fundamental concepts of synchronous machine reactances in a form suitable for college seniors and recent graduates. Part I builds up the "physical concepts" of flux linkage and inductance, part II applies the concepts to synchronous machines, developing a physical picture of machine reactances. Part III starts with the fundamental circuit differential equations of a machine and obtains expressions for the reactances in terms of self- and mutual inductances, ending with the machine equations in the direct, quadrature, and zero axes, which give a physical picture of the machine "viewed" from these axes.

## Introduction

THIS IS an educational paper designed specifically to assist the college student in bridging the gap between his formal, fundamental education, and current engineering knowledge and practice in the field of synchronous-machine theory. The development of the modern theory of synchronous machines started about 10 years ago when Doherty and Nickle[1,2,3,4] extended Blondel's 2-reaction theory and developed methods for determining the performance of a salient-pole machine under certain steady-state and transient conditions. They proposed new definitions and divisions of synchronous-machine reactances to facilitate the analysis. Subsequently, Park[5,6] generalized the method by a more mathematical approach. Wieseman[7] and Alger[8] gave methods of calculating the reactances for design, and Park and Robertson[9] reviewed the whole field of synchronous-machine reactances from both the operating engineer's and designing engineer's viewpoints. Kilgore[10] has given additional methods for calculating the reactances and time constants in design and Wright[11] has given methods of test and test results for reactances, resistances, and time constants. Subsequent contributions in the field have been numerous and valuable.

The new ideas presented were and are considerably beyond the training given undergraduates in most colleges. This is as it should be, for there is scarcely time in a college course to do much more than give the student a sound foundation in fundamentals, and this should certainly not be sacrificed in order to progress far in special fields. A simple, easily understandable explanation of machine reactances was given by Shildneck in an article,[12] "Synchronous Machine Reactances—A Fundamental and Physical Viewpoint." This paper presents a viewpoint similar to that presented by Shildneck, and a number of others all of which have been found advantageous in the advanced course in engineering[14] of the General Electric Company in the study of synchronous-machine theory.

In the design and analysis of electrical machines, the engineer may or may not need to solve complex mathematical problems so that advanced mathematical knowledge is not essential to every engineer. However, one of his most necessary requirements is a comprehensive, clear understanding of the basic, underlying phenomena. In analysis or design this "physical picture" or "mental picture" is the foundation on which the mathematical relations are set; is the basis for approximations to simplify the formulation and solution; serves as a worthy guide in the straightforward manipulation of the mathematics; and, finally, enables the engineer to interpret his results intelligently. Such a process is present to a considerable degree in the methods of all engineers; those of a highly mathematical bent require a good physical picture to make the fullest use of their powers and those who are endowed with, or have developed, that fine sense that enables them to know the result intuitively—with little or no calculation—have the most complete mental image imaginable.

Since the possession of a clear physical picture is so essential, it is well to investigate how it may be obtained and developed. In mechanics it is easy to visualize forces, torques, velocities, accelerations, mass, etc., because one can see or feel them. The visualization of current, voltage, flux, inductance, etc., is more difficult, and special, artificial concepts such as vectors, sine waves, lines of flux, right-hand rules, etc., are needed to aid the imagination. Since but few of these artifices are either useful or valid in every possible situation, it is desirable to have at one's command a large number of points from which to view a problem. Therefore, the purpose of this paper is to aid in broadening and clarifying the reader's understanding of machine reactances by presenting the concepts from a large number of fundamental points of view.

## Part I. Fundamental Concepts of Inductance

### Circuit Concepts of Inductance

The basic study of any engineering phenomenon should ordinarily proceed by

1. Gaining or defining fundamental concepts.

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1. For all numbered references, see list at end of paper.

2. Observing some experimental relation between the defined concepts.

3. Developing, by means of mathematics, new useful relationships based on the experimental law.

In step 3 it is frequently convenient to define and name additional auxiliary quantities to simplify the analysis and physical reasoning.

The purpose of part I is to develop clear concepts and useful properties of inductance. Proceeding, then, with step 1, primary concepts of the following quantities are presupposed:

Electromotive force or emf or voltage, $e$

Current, $i$

Time, $t$

Magnetic flux, $\phi$

Flux linkage or (simply) linkage, $\psi$

The respective units used are: volts, amperes, seconds, lines, lines-turns, the "practical" system.

The linkage of a closed circuit is defined as the sum of the numbers of flux lines linking each turn of the closed circuit. In practice the circuit need not be closed by a wire; if not, the terminals must be remote from the major magnetic field and then the voltage between the terminals is considered to close the circuit. Thus, if in the $N$ turn circuit of figure 1, $\phi_1$ lines of flux link turn 1 and $\phi_2$ link turn 2, etc., the total linkage is

$$\psi = \phi_1 + \phi_2 + \ldots\ldots + \phi_N$$

The fundamental, experimentally established law accepted as the basis (in step 2) for this analysis is Faraday's law. It states that whenever the linkage of a closed circuit changes, an electromotive force is induced equal to $10^{-8}$ times the time rate of decrease of linkage, that is,

$$e = -\frac{d\psi}{dt}10^{-8}\dagger \tag{1}$$

If the circuit is fixed in the inertial system of the observer, that is if measurements of induced electromotive force are made by, say, attaching a voltmeter to the terminals of the circuit, Faraday's law gives all of the electromotive force induced by changing flux regardless of how the change in linkage is produced, whether by self-induction, relative motion of other circuits, changing current in adjacent circuits, motion or change in permeability of the magnetic circuit, and whether the flux is visualized as moving relative to the coil and cutting it or not. This includes the case where the voltmeter is connected to a moving coil through slip rings for then, electrically, the observer is stationary with respect to the coil. An additional "motional electromotive force" is induced when the circuit is actually moving relative to the observer, as when the voltmeter is attached to a series of similar circuits through a commutator, however it is due entirely to, and is proportional to, the velocity of the circuit relative to the observer's inertial system, and not any real or supposed velocity relative to the field of flux. Page[19] writes, "Indeed the prevalent statement in elementary texts that induced electromotive forces are due to the cutting of lines of force by a conductor is not of general validity and may lead to quite erroneous conclusions in specific problems." In this paper, equations will always be originally set up with the circuits fixed relative to the observer so that Faraday's law gives the total induced electromotive force. This procedure is strongly recommended to avoid errors in circuit problems. Equations involving such a motional electromotive force will be derived in part III, resulting automatically from a transformation to co-ordinates where the observer moves relative to the circuit.

In many practical cases, the linkage of self-induction in a circuit (produced by current in the circuit) is, within reasonable accuracy, directly proportional to the current. When this is the case, the circuit is said to be linear, that is, the linkage is a linear function of the current. Thus

$$\psi = Li \times 10^8 \tag{2}$$

where $L$ is the constant of proportionality. Obviously $L$ is a physical property of the coil and its associated magnetic path. This constant of proportionality occurs so frequently in analysis that it has been named self-inductance. In practical units inductance is then defined by (2) or,

$$L = \frac{\psi}{i}10^{-8}* \text{ henrys} \tag{3}$$

Likewise, the linkage in one circuit is frequently a linear function of the current in another circuit. When this is the case the constant of proportionality is called mutual inductance which is defined by

$$\pm M_{21} = \frac{\psi_{21}}{i_1}10^{-8}** \text{ henrys} \tag{4}$$

The first subscript designates the circuit in which the effect is observed and the second that in which the cause appears. Both self- and mutual inductance can now be visualized as linkage per unit current, or in more usual terms, linkage per ampere.

If the definitions of inductance are combined with equation 1, the following relations result,

$$\left.\begin{aligned} e &= -\frac{d}{dt}(Li) \text{ volts} \\ \text{and} \\ e_2 &= \pm\frac{d}{dt}(M_{21}\,i_1) \text{ volts} \end{aligned}\right\} \tag{5}$$

† Equation 1 establishes an arbitrary convention of sign. Stated differently, a positive *applied electromotive force* gives rise to a *positive increase* in linkage, since *applied electromotive force* is opposite in sense to *induced electromotive force*. The positive direction of flux and flux linkage is related to the positive sense of electromotive force along the conductor by the right-hand rule. Thus if the fingers of the right hand are pointed in the direction of positive electromotive force along a conductor, the thumb points in the direction of positive flux and flux linkage.

* The sign here is arbitrary. Self-inductance is taken as always numerically positive so the positive sign shows that a positive current in a circuit produces positive linkage in the same circuit. The conventions established in equation 1 require that a positive applied electromotive force produce an increase in positive linkage. Hence, according to the convention chosen here, a positive electromotive force will tend to produce a positive current.

** The sign of equation 4 depends on the relative position of the 2 windings and the arbitrary directions chosen for positive current in each circuit. Thus, if positive $i_1$ produces linkage in circuit 2 in the same direction as produced by positive $i_2$, then $M$ is positive. The algebraic sign may be associated with the numerical value of $M$ rather than the literal value as used here.

Even though the inductances are independent of the value of the current, that is constant with respect to $i$, they may still vary with time, due to the motion of some part of the magnetic circuit or the relative motion of circuits. Hence, it is not permissible to write the more common relations,

$$\left.\begin{aligned} e &= -L\frac{di}{dt} \\ \text{and} \\ e_2 &= \pm M_{21}\frac{di_1}{dt} \end{aligned}\right\} \quad (6)$$

without further restricting the definition to apply to stationary coils with fixed magnetic circuits. This would obviously be folly in the study of rotating machines where circuits move relative to each other and inductances are functions of the position of the rotor, so that equations 5 will be used except when the problem involves only stationary devices.

Inductance in stationary circuits may further be visualized as electromotive-force per unit rate of change of current.

$$L = -\frac{e}{\frac{di}{dt}} \quad (7)$$

## Geometric Concept of Inductance

So far, inductance has been considered from the circuit standpoint. However, a clear physical picture of its geometric nature is most important. As defined, inductance is the constant of proportionality between linkage and current. This constant depends upon the size, shape, and permeability of the magnetic path, the number of turns in the coil and their arrangement.

Permeance $\mathcal{P}$ of a magnetic circuit is defined as the ratio of the flux to the magnetomotive force (mmf) producing it. In practical units, the magnetomotive force of a coil is $F = 0.4\pi NI$, so

$$\mathcal{P} = \frac{\phi}{0.4\pi NI} = \frac{N\phi}{0.4\pi N^2 I} = \frac{\psi}{0.4\pi N^2 I} \quad (8)$$

More precisely, if there is fractional linkage as in figure 1, the linkage is not expressible as $N\phi$ so that permeance is defined in terms of linkage as in equation 8. Then inductance, expressed in terms of the geometric property of the circuit, permeance, is

$$L = \frac{\psi}{I}10^{-8} = 0.4\pi N^2\mathcal{P}\ 10^{-8} \quad (9)$$

If the magnetic path can be characterized by single length $l$, area $A$, and permeability $\mu$, fundamental consideration of the definition shows that permeance is

$$\mathcal{P} = \frac{\mu A}{l} \quad (10)$$

and in more complex cases, is still a purely geometric constant depending on the magnetic path and arrangement of turns. Thus, inductance is proportional to the number of turns squared, the area of the magnetic path and the permeability, and is inversely proportional to the length of the magnetic path. A similar analysis of the self-inductance of, and mutual inductance between, 2 coils shows that

$$L_1 = 0.4\pi\ 10^{-8}N_1^2\mathcal{P}_1 \quad (11)$$

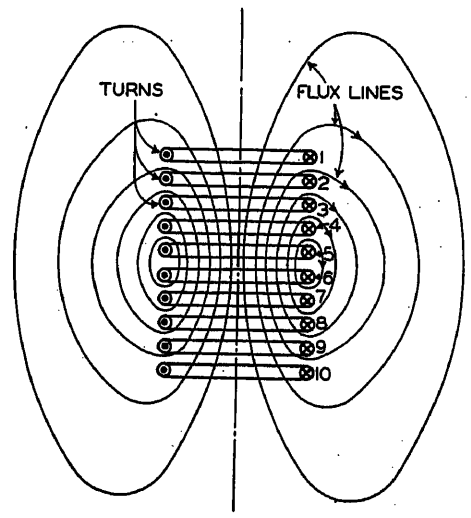
$$L_2 = 0.4\pi\ 10^{-8}N_2^2\mathcal{P}_2 \quad (12)$$

$$M_{12} = M_{21} = 0.4\pi\ 10^{-8}N_1N_2\mathcal{P}_{12} \quad (13)$$

where $\mathcal{P}_1$ and $\mathcal{P}_2$ represent the respective permeances of the coils and $\mathcal{P}_{12}$ that of the mutual flux path.

The foregoing concepts are extremely useful in visualizing the inductances of various windings of a machine, by examining their configuration, their relative arrangement, and the position and character of the magnetic circuit.

**Figure 1. Flux linkage**




## Concept of Leakage Inductance

Leakage, prefixed to flux, linkage, inductance, or reactance, is a very broad term being given many interpretations by various authorities. For instance, flux not crossing the useful air gap of an electromagnet is called leakage, primary flux not linking the secondary of a transformer is called leakage, and so on. In general, however, the term is applied to those portions of the quantity so described which are not useful, and on this broad viewpoint are based the various conceptions and definitions used in this paper.

In the simple transformer of figure 2,* let mutual inductance and secondary voltage, linkage, current, and self-inductance be referred to primary terms. That is, if primed quantities are referred to the primary and unprimed quantities are actual values and,

$$n = \frac{N_1}{N_2} = \frac{\text{primary turns}}{\text{secondary turns}}$$

* The transformer of figures 2, 3, and 4 is shown with primary and secondary windings placed on separate legs of the core. Obviously a power transformer would never be constructed in this manner because of the tremendous leakage reactance. However, the arrangement shown is better for the purposes of illustration than the usual concentric location of windings.

then,

$$e_2' = n\, e_2$$

$$\psi_2' = n\, \psi_2 \cong \frac{N_1}{N_2}(N_2\phi_2) = N_1\phi_2$$

$$i_2' = i_2/n$$

$$L_2' = n^2 L_2 = 0.4\pi 10^{-8}\, N_1^2 \mathcal{P}_2$$

$$M' = nM = 0.4\pi 10^{-8}\, N_1^2 \mathcal{P}_{12}$$

Since the resistances of transformer or machine windings have little effect on the distribution of flux when either alternating current of rated frequency or rapidly changing direct currents flow, and only these cases are considered here, resistances are neglected.

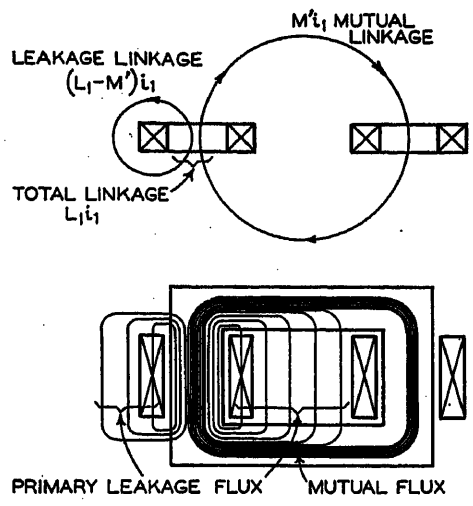



**Figure 2. Primary leakage reactance**

Flux linkage with primary excited and secondary open

Now, with the secondary open, apply sinusoidal voltage of angular frequency $\omega$ ($\omega = 2\pi f$) to the primary. In complex notation, the voltage equations are

$$\left.\begin{aligned} \mathbf{e}_1 &= j\omega\bar{\psi}_1 = j\omega L_1 \mathbf{i}_1 \dagger \\ \mathbf{e}_2' &= j\omega\bar{\psi}_2' = j\omega M' \mathbf{i}_1 \end{aligned}\right\} \quad (14)$$

and the instantaneous primary and secondary linkages are,

$$\left.\begin{aligned} \psi_1 &= L_1 i_1 \\ \psi_2' &= M' i_1 \end{aligned}\right\} \quad (15)$$

According to the concept of leakage stated previously, the nonuseful portion of the primary linkage should be defined as the leakage linkage. Obviously the nonuseful portion is that linkage which does not link the secondary or

$$\psi_1 - \psi_2' = (L_1 - M')i_1$$

The various linkages are shown graphically in figure 2.

Therefore, the open-circuit leakage inductance, $l_{oc}$, of the transformer, referred to the primary is

$$\left.\begin{aligned} l_{oc} &= L_1 - M' \\ &\text{and the leakage reactance is} \\ x_{oc} &= \omega(L_1 - M') \end{aligned}\right\} \quad (16)$$

† Bold-face type or overscoring indicates complex or vector representation of the sinusoidal quantities.

If the secondary were excited and primary open, the transformer leakage inductance referred to the primary would be $(L_2' - M')$. These leakage inductances are commonly called primary and secondary leakage inductances, respectively.

It will be evident from what follows that the transformer has an entirely different leakage inductance under every other condition of operation and the purpose of this section is to clarify these diverse concepts of the quantity and build a sound physical picture to be used in visualizing machine reactances.

Consider the transformer operating under the other extreme condition with secondary short circuited and primary excited. Then,

$$\left.\begin{aligned} e_1 &= j\omega\bar{\psi}_1 = j\omega(L_1 i_1 - M' i_2') \\ 0 &= j\omega\bar{\psi}_2' = j\omega(L_2' i_2' - M' i_1) \end{aligned}\right\} \quad (17)$$

Positive current conventions are chosen so that $M$ is negative; that is positive $i_1$ produces positive $\psi_1$, and negative $\psi_2$; positive $i_2$ produces positive $\psi_2$ and negative $\psi_1$. On elimination of $i_2'$,

$$e_1 = j\omega\bar{\psi}_1 = j\omega\left(L_1 - \frac{M'^2}{L_2'}\right) i_1 \quad (18)$$

and

$$\psi_1 = \left(L_1 - \frac{M'^2}{L_2'}\right) i_1$$

$$\psi_2' = 0$$

These linkages are shown graphically in figure 3. As

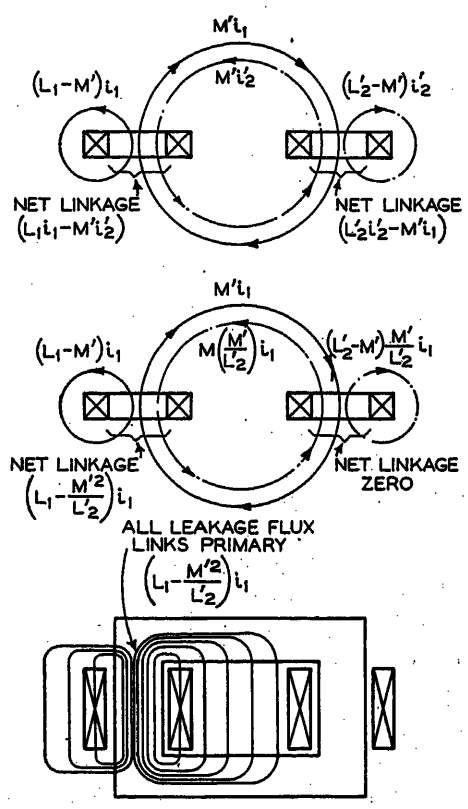



**Figure 3. Short-circuit reactance**

Flux linkage with primary excited with alternating current, secondary short circuited

Full lines show components of linkage produced by primary current, dotted lines, those due to secondary current

there is no net mutual linkage, or secondary linkage, all of the primary linkage is leakage linkage. Therefore, the transformer short-circuit leakage inductance is

$$l_{sc} = L_1 - \frac{M'^2}{L_2'}$$

and the leakage reactance is

$$x_{sc} = \omega\left(L_1 - \frac{M'^2}{L_2'}\right) \qquad (19)$$

If the secondary were excited with primary short-circuited, the corresponding leakage inductance would be

$$L_2' - \frac{M'^2}{L_1}$$ referred to the primary.

Before comparing these results with (16) it is advantageous to consider one other common definition of leakage reactance, "bucking" reactance. If magnetizing current be neglected, the primary and secondary ampere turns will be equal. This distribution of ampere turns may be accomplished physically by adjusting the voltages applied to primary and secondary such that

$$i_1 = i_2' = i$$

then,

$$e_1 = j\omega\bar{\psi}_1 = j\omega(L_1 i - M' i)$$

$$e_2 = j\omega\bar{\psi}_2' = j\omega(L_2' i - M' i)$$

Physical reasoning shows that there is no net mutual linkage. Hence the total linkage is the nonuseful linkage,

$$\psi_1 + \psi_2' = (L_1 + L_2' - 2M')i$$

The relations between the various linkages are shown in figure 4. Hence, the bucking leakage inductance is

$$\begin{aligned} l_B &= L_1 + L_2' - 2M' \\ &= (L_1 - M') + (L_2' - M') \\ &= l_{oc}\,(\text{primary}) + l_{oc}\,(\text{secondary}) \end{aligned} \qquad (20)$$

and the bucking reactance is

$$x_B = \omega(L_1 + L_2' - 2M')$$

Now to compare the 3 different values of leakage inductance note first that since

$$0.4\pi N_1^2 \mathcal{P}_1 10^{-8} = L_1 \cong L_2' = 0.4\pi N_1^2 \mathcal{P}_2 10^{-8}$$

the bucking inductance $l_B$ is approximately twice the open-circuit leakage inductance. This may be surprising for inspection of figures 2 and 4 shows that in both cases the leakage flux path in air is of the same area and length. The reason lies in the variation of the magnetomotive force across the leakage path. In figure 2, with the secondary open, the magnetomotive-force drop near the secondary leg of the core is zero and it increases nearly linearly to a maximum at the primary leg of the core. In figure 4, the bucking connection, equal magnetomotive force is supplied by both windings so that the magnetomotive force across the leakage path is essentially constant. With equal primary ampere turns in both cases, the average magnetomotive force in figure 4 is, therefore, approximately twice the average magnetomotive force in figure 2, and, therefore, so is the leakage inductance.

That the short-circuit inductance and bucking inductance are nearly equal is clear when it is noticed that under short circuit, equation 17 gives

$$i_2' = \frac{M'}{L_2'} i_1$$

and if $M' \cong L_2'$, as in a practical transformer, the primary and secondary ampere turns are nearly equal. Consequently, essentially the same magnetomotive force exists across the same path in figure 3 as in figure 4 and the corresponding leakage inductances $l_{sc}$ and $l_B$, are essentially the same. The difference is so small it cannot be calculated or tested on commercial power transformers. Subtracting equation 19 from equation 20 gives the difference

$$l_B - l_{sc} = \frac{(L_2' - M')^2}{L_2'}$$

so that the bucking inductance is theoretically slightly larger.

The consequences of this comparison are:

1. The leakage inductance of 2 "closely coupled" circuits varies as much as 2 to 1 depending on operating conditions.

2. Since magnetizing current is usually negligible compared to load or short-circuit current, either $l_{sc}$ or $l_B$ can be used and $l_{oc}$ is of only academic interest.

3. The flux distribution shown in figure 4 for bucking reactance is convenient for the design calculation of reactance but it does not occur physically either under load or short circuit. The device commonly employed for calculation is to assume a surface ($A - A'$ figure 4) dividing the primary leakage from the secondary leakage flux, approximately midway between the 2 windings. Then the reactance associated with the secondary leakage flux is calculated and called secondary leakage reactance and that associated with primary leakage flux, primary leakage reactance. This artifice, though unnecessary, yields satisfactory numerical results. The division between the 2 reactances is purely arbitrary, and they cannot be separated by test.

4. To base a physical picture on the flux distribution of figure 4, as is done in some texts, or to visualize linkage in terms of the transformer equivalent circuit tends to confuse the thinking, particularly in problems involving the law of constant flux linkage.

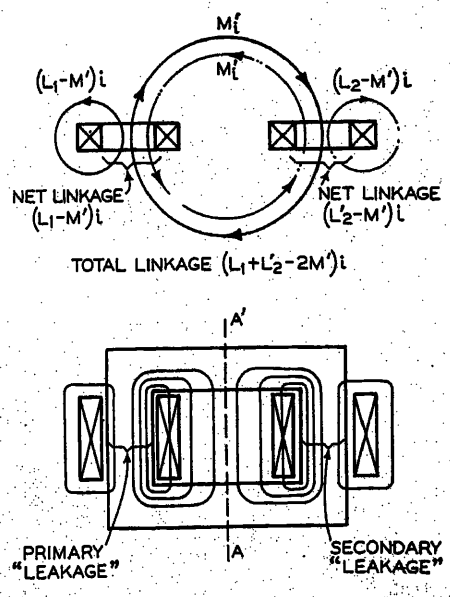



**Figure 4. Bucking reactance**

Flux linkage with primary and secondary excited with alternating current such that primary and secondary ampere turns are equal and opposite, $i_1 = i_2' = i$

Full lines show components of linkage due to primary current, dotted lines, those produced by secondary current

5. The flux distribution of figure 3 is the actual condition existing under short circuit (resistance neglected); furthermore, under load the leakage flux links only the excited winding. Therefore, this distribution should be used for purposes of visualization.

A further extension of the concepts of leakage reactance is necessary in order to visualize synchronous-machine transient reactances. Consider the static, short-circuited transformer of figure 3 to have d-c voltage applied suddenly to the primary.

$$\left.\begin{aligned} E1^* &= r_1 i_1 + \frac{d\psi_1}{dt} = r_1 i_1 + \frac{d}{dt}(L_1 i_1 - M' i_2') \\ 0 &= r_2' i_2' + \frac{d\psi_2'}{dt} = r_2' i_2' + \frac{d}{dt}(L_2' i_2' - M' i_1) \end{aligned}\right\} \quad (21)$$

Integrate both equations with respect to time.

$$\int_0^t E1\,dt = \int_0^t r_1 i_1 dt + \int_0^{\psi_1} d\psi_1$$

$$0 = \int_0^t r_2' i_2' dt + \int_0^{\psi_2'} d\psi_2'$$

In most practical machines the secondary resistance drop $r_s' i_2'$ is small compared to the induced and applied voltages; hence, if $t$ is made sufficiently small, the first term of the second equation can be made extremely small compared to the terms in the first equation and the change in secondary linkage is practically zero.

$$\psi_2' = \int_0^{\psi_2'} d\psi_2 \cong 0$$

This is one statement of the law of constant flux linkage. Therefore,

$$\psi_2' = L_2' i_2' - M' i_1 \cong 0$$

and

$$i_2' \cong \frac{M'}{L_2'} i_1,$$

and equation 21 becomes

$$E1 \cong r_1 i_1 + \left(L_1 - \frac{M'^2}{L_2'}\right)\frac{di_1}{dt}$$

Hence, exactly initially ($t$ infinitesimally small), and approximately for the first short interval of time, the effective inductance of the short-circuited transformer with suddenly applied d-c voltage is identical with its a-c short-circuit inductance. As time increases indefinitely the effective inductance gradually approaches the self-inductance $L_1$.

On first notice it might appear that neglecting the secondary resistance drop in deriving this expression is not warranted when it is intended to use this case as an analogy to machine circuits with the field winding as secondary; for the field resistance is large and cannot be neglected, particularly in determining rates of decay of currents. However, it must be emphasized that the expression is exact when the time interval is infinitesimally small and the effect of high resistance is to shorten the time during which the approximation is a good one.

Physically, this may be explained by realizing that when a sudden voltage is impressed on the primary and the primary current builds up on an exponential type curve, simultaneously the secondary current builds up on an exponential type curve, tending to keep the secondary linkage zero. During the first few instants of time the secondary linkage is essentially zero, and the primary flux is forced entirely into the leakage paths of very low permeance as shown in figure 3.

The constant flux linkage theorem was presented by R. E. Doherty[17] as a tool in the analysis of short-circuit problems. The principles involved are very useful in visualizing and analyzing transient phenomena and it is believed that better use of them could be made in the colleges. Although it will be used, a thorough treatment of the theorem is outside the scope of this paper. It may be briefly stated as follows: the *total linkage* in any closed electrical circuit cannot change instantly. A "closed circuit" is one which involves no infinite voltages or resistances but it may contain any number of finite resistances, inductances (including mutual inductance), and the inductance may vary as a function of time. The rate at which the total linkage does vary is, by Faraday's and Ohm's laws, proportional to the difference between the applied electromotive force and the $IR$ drop.

For the purposes of this paper, the discussion of leakage inductance and reactance serves to build up the following physical picture. When a closed winding is in magnetic proximity to another winding, and the latter winding is excited with either a-c or suddenly applied d-c voltage, the flux linkage of the closed winding remains essentially constant and practically all of the newly created flux present links the excited winding as shown in figure 3. This newly created flux passes through the very low permeance leakage path between the 2 windings so that the effective inductance and reactance are correspondingly small. The initial effective inductance of the excited winding is $(L_1 - M'^2/L_2')$ or approximately $(L_1 + L_2' - 2M')$.

## Part II. Synchronous-Machine Reactances—Physical Viewpoint

A fundamental physical picture of each of the more important synchronous-machine reactances will be built up on the basis of the concepts established in part I and considering the effects of a salient-pole rotor and its associated, closed field windings. Laminated cylindrical-rotor machines, being generally easier to visualize, are mentioned only as a special case of the salient-pole machines. Solid cylindrical-rotor machines may be approximately analyzed by salient-pole methods but a more comprehensive theory such as presented by Concordia and Poritsky[18] is necessary for an accurate treatment of transient problems. These concepts are based on the actual phenomena occurring within the machine. It is also possible to view the phenomena from the terminals of the machine, that is, on the basis of actual tests which might

* The unit function, 1, indicates that the voltage is zero until time zero, $E$ thereafter.

be conducted. Hence, in order to broaden the understanding of these reactances still further, a few methods of determining them by tests—which are simple enough to enhance the viewpoint without resorting to a detailed mathematical analysis—will be included in the discussion of each reactance. Finally, the analytic approach, which gives an understanding of the reactances from still a different angle, will be presented very briefly in part III.

A symmetrical, 3-phase, armature winding is assumed, and saturation, hysteresis, and eddy current losses are neglected. The effect of circuit resistance is neglected in visualizing the linkages but obviously resistance cannot be neglected in visualizing the decay of currents. The field structure and field windings are assumed to be symmetrical about the center lines of the poles, (direct axis) and also symmetrical about the axes midway between the poles (quadrature axis).

## Armature Leakage Reactance $x_l$

The armature leakage reactance of a synchronous machine is a part of nearly all of the other armature reactances, so that a knowledge of it is prerequisite.

If a voltage be applied to the armature terminals such that balanced, sinusoidal, fundamental-frequency, 3-phase currents of normal phase rotation (positive-sequence†) flow in the armature winding, these currents will set up a rotating flux wave in the air gap. Due to the finite number of slots, phases, etc., this flux wave will be composed of fundamental and harmonic components. For instance, the 3-phase currents produce a rotating magnetomotive force which has a fundamental component rotating forward at synchronous speed, a backward rotating fifth harmonic, a forward rotating seventh harmonic, etc., the relative magnitudes of which depend on the winding arrangement. These harmonic magnetomotive forces traveling at speeds different from that of a salient-pole rotor will produce, by interaction with the varying permeance of the air gap, flux harmonics of various orders, traveling at different speeds. (If the rotor is cylindrical and laminated the harmonic magnetomotive forces will give rise to harmonic fluxes of corresponding order and speed of rotation. However, if the cylindrical rotor is solid, currents will be induced in it changing the magnitude of the flux harmonics.) Some of these flux harmonics will be of such order and speed that they will induce voltage of fundamental frequency in the armature. However, they induce purely reactive armature voltage so that their effects are included in the armature leakage reactance, and the corresponding linkage is called differential leakage flux linkage.*

In addition to this armature linkage due to air gap flux harmonics, there will be armature linkages due to slot flux and flux in the end winding. If the differential, slot, and end winding linkages are added, the sum is defined to be the total armature leakage flux linkage. The ratio of this linkage in one phase to the armature phase current producing it $\times 10^{-8}$ gives the armature leakage inductance in henries. This value is multiplied by $\omega$, $\omega = 2\pi f$ (where $f$ is rated frequency in cycles per second) is the armature leakage reactance, per phase, in ohms. The ratio of this value to "base ohms" is $x_l$ in per unit.**

It should be noted that the armature leakage reactance includes the effect of that part of the mutual linkage between phases, due to other than the fundamental flux wave and, therefore, is a "3-phase" reactance, applicable without modification only under 3-phase balanced operation or when unbalanced operation is analyzed in terms of its symmetrical components. Unfortunately, this reactance cannot be determined directly from test. However, it is part of nearly all subsequent reactances, and a physical picture of it is, therefore, desirable.

## Direct Synchronous Reactance $x_d$

If positive-sequence currents flow in the armature, as discussed under $x_l$, the major component of armature linkage is due to the synchronously rotating, fundamental component of the air-gap flux which exists in addition to the leakage flux linkage. Unlike the latter, the amount of linkage due to the fundamental is greatly affected by the position of the field structure. If the unexcited field is rotated synchronously so that the poles are always directly in line with the fundamental component of armature magnetomotive force, maximum permeance is presented to the magnetomotive force as shown in figure 5 and maximum total armature linkage per armature ampere results. Under these conditions the ratio of the linkage in one phase to the current in that phase‡ $\times \omega 10^{-8}$ gives the direct synchronous reactance, per phase,§ in ohms. The ratio of this value to base ohms is $x_d$ in per unit. This reactance obviously includes the armature leakage reactance.

The physical picture of this reactance can be broadened by viewing the phenomena from the terminals of one phase. The phase linkage, due to leakage flux and the synchronously rotating, fundamental, air-gap flux, pulsates sinu-

† The usual symmetrical component[16] terms will be used: Positive-sequence (or positive phase-sequence) refers to those symmetrical components of quantities (such as current or voltage) which are of normal (positive) phase rotation; negative-sequence refers to those symmetrical components which are of opposite to normal (negative) phase rotation; zero-sequence refers to those symmetrical components which are of the same time phase or are "in phase" with each other. Any unbalanced 3-phase voltages or currents may be resolved into the 3 sets of symmetrical components listed above. However, an understanding of the system of analysis called symmetrical components is not essential for this paper, it being simply necessary to know the meaning of the defined terms.

* Voltage harmonics of other than fundamental frequency must in all cases be produced by permeance variations or other external influences, and are not themselves causes of reactance.

** The per-unit representation of quantities is similar to the familiar per-cent representation except that the per-unit value of a quantity is the ratio of the actual quantity to an arbitrary amount called the base; whereas the per-cent value is this times 100. Thus, if each phase of a 3-phase machine is rated at 500 amperes and 2,200 volts, "base ohms" is based on the machine rating and is

$$\frac{\text{rated volts}}{\text{rated current}} = \frac{2{,}200}{500} = 4.4 \text{ ohms}$$

Then if a particular reactance (or resistance or impedance) had an actual value of 8.8 ohms, its per-unit value would be

$$\frac{\text{actual ohms}}{\text{base ohms}} = \frac{8.8}{4.4} = 2 \text{ per unit}$$

If machine reactances are expressed in per unit on the machine rating as base, their numerical values have definite significance to one familiar with machines, and do not vary greatly with the size of machines as do ohmic values. This advantage of the per-unit system will become more apparent when table I is studied.

‡ It has not been stated whether the linkage and current used should be instantaneous, root-mean-square, peak, or some other value. It makes no difference as long as the same kinds are used for both. For indeed, the linkage is a linear function of the current, and their ratio is independent of the kind.

§ Invariably synchronous machine reactances are stated on a per phase base so that further mention of this fact will be omitted.

soidally at normal frequency producing the sinusoidal phase voltage, resistance drop being neglected. Now the axis of the rotating fundamental of armature magnetomotive force will coincide with a phase axis at the instant that that phase current is a maximum. Also, since the field pole is moving synchronously in line with the magnetomotive-force wave, it will be precisely in line with the phase at that instant. Consequently, the phase linkage at that instant will be the maximum possible which can be produced by armature current under any condition. This is the peak value of the sinusoidally varying linkage which induces the sinusoidal phase voltage. As they are proportional, the ratio of the phase voltage to the phase current gives $x_d$ in ohms. It is also apparent that $x_d$ is the largest possible 3-phase armature reactance definable.

In practice it is difficult to rotate the field structure mechanically so that the direct axis is always exactly in line with the axis of the rotating armature magnetomotive force. Consequently such a method is unsuited for the experimental determination of the reactance by test. However, when a synchronous machine is short circuited it is a well-known fact that the current which flows is almost entirely reactive, and, therefore, the armature magnetomotive force is almost directly in line with the poles, tending to demagnetize them. Since this condition obtains automatically it is suitable for determining $x_d$.

Saturation is neglected so the flux linkage in any one circuit at any particular instant of time is a *linear* function of the magnitudes of the currents existing in every other winding in the machine at that instant and the principle of superposition may then be used to determine the linkage. Thus, the linkage in one circuit due to the currents in certain circuits flowing alone may be determined; that linkage due to the rest of the currents may be determined separately; and then the 2 values of linkage thus obtained when added give the total linkage in the one circuit with all currents flowing. This is true provided that the motion of the rotor is the same in both cases.

Consider the conditions which must exist under steady-state, symmetrical, short circuit. The terminal voltage is zero. Neglecting resistance drop, the net armature linkage including leakage flux linkage, must, therefore, also be zero. Since the net armature linkage is produced by the armature currents and field current acting at the same time, the armature magnetomotive force opposes the field magnetomotive force; the armature linkage due to all armature currents acting alone must be exactly equal to, and opposite in direction to, the armature linkage due to the field current acting alone. If the field current were acting alone (open circuit) a certain terminal voltage would exist which would be proportional to the armature linkage produced by the field current. Now suppose that the armature currents flow alone (field open circuited). Since the armature linkage has the same value, but is in the opposite direction, the voltage which must have been applied to produce the armature currents must be exactly the same as the terminal voltage induced under open circuit. But notice, when the armature currents flow alone the case is exactly that used to define $x_d$. That is, they are positive phase-sequence, the magnetomotive force produced by them is in line with the poles, and the field is open. Hence, by definition, the ratio of the terminal phase voltage, which would produce the armature currents alone, to the armature phase current gives $x_d$ in ohms, but this voltage is the same as the open circuit voltage before short circuit. Finally, then, $x_d$ is the ratio of the open-circuit terminal voltage resulting from a certain field current to the steady-state, short-circuit, armature current resulting from the same field current.

$$x_d = \frac{E_{\text{open circuit}}}{I_{\text{short circuit}}} \text{ ohms}$$

Obviously these quantities can be determined from the saturation curve and synchronous impedance curve of the machine.*

This discussion of a possible test to determine $x_d$ has served 2 purposes. First to broaden the physical picture and second to indicate how the principle of superposition may be applied in the solution of synchronous machine problems. For standard definitions and methods of measuring this and subsequent reactances, see the AIEE Standards.[21]

## Quadrature Synchronous Reactance $x_q$

With positive-sequence, steady-state currents flowing in the armature and the unexcited field structure rotated mechanically at synchronous speed, such that the interpolar spaces (quadrature axis) are directly in line with the peaks of the rotating armature magnetomotive-force wave, minimum permeance is presented, and the armature linkage will be the minimum for any position of the poles. The flux paths may be visualized by inspecting figure 6 which shows graphically that the permeance of the air gap in the quadrature axis is much lower than that in the direct axis. (If the rotor is cylindrical the permeances will be equal and $x_d = x_q$.) Under this condition the armature linkage per ampere $\times$ $\omega 10^{-8}$ gives the quadrature synchronous reactance, $x_q$, in ohms. The ratio of this value to base ohms gives $x_q$ in per unit. This reactance includes the leakage reactance $x_l$.

If viewed from the armature terminals, the magnitude of the root-mean-square, reactive voltage induced in a phase will be a minimum when the interpolar space is in line with the magnetic axis of the phase at the instant when the current in the phase is a maximum, for if the field structure had any other position at the instant that the phase current was a maximum, a greater armature linkage would result. The ratio of the phase voltage to the phase current under this condition gives $x_q$ in ohms. It is important to note that both $x_d$ and $x_q$ are defined with the field structure in a symmetrical position with respect to the rotating magnetomotive-force wave. Thus, in either case, the field structure has no tendency to be turned by the flux in either direction so that there is no magnetic torque. Therefore, since no electrical power is transferred to the

* The saturation curve is a plot of terminal voltage versus field current and the synchronous impedance curve is a plot of steady-state, short-circuit current versus field current. Normally, the ratio is taken at rated terminal voltage, and to obtain an unsaturated value for $x_d$ the field current at rated terminal voltage on the "air-gap line" is used. The "air-gap line" is a straight line tangent to the straight portion of the magnetization curve.

rotor, the currents are purely reactive (neglecting resistance) and it is legitimate to define a reactance for each case as the ratio of total voltage to total current.

It is difficult to rotate the field structure mechanically so that the quadrature axis is always exactly in line with the armature magnetomotive force for if it deviates slightly a torque will appear (reluctance torque) tending to pull the direct axis into line with the armature magnetomotive force. Hence it is even more impractical in this case to rotate the field structure in its proper position than it was in the case of direct synchronous reactance. However, suppose that the unexcited field is rotated mechanically in the direction of the synchronously revolving armature magnetomotive force, but at a speed slightly below synchronism, and at the same time positive phase-sequence voltages are impressed at the terminals. Obviously the current will be modulated at slip frequency, being a maximum when the quadrature axis is in line with the armature magnetomotive force and a minimum when the direct axis is in that position. Also, due to the reactance in the supply line, the applied voltage will probably be modulated at slip frequency being a maximum at minimum current. Figure 11 is an oscillogram showing this variation. If the applied voltage and current in one phase are observed by means of instruments and the slip is small enough, the maximum and minimum values of the modulated current and voltage can be read directly from instruments. Minimum voltage and maximum current will occur when the quadrature axis is in line with the magnetomotive-force wave peak. Quadrature synchronous reactance in ohms

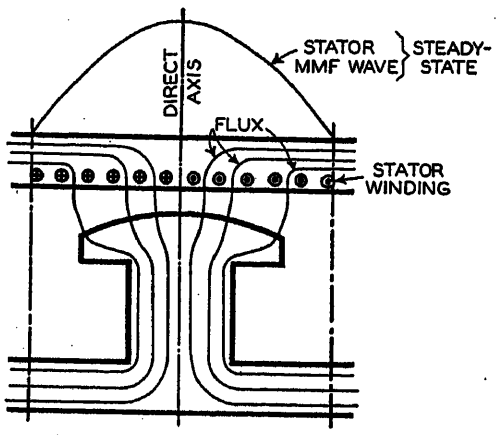



**Figure 5. Direct synchronous reactance flux paths**

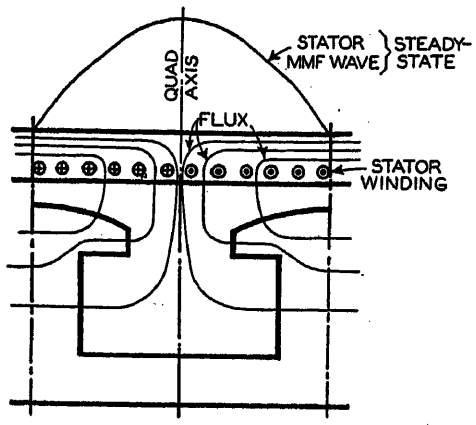



**Figure 6. Quadrature synchronous reactance flux paths**

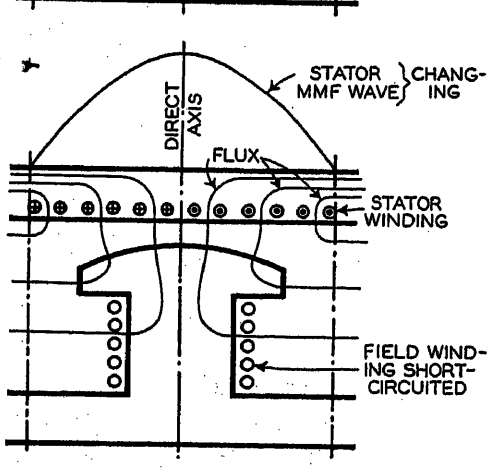



**Figure 7. Direct transient reactance flux paths**

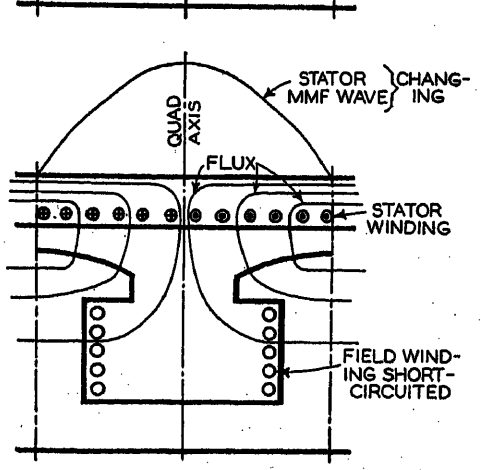



**Figure 8. Quadrature transient reactance flux paths**

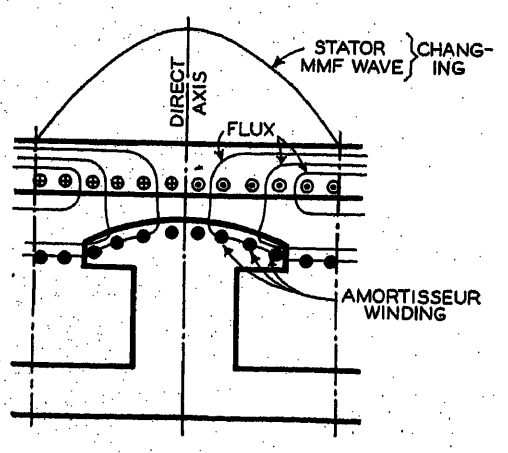



**Figure 9. Direct subtransient reactance flux paths**

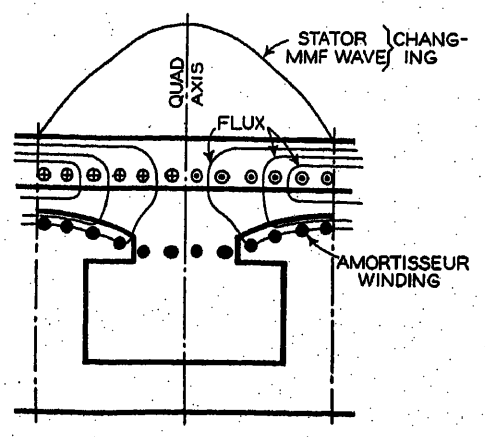



**Figure 10. Quadrature subtransient reactance flux paths**

is then the ratio of minimum voltage to maximum current. From this same test, the ratio of maximum voltage to minimum current gives direct synchronous reactance in ohms.

## Direct Transient Reactance $x_d'$

Direct synchronous reactance is analogous to the self-inductance of the primary of the open-circuit transformer of figure 2. This is true regardless of whether the rotor rotor circuits, such as the amortisseur or damper windings, imagined to be open. Suddenly, terminal voltages are applied at such an instant that fundamental-frequency, positive-sequence armature currents result* and produce a rotating magnetomotive force the axis of which is directly in line with the poles. This condition is identical with that used for defining direct synchronous reactance except that the voltages are now suddenly applied. The sudden appearance of the magnetomotive force in the direct axis is resisted by the current induced in the closed field winding

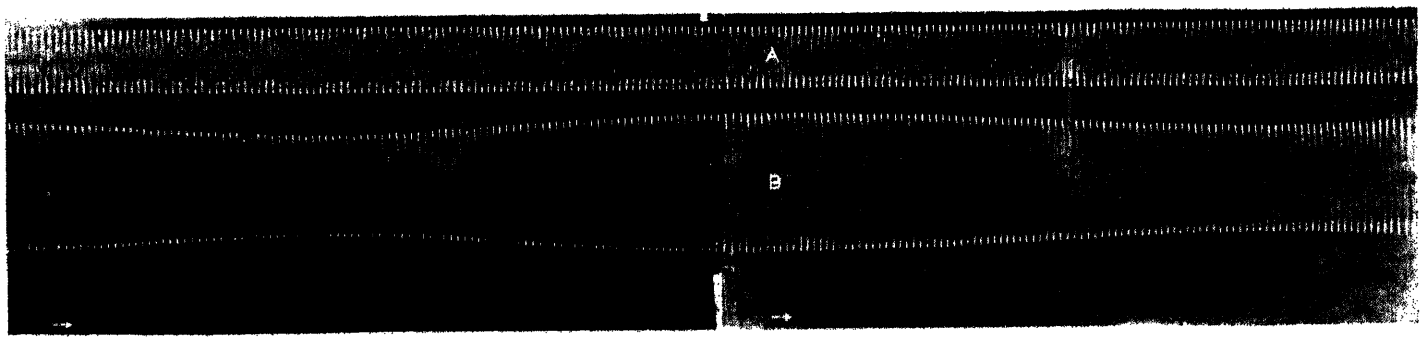



**Figure 11. Determination of $x_d$ and $x_q$ by a "slip test"**

Balanced voltages applied to armature, field open and rotated near synchronous speed

A—Armature voltage
B—Armature current

$$x_d = \frac{\text{maximum voltage}}{\text{minimum current}} \qquad x_q = \frac{\text{minimum voltage}}{\text{maximum current}}$$

circuits are open or closed because, as defined, the steady-state, constant-magnitude, rotating fundamental of the armature magnetomotive force is always stationary with respect to the poles. Since there is no rate of change of magnetomotive force when viewed from the field structure, there will be no currents induced in any field winding, so that the armature magnetomotive force meets a constant permeance, the value of which is determined only by the air gap and magnetic circuit and not by the magnetomotive force of any field winding. Theoretically, any problem involving transformer circuits can be solved in terms of the self- and mutual inductances of windings. Likewise, any synchronous machine problem can theoretically be solved in terms of the synchronous reactances and the self- and mutual inductances of rotor circuits with themselves and with the armature. However, transformer-circuit calculations are greatly simplified and their accuracy improved by employing the short-circuit reactances between windings instead of self- and mutual inductances. A similar simplification can be made in synchronous machine calculations by the use of reactances which *take into account the transient effects of closed rotor windings.*

Thus, when conditions are changing (transient conditions) induced currents will flow in the closed rotor circuits, modifying the effective permeance of the armature flux paths and reducing the corresponding effective reactances. These reactances are analogous to the transformer short-circuit reactance discussed in part I which takes the effect of the closed secondary into account.

Consider the machine operating at normal speed with the unexcited main field winding closed, but with all other just as the current in the transformer secondary of figure 3 resisted a sudden change in the primary magnetomotive force when a d-c voltage was suddenly impressed. Of course, the induced field current will die out eventually. However, during the first interval of time the field current will maintain the field linkage at practically zero value, and the armature flux is forced into the low permeance paths of the interpolar space, see figure 7, just as the transformer primary flux is forced into the leakage path between the primary and secondary in figure 3. The armature linkage per symmetrical, fundamental-frequency, armature ampere will be much less than under synchronous conditions and its value $\times \omega 10^{-8}$ gives direct transient reactance, $x_d'$, in ohms. This value divided by base ohms gives $x_d'$ in per unit.

In order to visualize direct transient reactance from a test which might actually be conducted, it will again be necessary to conduct one which is different from the conditions used to define the reactance. Since we are now dealing with transient quantities, it will also be necessary to employ an oscillograph rather than instruments. Just as in the case of direct synchronous reactance, superposition allows a determination of direct transient reactance from a 3-phase short-circuit test; for in transient as well as steady short circuit the rotating fundamental component of armature magnetomotive force is directly in line with the poles tending to demagnetize them. Now it is possible to superpose the results of various *components* of the current in one circuit, considered separately, just as it is

* It is shown later that suddenly applied currents tend to contain d-c and harmonic components. Hence to obtain the current used in defining $x_d'$ an unusual voltage would be required.

possible to superpose the results of *total currents* in separate circuits. For indeed, the linkage in any one circuit is directly proportional to the total current in each circuit, and hence, to the sum of any components into which each current may be divided in every circuit in the machine. Before short circuit, a certain steady field current existed which gave rise to a certain a-c terminal voltage. After, short circuit armature currents will suddenly start to flow. The sudden magnetomotive force appearing before the field will be resisted by a sudden increase in field current over its initial value. Also after short circuit the terminal voltage is zero, so the change of armature linkage must also be zero. Consequently, the armature linkage produced by the armature current plus that produced by the *increase* in field current has exactly the same value and is in opposite direction to the armature linkage produced by the initial value of field current acting by itself. Now this armature linkage, produced by the armature current plus the *increase* in field current acting together, is produced under exactly the same conditions which were used to define direct transient reactance; for indeed, the armature magnetomotive force appears suddenly in the direct axis and induces field current which opposes it, and the ratio of the symmetrical part† of the phase voltage to the symmetrical part of the phase current is $x_d'$. However, this voltage has exactly the same magnitude as the open-circuit voltage which existed before short circuit. Therefore, the ratio of the voltage before short circuit to the symmetrical part of the armature current immediately after short circuit is direct transient reactance, $x_d'$, in ohms.

In the foregoing analysis one important part of the phenomena has been barely mentioned, the presence of d-c and harmonic components in the armature current. At the instant of short circuit each of the 3 armature phase circuits will be linked by some fraction of the flux produced by the main field excitation. Thus if the short circuit occurred at the instant the direct axis was in line with phase *a*, phase *a* would have maximum positive linkage and the linkages in phases *b* and *c* would be negative and half the maximum.

By the law of constant flux linkage, currents will flow in the armature and field to maintain the armature and field linkages at essentially constant value for a short time after short circuit. The jump in d-c field current to maintain the field linkage constant in the face of the magnetomotive force produced by the a-c, short-circuit armature current has been emphasized. However, the a-c armature current and d-c field current could produce constant armature phase linkages of only zero value. Hence, the armature current will contain d-c components to maintain the initial linkage. This results in a displaced wave of phase current such as shown in figure 13. An oscillogram of symmetrical short-circuit phase current when the phase linkage happened to be zero at the instant of short is shown in figure 12. Here no d-c component was necessary to maintain zero linkage.

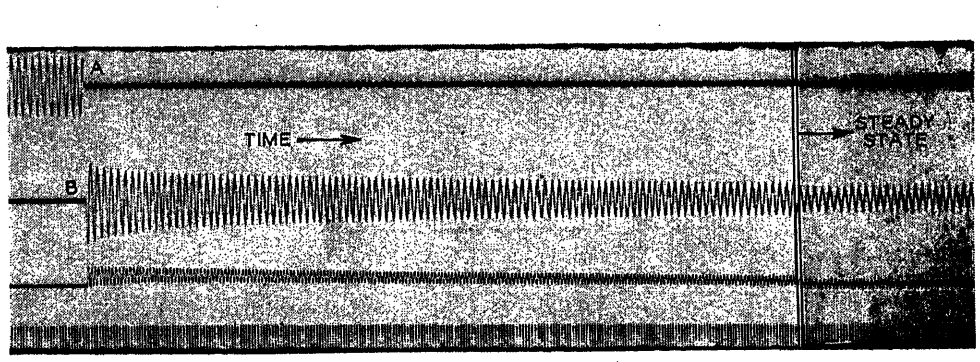



**Figure 12. Nearly symmetrical short-circuit armature current on a 35,000-kva 25-cycle water-wheel generator**

*A*— Armature voltage
*B*— Armature current

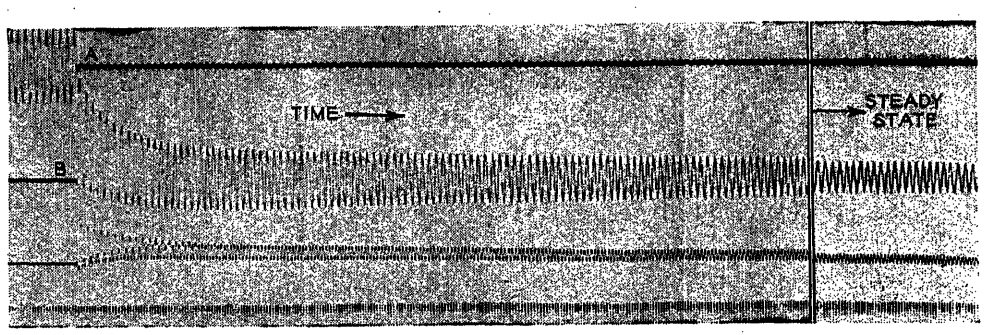



**Figure 13. Nearly pure asymmetrical short-circuit armature current on the same machine as figure 12**

*A*— Armature voltage
*B*—Armature current

The d-c component of armature current results in a stationary magnetomotive force in the air gap. This would produce fundamental-frequency linkage in the field did not a fundamental-frequency field current flow to prevent it. The fundamental-frequency field current gives a pulsating magnetomotive force stationary with respect to the poles which may be resolved into 2 fundamental, magnetomotive-force waves rotating, one forward and one backward with respect to the poles at synchronous

† The symmetrical part of a wave is the part symmetrical about the axis of zero deflection, that is the residue after the d-c component has been subtracted.

speed. The backward rotating component is stationary with respect to the armature and opposes the d-c armature magnetomotive force. The forward rotating component is traveling at twice normal speed with respect to the armature so that a second-harmonic component of armature current must flow to prevent a change of armature linkage. This current will also have its effect on the field and so on. The purpose of this discussion is to complete, in a measure, the physical picture of the phenomena on short circuit. It is evident that the different components of current, existing for different purposes, meet different permeances. Consequently, direct axis transient reactance is defined for only the symmetrical, fundamental-frequency part of the armature current.

The actual test to determine the initial value of short-circuit current could be conducted by taking enough oscillograms of the current, till one was obtained which was symmetrical, or by graphically determining the symmetrical part of an asymmetrical wave, then drawing a line through the peaks of the successive decaying armature current waves and project it back to the time of short circuit neglecting the first few peaks of current which will be discussed under subtransient reactance. The initial value of short-circuit armature current may then be estimated as in the dotted line of figure 14 which was obtained from the oscillogram figure 12. Of course, if the peak value of the current is used, the peak value of the voltage must also be used.

## Direct Subtransient Reactance $x_d''$

In defining direct transient reactance all field windings except the main field winding in the direct axis were assumed to be open. An amortisseur winding as shown in figure 9 may be present in both the direct and quadrature axes. If it is, and armature voltages are suddenly applied to the machine so that armature currents increase rapidly, current will be induced in the amortisseur winding resisting the change in flux in addition to the current induced in the main field winding. Since the amortisseur winding is closer to the air gap than the main field, the permeance of the air-gap leakage-flux paths under this condition is still less than the corresponding permeance in the case of direct transient reactance. The corresponding armature linkage and reactance are also less. Invariably, the per-unit resistance of the amortisseur winding is considerably larger than the per-unit resistance of the main field, so that the induced amortisseur currents tend to die out much more rapidly. The high resistance is used to get the high induction-motor torque required for starting or to produce effective damping if the purpose of the amortisseur is to damp out oscillations. This rapid decay gives rise to the term subtransient reactance, indicating a very high speed phenomenon while transient reactance is the lower speed phenomenon caused by the main field windings.

Let the field structure be rotated mechanically at synchronous speed with the main field winding unexcited but closed, and all other field windings closed. If terminal voltages are now impressed at such an instant that positive-phase-sequence currents are produced, an armature magnetomotive force will be set up which rotates synchronously with its axis directly in line with that of the poles and amortisseur winding currents will be induced resisting the establishment of armature flux. The armature flux is then forced into the very low permeance air-gap leakage path as shown in figure 9 and the net armature linkage per armature ampere under this condition $\times \omega 10^{-8}$ gives direct subtransient reactance in ohms. This value divided by base ohms is $x_d''$ in per unit.

The test procedure described for determining direct transient reactance may also be used to determine direct subtransient reactance. If a closed amortisseur winding is present, the short-circuit current will have a form such as shown in figure 12 or 13. The same argument used in

**Table I. Components of Synchronous Machine Reactances**

| Symbol | Name of Reactance | Position of Magnetomotive-Force Fundamental | Magnitude of Magnetomotive-Force Fundamental | Synchronous Motors: General Purpose | Synchronous Motors: Heavy Starting Duty | Synchronous Condensers | Water-Wheel Generator** | Turboalternator: Solid Rotor | Turboalternator: Laminated Rotor |
|---|---|---|---|---|---|---|---|---|---|
| $x_d$ | Direct synchronous | Directly over pole | Constant | 0.80 ... 0.65<br>1.5 ... 0.90 | | 1.60 avg | 0.60<br>1.25 | 1.15 avg | 1.15avg. |
| $x_q$ | Quadrature synchronous | Midway between poles | Constant | 0.60 ... 0.50<br>1.10 ... 0.70 | | 1.00 avg | 0.40<br>0.80 | 1.0 avg | 1.0 avg. |
| $x_d'$ | Direct transient | Directly over poles | Changing | 0.25 ... 0.15<br>0.45 ... 0.35 | 0.40<br>0.50 | | 0.20<br>0.45 | 0.13<br>0.25 | 0.15<br>0.25 |
| $x_q'$ | Quadrature transient | Midway between poles | Changing | 0.60 ... 0.50<br>1.10 ... 0.70 | | 1.00 avg | 0.40 ... 0.13<br>0.80 ... 0.25 | | 1.0 avg. |
| $x_d''$ | Direct subtransient | Directly over pole | Changing | 0.20 ... 0.10<br>0.40 ... 0.25 | 0.25<br>0.3 | | 0.15<br>0.35 | 0.08<br>0.15 | 0.08<br>0.12 |
| $x_q''$ | Quadrature subtransient | Midway between poles | Changing | 0.30 ... 0.12<br>0.50 ... 0.30 | 0.25<br>0.35 | | 0.25<br>0.45 | 0.10<br>0.20 | 0.20<br>0.30 |
| $x_2$ | Negative sequence | Moving relative to poles | Changing in each axis | 0.25 ... 0.11<br>0.45 ... 0.27 | 0.25<br>0.32 | | 0.20<br>0.40 | 0.08<br>0.13 | 0.11<br>0.21 |
| $x_0$* | Zero sequence | No fundamental | | 0.04 ... 0.02<br>0.27 ... 0.15 | 0.04<br>0.10 | | 0.02<br>0.21 | 0.01<br>0.08 | 0.01<br>0.08 |

* $x_0$ varies from about 15 per cent to 60 per cent of $x_d''$, depending upon winding pitch.
** These values apply to machines with amortisseur windings. For water-wheel generators without amortisseur windings, $x_d'' = x_d'$, $x_q'' = x_q' = x_q$. $x_2$ will be an average of $x_d''$ and $x_q''$ and $x_0$ will be unchanged.

deriving the expression for $x_d'$ from the short-circuit test leads to the obvious result that $x_d''$ is the ratio of the open-circuit voltage existing before short circuit to the symmetrical part of the armature current existing immediately after short circuit. This value of the current may then be obtained by projecting the line connecting the peaks of the short-circuit current back to the zero axis as shown in figure 14. It has been pointed out that the amortisseur-winding currents die out very rapidly, so that their effect soon becomes negligible. Hence, $x_d'$ may be determined from the same test by projecting the line connecting the more slowly decaying peaks of current back to the zero axis as shown.

## Quadrature Transient Reactance $x_q'$

Consider the machine to be operated as in the case of direct transient reactance except that the terminal voltages are applied at a different instant so that the axis of the suddenly appearing armature magnetomotive force is now directly in line with the quadrature axis. Now if there are no closed rotor circuits in addition to the main field winding, the armature flux will pass through the main field winding from one side to the other as shown in figure 8. The net field linkage due to this flux is zero and hence no main-field-winding currents will be induced tending to distort the flux. The armature linkage under this condition per armature ampere $\times \omega 10^{-8}$ gives quadrature transient reactance in ohms. This value divided by base ohms gives $x_q'$ in per unit.

Since the permeance presented to the armature magnetomotive force under this condition is exactly the same as that presented under the conditions defining quadrature synchronous reactance, the armature linkage per ampere will be the same in both cases, and the quadrature transient reactance is exactly equal to the quadrature synchronous reactance. This is literally true if the field structure is perfectly laminated. If the machine has a solid rotor, currents will be induced in the rotor iron resisting the change in flux so that $x_q'$ will be less than $x_q$.

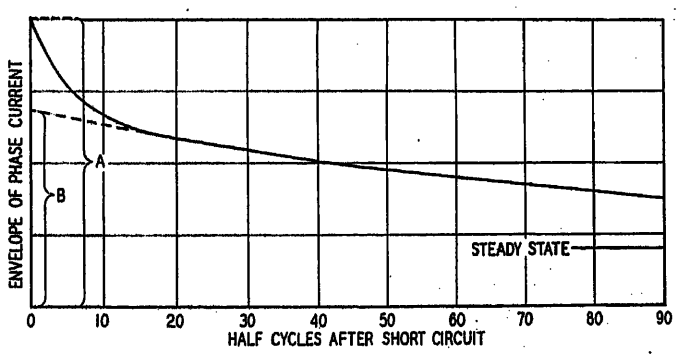



**Figure 14. Determination of $x_d'$ and $x_d''$ from test oscillogram, figure 12**

Curve shows envelope of symmetrical short-circuit phase-current wave. $x_d''$ inversely proportional to initial current $A$.
Dotted curve shows envelope of symmetrical current after high-speed transient has been subtracted. $x_d'$ inversely proportional to $B$

## Quadrature Subtransient Reactance $x_q''$

If an amortisseur winding exists in the quadrature axis, and terminal voltages are suddenly applied such that fundamental-frequency positive-sequence currents flow so that the resultant rotating armature magnetomotive force is in line with the quadrature axis of the mechanically rotated field structure, current will be induced in the amortisseur winding tending to maintain its linkage zero and forcing the armature flux into the very low permeance air-gap path as shown in figure 10. Under this condition the armature linkage per armature ampere $\times \omega 10^{-8}$ gives quadrature subtransient reactance in ohms. This value divided by base ohms gives $x_q''$ in per unit.

No simple convenient method of test exists to aid in visualizing this reactance. Methods of test exist[10,11] but the mathematical analysis, required for establishing them, complicates the physical picture.

## Negative-Sequence Reactance $x_2$

If terminal voltages are impressed such that fundamental-frequency negative-sequence currents flow while the unexcited field structure with all field windings closed is rotated mechanically at synchronous speed in the forward direction, the armature magnetomotive force will be traveling in the opposite direction at synchronous speed and hence will be traveling with twice synchronous speed with respect to the field structure. Then alternating currents of twice normal frequency will be induced in the rotor circuits, holding the field linkage at essentially zero value. This case is analogous to the a-c excited, short-circuited transformer of figure 3 for in the transformer an a-c magnetomotive force attempts to force flux through the short-circuited secondary and alternating currents are induced in the secondary holding the secondary linkage zero. In the case at hand the armature flux is forced into the very low permeance air-gap paths. Of course the actual permeance of the air-gap path varies as a function of time, for the armature magnetomotive force meets alternately the direct and quadrature axis. Under this condition the average armature linkage per armature ampere $\times \omega 10^{-8}$ gives the negative-sequence reactance in ohms. This value divided by base ohms is $x_2$ in per unit.

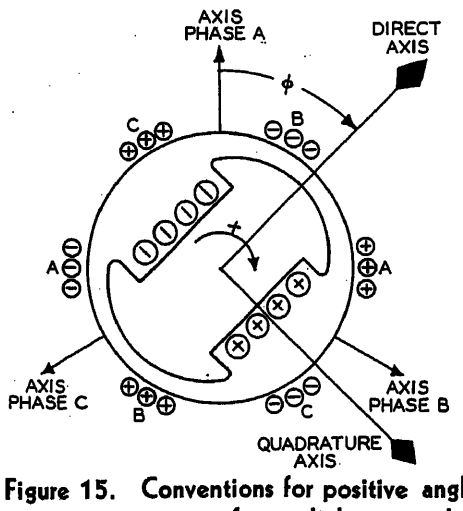
The permeance presented to the armature magnetomotive force at the instant that the magnetomotive force is over the axis of the poles is evidently essentially the same as the permeance presented under direct subtransient conditions and the effective reactance if the permeance were constant at this value would be $x_d''$. However, an instant later the magnetomotive force is directly over the quadrature axis and at this instant the effective reactance is $x_q''$. Hence, the average value of $x_2$ must lie between $x_d''$ and $x_q''$. For most purposes the value of $x_2$ is taken as the arithmetic average of $x_d''$ and $x_q''$.

$$x_2 = \frac{x_d'' + x_q''}{2}$$

The conditions used to define negative-sequence reactance may also be used to measure it. It is simply necessary to rotate the rotor mechanically at normal speed with the main field winding unexcited but short circuited, and to apply terminal voltages such that fundamental-frequency negative-sequence currents flow in the armature. The ratio of the average phase voltage to the average phase current under this condition gives $x_2$ in ohms. Tests may also be made with the rotor stationary[21] but here again, they are of little use for visualization.

## Zero-Sequence Reactance $x_0$

Zero-sequence currents are defined as currents which would flow if the 3 line terminals of a Y-connected machine were joined and single-phase voltage applied between the neutral and the terminals. Under this condition currents will flow in the 3 armature windings and will be of the same time phase. If such currents be impressed on a synchronous machine, no space fundamental of air-gap magnetomotive force will be produced so that the motion of the rotor is unimportant and the reactance is very small. The 3-phase armature windings will, in general, set up a third space harmonic of air-gap magnetomotive force which is stationary but pulsating. Currents will be induced in closed rotor circuits opposing this harmonic magnetomotive force and forcing the armature flux due to it into the low-permeance air-gap paths so that this reactance is indeed very small. The actual value depends greatly on winding pitch, being a minimum at $^2/_3$ pitch in a 3-phase winding. For at this pitch each slot contains coil sides of adjacent phases carrying currents in time phase but opposite direction. Consequently the net air-gap magnetomotive force of the slot is zero and the only flux produced in addition to end winding leakage is the slot leakage flux between the 2 conductors with opposite currents.




Plus signs indicate current entering plane of paper, minus signs—current leaving. Positive electromotive force in direction of positive current. Arrows indicate positive direction of flux or linkage or angle

**Figure 15. Conventions for positive angles, currents, electromotive forces, linkages, and rotation**

If zero-sequence currents be applied, the ratio of the phase linkage to phase current $\times\ \omega 10^{-8}$ gives zero-sequence reactance in ohms. This value divided by base ohms is $x_0$ in per unit.

Zero-sequence currents do not produce the same slot, end winding, or differential air-gap leakage fluxes as positive-sequence currents so that $x_l$ is not included in $x_0$.

The conditions used to define zero-sequence reactance are easily reproduced in an actual test, and if the machine were operated as described, the ratio of the voltage applied between the neutral and the 3 connected terminals to the current in one phase gives zero-sequence reactance in ohms.

## Summary

The various synchronous machine armature reactances have been discussed from a number of different viewpoints, each designed to enhance the physical picture: (1) linkage per ampere, (2) effective permeance, (3) a-c voltage per a-c ampere, (4) test and (5) figures illustrating the flux paths. The foregoing discussion is summarized in table I which gives the various pertinent factors influencing each reactance, and typical numerical values.

# Part III. Analytical Approach to Synchronous Machine Reactances

In the preceding parts a physical picture of certain arbitrary reactances has been built up. The uninitiated reader is, no doubt, in a quandary as to why these particular arbitrary definitions were selected. Furthermore, he is probably at a loss as to how to use such reactances in actual calculations of performance. It is not the purpose of this paper to present the whole of synchronous-machine analysis. However, the concepts of synchronous-machine reactance would be most incomplete without some idea as to their purpose and use. The following derivation is made from a most fundamental starting point and it will serve as a sound basis for proceeding with synchronous machine analysis as well as for broadening the physical picture already developed. Values of the various reactances are obtained in terms of the self- and mutual inductances of the various windings.

## Fundamental Synchronous Machine Parameters

It is proposed to set up the differential equations of the synchronous machine in terms of the fundamental parameters of the machine, the self- and mutual inductances of the various circuits.

The self-inductance of an armature phase depends upon the position of the rotor, being a maximum when the direct axis is lined up with the magnetic axis of the phase and a minimum when the quadrature axis is in line with it. The variation of the self-inductance between these 2 positions can be calculated from design data or it may be determined from tests. It is found by both means that the variation in practical machines is approximately sinusoidal as shown in figure 16. Since the maximum value will obtain whether the pole which is before the phase is normally north or normally south in magnetic polarity, the self-

inductance will vary through 2 maximum values if the rotor is rotated through 360 electrical degrees. Since it will have some positive value at every position of the poles, it will be of the form,

$$L_a = L_0 + M_0 \cos 2\phi \qquad L_0 > M_0 \tag{22}$$

where $L_0$ is the average and $M_0$ the amplitude of variation of the phase self-inductance in henries, ($M_0$ is not a mutual inductance as used here). $\phi$ is the electrical angle between the magnetic axis of the phase and the direct axis as shown in figure 15. This variation can be visualized by applying the concepts of part I to figure 15 and noting how the linkage per ampere of a phase varies as the rotor moves.

If $\phi$ be measured from the axis of phase $a$ then 22 gives the self-inductance of phase $a$, for at $\phi = 0$, $L_a$ is a maximum. Obviously, in a symmetrical machine, the self-

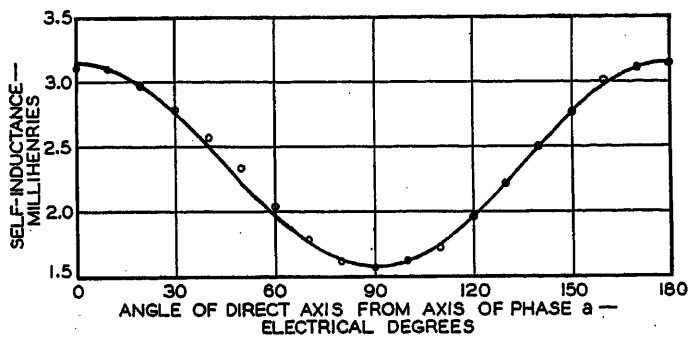



**Figure 16. Variation of self-inductance of armature phase a with position of the field**

The test points, taken on a 4-pole 15-kva 220-volt 1,800-rpm synchronous motor, compare favorably with the curve showing the theoretical variation of an ideal machine,

$$L_a = L_0 + M_0 \cos 2\phi = 2.36 + 0.796 \cos 2\phi \text{ (millihenries)}$$

inductance of each phase will have the same form except the maximum value will occur at a different value of $\phi$. That of phase $b$ will be a maximum when $\phi = 120$ electrical degrees,

$$L_b = L_0 + M_0 \cos 2(\phi - 120) = L_0 + M_0 \cos (2\phi + 120) \tag{23}$$

Likewise, the self-inductance of phase $c$ will be a maximum when $\phi = -120$ degrees,

$$L_c = L_0 + M_0 \cos 2(\phi + 120) = L_0 + M_0 \cos (2\phi - 120) \tag{24}$$

The mutual inductances between armature phases will also be functions of the rotor position. Positive currents are logically defined in the same relative direction in each of the phases as shown in figure 15. Thus, positive current in phase $b$ tends to produce linkage in phase $a$ in the opposite direction to that produced by positive current in phase $a$ (see figure 15). Hence, the sign of the mutual inductance between phases $a$ and $b$ is negative regardless of rotor position. The absolute magnitude of this mutual inductance will have a minimum value when the axis of the poles is midway between the phases (for phases $a$ and $b$, at $\phi = 60$ degrees), and a maximum value when the rotor has advanced 90 degrees from the position of minimum value. Hence, the mutual inductance between 2 phases also varies through 2 maximum values for a 360 degree rotation of the rotor. Experiments and calculations both show that the mutual inductance also varies approximately sinusoidally with $\phi$ as shown by the test on a particular machine in figure 17. Furthermore, experiments show that the amplitude of variation of mutual inductance in

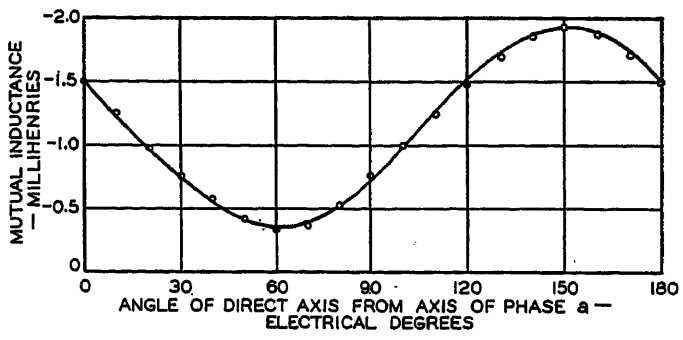



**Figure 17. Variation of mutual inductance between armature phases a and b with position of the field**

The test points taken on the same machine as in figure 16 are close to the curve which shows theoretical variation for an ideal machine

$$M_{ab} = -M_s + M_0 \cos (2\phi - 120°)$$
$$= -1.14 + 0.796 \cos (2\phi - 120°) \text{ millihenries}$$

practical machines is nearly the same as the amplitude of variation of self-inductance (see figures 16 and 17). Then, if $M_s$ is the average value of the mutual inductance between phases, the same $M_0$ used in equations 22, 23, and 24 is the amplitude of pulsation of the mutual inductance. Hence, the mutual inductance between phases $a$ and $b$ is

$$M_{ab} = -[M_s - M_0 \cos 2(\phi - 60)]$$
$$= -M_s + M_0 \cos (2\phi - 120) \qquad M_s > M_0 \tag{25}$$

Likewise, the minimum absolute magnitude of the mutual inductance between phases $b$ and $c$ will occur at $\phi = 0$ and

$$M_{bc} = -[M_s - M_0 \cos 2\phi] = -M_s + M_0 \cos 2\phi \tag{26}$$

Also

$$M_{ac} = -[M_s - M_0 \cos 2(\phi + 60)] = -M_s + M_0 \cos (2\phi + 120) \tag{27}$$

A complete analysis would, of course, include the effect of an arbitrary number of field circuits. However, the complexity of the equations which arise obscures the physical picture so that in this analysis no other rotor circuits except the main, direct-axis, field winding are assumed. Inspection of figure 15 shows that $M_d$, the maximum mutual inductance between phase $a$ and the main field winding will exist when the direct axis is in line with the magnetic axis of phase $a$, at $\phi = 0$, and its value will be equal but negative at $\phi = 180$ degrees. Test and calculation show that it varies approximately sinusoidally between these limits, so

$$M_{ad} = M_d \cos \phi \tag{28}$$

The mutual inductance between phase $b$ and the main field winding will have the same form but will be a maximum at $\phi = 120$ degrees, so

$$M_{bd} = M_d \cos(\phi - 120) \tag{29}$$

Likewise,

$$M_{cd} = M_d \cos(\phi + 120) \tag{30}$$

## Fundamental Synchronous Machine Equations

The assumptions which have been made are:

1. Saturation, hysteresis, and eddy currents are negligible.
2. Self- and mutual inductances vary sinusoidally as the rotor moves.

On the basis of the fundamental, experimental laws of Faraday, equation 1, and Ohm, the voltage, $e$, impressed on an armature phase may be expressed in terms of the phase resistance, $r$, phase linkage, $\psi$ and phase current $i$, in phase $a$ as

$$e_a = ri_a + \frac{d}{dt}\psi_a \times 10^{-8}$$

noting the time derivative operator, $d/dt$, by $p$,

$$e_a = ri_a + p\psi_a \times 10^{-8} \tag{31}$$

and for phases $b$ and $c$,

$$e_b = ri_b + p\psi_b \times 10^{-8} \tag{32}$$

$$e_c = ri_c + p\psi_c \times 10^{-8}* \tag{33}$$

A similar equation may be written for the main field winding in terms of its applied voltage $E_d$, current $I_d$, linkage $\Psi_d$ and resistance $R_d$.

$$E_d = R_d I_d + p\Psi_d \times 10^{-8} \tag{34}$$

Before these differential equations (31 to 34) can be solved for the currents in terms of the applied voltages it is necessary, of course, to express the linkages as functions of the currents in all circuits. Thus, from the definitions of self- and mutual inductance, equations 3 and 4, the linkage in phase $a$ is

$$\psi_a = \{L_a i_a + M_{ab} i_b + M_{ac} i_c + M_{ad} I_d\} 10^8$$

From equations 22, 25, 27, and 28,

$$\psi_a = \{i_a[L_0 + M_0 \cos 2\phi] + i_b[-M_s + M_0 \cos(2\phi - 120)] + i_c[-M_s + M_0 \cos(2\phi + 120)] + I_d M_d \cos\phi\} 10^8$$

$$\psi_a = \{L_0 i_a - M_s[i_b + i_c] + M_0[i_a \cos 2\phi + i_b \cos(2\phi - 120) + i_c \cos(2\phi + 120)] + I_d M_d \cos\phi\} 10^8 \tag{35}$$

Likewise, from equations 23, 25, 26, and 29,

$$\psi_b = \{L_0 i_b - M_s[i_c + i_a] + M_0[i_c \cos 2\phi + i_a \cos(2\phi - 120) + i_b \cos(2\phi + 120)] + I_d M_d \cos(\phi - 120)\} 10^8 \tag{36}$$

and from equations 24, 26, 27, and 30,

$$\psi_c = \{L_0 i_c - M_s[i_a + i_b] + M_0[i_b \cos 2\phi + i_c \cos(2\phi - 120) + i_a \cos(2\phi + 120)] + I_d M_d \cos(\phi + 120)\} 10^8 \tag{37}$$

If the main field winding self-inductance is $L_{fd}$—obviously it is a constant—the main field linkage may be expressed in terms of all currents by considering figure 15 and equations 28, 29, and 30

$$\Psi_d = M_{ad} i_a + M_{bd} i_b + M_{cd} i_c + L_{fd} I_d$$
$$= M_d[i_a \cos\phi + i_b \cos(\phi - 120) + i_c \cos(\phi + 120)] + L_{fd} I_d \tag{37a}$$

If equations 35, 36, 37, and 37$a$ are substituted in equations 31 to 34, the fundamental simultaneous differential equations of the synchronous machine will have been set up from Faraday's experimental law, equation 1, and measurable self- and mutual inductances.

Theoretically, the resulting differential equations can be solved simultaneously for the currents with any given applied voltages and motion of the rotor either in transient or steady state. However, if the rotor is moving, $\phi$ is a function of time. Consequently, when the differentiations indicated in equations 31 to 34 are performed, terms such as the following arise,

$$\frac{d}{dt}\left[M_0 i_b \cos(2\phi - 120)\right] =$$
$$-2M_0 i_b \sin(2\phi - 120)\frac{d\phi}{d} + M_0 \cos(2\phi - 120)\frac{di_b}{dt}$$

When the resulting differential equations are combined simultaneously to get a differential equation in terms of one of the currents only, a multitude of terms, even more complex than the one shown, arise which include functions of time—such as cose $2\phi$—as coefficients of the derivatives. The solution of these differential equations with variable coefficients as they stand is so difficult that it has never been carried out in a general case, and this is the reason for resorting to direct and quadrature axes, namely, in order to simplify the mathematics.

All are familiar with linear and nonlinear changes of variables in the calculus in order to simplify integration. Also, the change of co-ordinate axes such as from Cartesian to polar, or 3-dimensional Cartesian to spherical, etc., are nonlinear changes of variable, and rotation or translation of Cartesian reference axes are linear changes of variable which are commonplace. In the latter cases it is important to note that the number of degrees of freedom is not reduced and the new variables are independent of each other and related to the old ones by linear equations. Now if someone suggested that new, independent currents, flux linkages, etc., might be assumed, related to the old currents, flux linkages, etc., by linear equations which would facilitate the solution; we might throw up our hands in horror at this unorthodox procedure if we did not realize that the differential equations to be solved were really mathematical statements which can be manipulated at will so long as the fundamental rules of calculus, algebra, etc., are not violated. Consequently, it is sensible to take the view that the proposed transformation is a mathematical one and as long as it is eventually possible to return and find the old currents, linkages, etc., it is possible to proceed with confidence.

* This method of analysis is similar to that used by Park[12] except for different sign conventions, but is not the same as that used by Park[6] as it avoids the use of permeance coefficients. The sign conventions used here are those widely accepted in classical literature and were defined in part I.

Assume then, that someone has suggested the following new variables:

$i_d$, $\psi_d$, $e_d$—direct axis current, linkage, voltage

$i_q$, $\psi_q$, $e_q$—quadrature axis current, linkage, voltage

$i_0$, $\psi_0$, $e_0$—zero axis current, linkage, voltage

which are linearly related to the old variables by the equations,

$$\left.\begin{aligned} i_d &= \frac{2}{3}\left\{ i_a \cos\phi + i_b \cos(\phi - 120) + i_c \cos(\phi + 120) \right\} \\ i_q &= -\frac{2}{3}\left\{ i_a \sin\phi + i_b \sin(\phi - 120) + i_c \sin(\phi + 120) \right\} \\ {}_0 &= \frac{1}{3}\left\{ i_a + i_b + i_c \right\} \end{aligned}\right\} \quad (38)$$

and

$$\left.\begin{aligned} \psi_d &= \frac{2}{3}\left\{ \psi_a \cos\phi + \psi_b \cos(\phi - 120) + \psi_c \cos(\phi + 120) \right\} \\ \psi_q &= -\frac{2}{3}\left\{ \psi_a \sin\phi + \psi_b \sin(\phi - 120) + \psi_c \sin(\phi + 120) \right\} \\ \psi_0 &= \frac{1}{3}\left\{ \psi_a + \psi_b + \psi_c \right\} \end{aligned}\right\} \quad (39)$$

and

$$\left.\begin{aligned} e_d &= \frac{2}{3}\left\{ e_a \cos\phi + e_b \cos(\phi - 120) + e_c \cos(\phi + 120) \right\} \\ e_q &= -\frac{2}{3}\left\{ e_a \sin\phi + e_b \sin(\phi - 120) + e_c \sin(\phi + 120) \right\} \\ e_0 &= \frac{1}{3}\left\{ e_a + e_b + e_c \right\} \end{aligned}\right\} \quad (40)$$

Actually, these new variables were conceived and developed by engineers[1,2,3,4,5] by virtue of their very thorough and complete "physical picture" of the phenomena. For the present purpose, the physical picture and the physical reasoning back of the selection of such a set of transformations will be discussed after the results are obtained.

If the proposed change of variables enables solution of the equations, the actual physical phase currents, linkages, voltages, etc., can then finally be obtained from the following expressions for the phase quantities in terms of the new variables. Thus, solving simultaneously equations 38:

$$\left.\begin{aligned} i_a &= i_d \cos\phi - i_q \sin\phi + i_0 \\ {}_b &= i_d \cos(\phi - 120) - i_q \sin(\phi - 120) + i_0 \\ i_c &= i_d \cos(\phi + 120) - i_q \sin(\phi + 120) + i_0 \end{aligned}\right\} \quad (41)$$

and equations 39:

$$\left.\begin{aligned} \psi_a &= \psi_d \cos\phi - \psi_q \sin\phi + \psi_0 \\ \psi_b &= \psi_d \cos(\phi - 120) - \psi_q \sin(\phi - 120) + \psi_0 \\ \psi_c &= \psi_d \cos(\phi + 120) - \psi_q \sin(\phi + 120) + \psi_0 \end{aligned}\right\} \quad (42)$$

* A hint to the student in solving, say, equations 40 to obtain equations 43 is to multiply the first one of equations 40 by cos $\phi$, the second by $-$ sine $\phi$ and add. The trigonometric coefficients of $e_b$ and $e_c$ can be shown to be zero, that of $e_a$ unity which gives a ready solution for $e_a$ in terms of $e_d$, $e_q$, and $e_0$. Similar operations yield $e_b$ and $e_c$.

and equations 40:

$$\left.\begin{aligned} e_a &= e_d \cos\phi - e_q \sin\phi + e_0 \\ e_b &= e_d \cos(\phi - 120°) - e_q \sin(\phi - 120°) + e_0 \\ e_c &= e_d \cos(\phi + 120°) - e_q \sin(\phi + 120°) + e_0* \end{aligned}\right\} \quad (43)$$

Now to proceed with the change of variable. Substitute equations 38 in equations 35, 36, and 37. Combine the resulting expressions for $\psi_a$, $\psi_b$, and $\psi_c$ according to equations 39 to get $\psi_d$, $\psi_q$, and $\psi_0$ wholly in terms of $i_d$, $i_q$, $i_0$ the self- and mutual inductances and trigonometric expressions. The algebra and trigonometry of these transformations are formidable but if the student has sufficient fortitude he will find that the many multiple products of trigonometric functions are all reducible to single simple constants and he will be rewarded by the following very simple equations:

$$\psi_d = \left\{ M_d I_d + \left( L_0 + M_s + \frac{3}{2} M_0 \right) i_d \right\} 10^8 \quad (44)$$

$$\psi_q = \left\{ \left( L_0 + M_s - \frac{3}{2} M_0 \right) i_q \right\} 10^8 \quad (45)$$

$$\psi_0 = \left\{ (L_0 - 2M_s) i_0 \right\} 10^8 \quad (46)$$

These expressions are relations between the new variables, linkages, and currents, in the direct, quadrature, and zero axes. Note that each equation contains only variables in the same axis. Mathematically this means that the choice of new variables has been particularly appropriate and that the equations will be relatively simple to solve in terms of the new variables.

Now each equation physically is a relation between currents and linkage and the factors of proportionality are constants. Consequently it requires only a little imagination to see that the bracketed constants of proportionality are really equivalent inductances in the new system of variables. Furthermore, it is natural to suspect that the constant of proportionality in equation 44 is the inductance corresponding to direct synchronous reactance $x_d$, that of equation 45 to $x_q$, and that of equation 46 to $x_0$. That this is true can be proved quickly by applying the conditions defining these reactances in part II to equation 35, and finding the linkage in phase $a$, $\psi_a$, per unit current in phase $a$, $i_a$. Either of the other phases might be used.

## Direct Synchronous Reactance $x_d$

The conditions specified are:

1. Positive-sequence steady-state currents applied to the armature

$$\left.\begin{aligned} i_a &= i \cos \omega t \\ i_b &= i \cos(\omega t - 120) \\ i_c &= i \cos(\omega t + 120) \\ &\text{and} \\ i_b &+ i_c = -i_a \end{aligned}\right\} \quad (46a)$$

2. Field circuit open,

$$I_d = 0$$

3. Field rotated at constant synchronous speed so that the direct axis is in line with the axis of the armature magnetomotive-force wave,

$\phi = \omega t$

Substitute these conditions in equation 35.

$$\psi_a = \{i \cos \omega t\,(L_0 + M_s) + M_0 i\,[\cos \omega t \cos 2\omega t + \cos(\omega t - 120) \times \cos(2\omega t - 120) + \cos(\omega t + 120)\cos(2\omega t + 120)]\}10^8$$

which, upon trigonometric reduction becomes

$$\psi_a = \left[\left(L_0 + M_s + \frac{3}{2}M_0\right) i \cos \omega t\right] 10^8$$

$$= \left(L_0 + M_s + \frac{3}{2}M_0\right) i_a \times 10^8$$

and as defined, $x_d$ in ohms is the armature linkage per armature ampere times $\omega\, 10^{-8}$ so

$$x_d = \frac{\psi_a}{i_a}\omega\, 10^{-8} = \left(L_0 + M_s + \frac{3}{2}M_0\right)\omega \qquad (47)$$

## Quadrature Synchronous Reactance $x_q$

The conditions specified are:

1 and 2 are the same as under $x_d$.

3. Field rotated at constant speed so that the quadrature axis is in line with the axis of the armature magnetomotive-force wave,

$\phi = \omega t - 90°$*

Then equation 35 becomes

$$\psi_a = \{i \cos \omega t\,(L_0 + M_s) + M_0 i[\cos \omega t \cos 2(\omega t - 90) + \cos(\omega t - 120)\cos\{2(\omega t - 90) - 120\} + \cos(\omega t + 120)\cos\{2(\omega t - 90) + 120\}]\}10^8$$

$$= \{i \cos \omega t\,(L_0 + M_s) - M_0 i[\cos \omega t \cos 2\omega t + \cos(\omega t - 120)\cos(2\omega t - 120) + \cos(\omega t + 120)\cos(2\omega t + 120)]\}10^8$$

which, by comparison with the previous example is

$$\psi_a = \left(L_0 + M_s - \frac{3}{2}M_0\right) i \cos \omega t \times 10^8$$

and

$$x_q = \left(L_0 + M_s - \frac{3}{2}M_0\right)\omega \qquad (48)$$

## Zero-Sequence Reactance $x_0$

The conditions specified are:

1. Zero-sequence, steady-state currents applied to the armature,

$i_a = i_b = i_c = i \cos \omega t$

2. Effect of field circuits, negligible,

$I_d = 0$

3. Motion of the rotor immaterial as will be evident,

$\phi = \phi$

* The sign is negative because the usual convention is to designate the interpolar space *ahead* of the poles as the quadrature axis. This is explicitly required by the signs in equations 38, 39, and 40.

Equation 35 becomes,

$$\psi_a = \{i \cos \omega t\,[L_0 - 2M_s] + M_0 i \cos \omega t\,[\cos \phi + \cos(\phi - 120) + \cos(\phi + 120)]\}10^8$$

The last term is obviously zero regardless of how $\phi$ varies, so

$$\psi_a = \{[L_0 - 2M_s] i \cos \omega t\}10^8$$

and

$$x_0 = (L_0 - 2M_s)\omega \qquad (49)$$

Equations 44, 45, and 46 then become,

$$\left.\begin{aligned} \psi_d &= \left[M_d I_d + \frac{x_d i_d}{\omega}\right]10^8 \\ \psi_q &= \frac{x_q i_q}{\omega} \times 10^8 \\ \psi_0 &= \frac{x_0 i_0}{\omega} \times 10^8 \end{aligned}\right\} \qquad (50)$$

## Machine Equations in the Direct, Quadrature, and Zero Axes

Before deriving an expression for $x_d'$ the machine equations in terms of the direct-, quadrature-, and zero-axis quantities will be determined. They will then be employed to obtain $x_d'$ to illustrate the use of these equations rather than using the method just applied to get $x_d$, $x_q$, and $x_0$. The following derivation was given by Park[6] with different sign conventions. Combining the fundamental phase voltage equations 31, 32, and 33 with the definition of $e_d$, equation 40,

$$e_d = \frac{2}{3}\left\{\cos\phi\,(ri_a + p\psi_a \times 10^{-8}) + \cos(\phi - 120) \times (ri_b + p\psi_b \times 10^{-8}) + \cos(\phi + 120)(ri_c + p\psi_c \times 10^{-8})\right\}$$

and the definition of $i_d$, equation 38, allows a reduction to

$$e_d = ri_d + \frac{2}{3}\left\{\cos\phi\, p\psi_a + \cos(\phi - 120)\, p\psi_b + \cos(\phi + 120) p\psi_c\right\} \times 10^{-8} \qquad (51)$$

The bracketed term is unfamiliar; however, differentiate $\psi_d$, equation 39,

$$p\psi_d = \frac{2}{3}\left\{\cos\phi\, p\psi_a + \cos(\phi - 120)\, p\psi_b + \cos(\phi + 120) p\psi_c\right\} - \frac{2}{3}\left\{\psi_a \sin\phi + \psi_b \sin(\phi - 120) + \psi_c \sin(\phi + 120)\right\} p\phi \qquad (52)$$

The first bracketed term of this expression is identical with the bracketed term in equation 51. However, the last bracketed term in equation 52 is, by comparison with the

definition of $\psi_q$, equation 39, $\psi_q p\phi$. Therefore the bracketed expression in equation 51 is

$$p\psi_d - \psi_q p\phi$$

and

$$\left.\begin{aligned} e_d &= ri_d + (p\psi_d - \psi_q p\phi)10^{-8} \\ &\text{By similar substitutions Park}^6 \text{ shows that} \\ e_q &= ri_q + (p\psi_q + \psi_d p\phi)10^{-8} \\ &\text{and} \\ e_0 &= ri_0 + p\psi_0 \times 10^{-8} \end{aligned}\right\} \quad (53)$$

Now, $\psi_d$, $\psi_q$, and $\psi_0$ are known in terms of currents and measurable reactances, equations 50. Consequently, equations 50, 53, and 34 may be used to solve for $i_d$, $i_q$, $i_0$, and $I_d$ if the applied voltages $e_d$, $e_q$, $e_0$, and $E_d$ are known, and the motion of the rotor is known. The phase currents may then be obtained from equations 41. This is one of the first steps in a complete method of synchronous machine analysis as given by Park.[6]

## Direct Transient Reactance $x_d'$

The conditions used to define direct transient reactance were:

1. Positive-phase-sequence currents suddenly applied to the armature, expressions for which are given in equation 46*a*.
2. Field circuit closed, not excited. By the constant linkage law.

$$\Psi_d = 0$$

3. Field rotated at constant speed so that the direct axis is in line with the peak of newly established armature magnetomotive-force wave.

$$\phi = \omega t$$

If conditions 1 and 3 be put in equation 38, the direct-, quadrature-, and zero-axis currents as functions of time are found to be

$$i_d = i$$

$$i_q = 0$$

$$i_0 = 0$$

Comparison of equation 50 with condition 1 shows that

$$\psi_d = \left[ M_d I_d + \frac{x_d}{\omega} i_d \right] 10^8 \quad (54)$$

$$\psi_q = 0$$

$$\psi_0 = 0$$

Comparing equation 37*a* with $i_d$ in equation 38 shows that

$$\Psi_d = L_{fd} I_d + \frac{3}{2} M_d i_d \quad (55)$$

which gives a ready solution for $I_d$ on application of condition 2, thus

$$I_d = -\frac{3}{2}\frac{M_d}{L_{fd}} i_d$$

Then, equation 54 gives $\psi_d$ in terms of $i_d$

$$\psi_d = \left[ \frac{x_d}{\omega} - \frac{3}{2}\frac{M_d^2}{L_{fd}} \right] i_d \, 10^8 \quad (56)$$

Since $\psi_q = \psi_0 = i_q = i_0 = 0$, equations 41 and 42 show that

$$\frac{\psi_a}{i_a} = \frac{\psi_d}{i_d}$$

Therefore, the armature linkage per armature ampere under this condition is

$$\frac{\psi_d}{i_d} = \left[ \frac{x_d}{\omega} - \frac{3}{2}\frac{M_d^2}{L_{fd}} \right] 10^8 = \left[ L_0 + M_s + \frac{3}{2} M_0 - \frac{3}{2}\frac{M_d^2}{L_{fd}} \right] 10^8$$

and the direct transient reactance is

$$\left.\begin{aligned} x_d' &= \frac{\psi_a}{i_a}\omega \, 10^{-8} = \left[ L_0 + M_s + \frac{3}{2} M_0 - \frac{3}{2}\frac{M_d^2}{L_{fd}} \right]\omega \\ &= x_d - \frac{3}{2}\frac{M_d^2}{L_{fd}}\omega \end{aligned}\right\} \quad (57)$$

The similarity between the expression for $x_d'$ and the short-circuit transformer leakage reactance equation 19 is striking.

$$x_{sc} = \omega L_1 - \frac{M'^2}{L_2'}\omega \quad (19)$$

The analogy is obvious. Recall, for instance that the physical argument used in part II in discussing $x_d'$ which was based on short-circuit transformer phenomena. The presence of the $^3/_2$ may be physically explained on the basis that all 3 phase currents contribute to the armature magnetomotive force attempting to establish flux in the field, whereas in the transformer only one primary coil was excited, however, space does not permit going through this interesting physical argument. Nevertheless, it is strongly recommended that the student make thoroughgoing physical explanations of the presence of the various terms in the equations for $x_d$, $x_q$, $x_0$, and $x_d'$. Such a task will both require and greatly enhance the physical picture of the synchronous machine.

## Per-Unit Quantities

In previous literature, mathematical developments such as given here have been carried out in the per-unit system even in literal form. In more complete derivations such procedure has advantage in the resulting simplicity of equations. However, for one not thoroughly familiar with the per-unit system, the nonhomogeneous appearance of equations is confusing. Consequently, in this educational paper, the derivations have been presented in classical notation, it being inadvisable to present 2 new viewpoints simultaneously. All equations in part III can be converted to equations in a consistent per-unit system simply by omitting all $\omega$'s, $10^8$'s, and $10^{-8}$'s.

The major value of the per-unit system lies in numerical work. If one has solved a problem for a typical machine in per unit, the results apply to any size or rating of ma-

chine with similar per-unit parameters. Furthermore, the numbers in a per-unit calculation are of convenient size and the engineer can check their approximate values from experience and physical reasoning, thus reducing the chance for error.

## Physical Picture

The final phase of the physical picture, which this paper attempts to build up, may now be developed from equations 53. We seek a concept of the fictitious direct-, quadrature-, and zero-axis windings which give rise to the rather unusual equations 53. The equations are unusual because of the presence of the $\psi_d p\phi$ and $\psi_d p\phi$ terms, the like of which do not occur in equations for the electromotive force in a circuit fixed in the observer's initial system.

Let us as observers, reside upon the rotating field structure and attempt to visualize the phenomena experienced in the direct axis. The armature phase currents, assumed to be positive phase sequence for this visualization, will produce a rotating sinusoidal magnetomotive-force wave which may be resolved into 2 space sinusoidal components, one in line with the direct axis, the other with the quadrature axis. The absolute and relative magnitudes of the components may, of course, vary with time. Now visualize a winding opposite the direct axis and rotating with it which has the same resistance as an armature phase, $r$. If this winding carried a current $i_d$ it would produce a magnetomotive force in the direct axis, and $i_d$ might be such a function of time that its magnetomotive force was always equal to the direct axis component of the magnetomotive force produced by phase currents. For instance, if *steady-state*, positive-sequence armature currents flowed, $i_d$ would be direct current, producing a constant magnetomotive force in the direct axis. The voltage equation of such a fictitious winding would be, by Faraday's and Ohm's laws,

$$e_d = ri_d + p\psi_d \times 10^{-8}$$

for $\psi_d$ is the component of armature linkage opposite the direct axis. But, this physical picture is not complete because of the absence of $\psi_q p\phi$. The reason is that we have attempted to replace a symmetrical series of armature windings moving past the field pole and relative to the observer with a velocity $p\phi$ by one *ordinary* winding stationary with respect to the field poles. Now note that the *sides* of the fictitious direct-axis winding lie in the quadrature axis and in a flux density proportional to $\psi_q$. If these sides of the winding are imagined to have an instantaneous velocity $p\phi$ relative to the poles and the observer, then they would have a motional electromotive force induced due to motion relative to the observer proportional to $\psi_q p\phi$, and, if the fictitious winding is chosen properly and $\psi_q$ is positive ahead of the poles, equal to $-\psi_q p\phi$. The resulting equation would then be

$$e_d = ri_d + (p\psi_d - \psi_q p\phi)10^{-8}$$

The complete physical picture of the fictitious direct-axis winding is, then, a winding, similar to an armature phase, moving with the speed of the poles so that its magnetic axis is always in line with the direct axis, but *extraordinary* to the extent that its coil sides have an instantaneous velocity relative to the field poles of $p\phi$. Study will show that this is equivalent to a commutated winding like, for instance, the armature winding of a d-c motor when viewed from the field poles. Furthermore, the motional voltage cannot be attributed to a velocity through flux for the flux is produced by the combined action of the moving field poles and stationary armature conductors.

Obviously the physical picture of the fictitious quadrature-axis winding is identical with that for the direct axis, except for location. The term $\psi_d p\phi$ appears with a positive sign since positive direct-axis linkage is "behind" the quadrature axis.

The physical picture of a zero-axis winding is unimportant. It may be a 3-phase winding, stationary on the armature, connected as described in part II under "Zero-Sequence Reactance."

## Summary and Recommendation to Students

It is important to recall that the references, mentioned in the introduction and throughout the paper, furnish the basis for this paper. Part I is a presentation of the fundamental concepts of inductance such as has been developed and clarified in the advanced course in engineering[14] of the General Electric Company by many lecturers. Part II includes the viewpoints presented by Shildneck,[12] some of the tests given by Park and Robertson,[9] and some ideas not heretofore published. Part III incorporates methods similar to those used by Park,[13] but with considerable emphasis on the physical picture.

This paper has been written specifically to bridge the gap existing between collegiate study and current synchronous-machine literature. Hence, it is appropriate to suggest a program to the student for further study leading to the actual analysis. The program suggested is essentially that which has been used in the $B$-class, electrical engineering section of the advanced course in engineering in training graduates, one year out of college. A knowledge of differential equations such as given by Doherty and Keller[15] is necessary, and a knowledge of operational calculus[15] is desirable before proceeding far in the program.

1. Reference 1 gives the theoretical proof of validity of direct- and quadrature-axis representation and a study of it gives an excellent physical picture of the actual fluxes, linkages, currents, etc., in the machine.

2. The student may then proceed directly to references 5 and 6 and study and use, the complete, powerful, analytical methods presented by Park therein. These references are extremely concise and considerable thinking will be required of the student to follow the analysis and extend it to new problems. However, the more thinking required the better will be his ultimate understanding. Either sign conventions may be employed. Those used in this paper probably agree with the students' previous training.

3. Concurrently with the study just recommended references 7, 8, and 9 should be used to extend the students'

knowledge of reactances and references 2, 3, and 4 should be studied when working any of the specific types of problems therein, to aid in forming a very clear, complete physical picture of the phenomena; a very important phase.

4. Having mastered the preceding ideas and methods, the student should be able to solve a large number of synchronous machine problems, granting sufficient engineering and mathematical ingenuity and available time, on the assumption of no saturation, hysteresis, or eddy currents. Then he may proceed with the more recent literature on the extensions of the theory and its associated reactances.

It should not be inferred from this paper that synchronous-machine problems are all of standard type, and solvable by standard methods. Quite to the contrary, new problems are arising all of the time which require analysis directly from fundamentals. For example, a few such problems which have become important recently are:

1. The effects of saturation on both steady-state and transient performance. In some cases the effect of saturation is even more pronounced than the effect of saliency.

2. The effects of eddy currents in the solid cylindrical rotor of turbine generators during transient conditions, mentioned in part II.

3. Analysis of phenomena contingent to internal faults in the machine. This problem involves analysis with nonsymmetrical windings; additional complications arise due to dissymmetry, not only between phases but between the various pairs of poles on the armature and field.

4. Determination of reactances and performance of large double-winding generators.

5. Determination of performance with external capacitance. This problem requires an extension of the 2-reaction theory such as given by Crary.[20]

As such novel problems are frequently of great consequence and a recourse to fundamentals is necessary for their solution, the paramount importance of a thorough knowledge of the fundamentals and their associated physical picture cannot be overemphasized.

## Nomenclature

### Subscripts

$a$, $b$, and $c$ refer to armature phases $a$, $b$, and $c$ of a machine.
$d$, $q$, and 0 refer to direct-, quadrature-, and zero-axis quantities.

### Notation

$i$ = current, amperes
$I_d$ = direct-axis main-field-winding current, amperes
$e$ = electromotive force, volts
$E_d$ = direct-axis main-field-winding electromotive force, volts
$\psi$ = flux linkage, lines times turns
$\Psi_d$ = direct-axis main-field-winding linkage, lines times turns
$L$ = self-inductance, henries
$L_0$ = average value of phase self-inductance, henries
$L_{fd}$ = direct-axis main-field-winding self-inductance, henries
$l_{oc}$ = open-circuit leakage inductance, henries
$l_{sc}$ = short-circuit leakage inductance, henries
$l_B$ = bucking leakage inductance, henries
$M$ = mutual inductance, henries
$M_0$ = amplitude of variation of phase self-inductance and of mutual inductance between phases, henries
$M_d$ = mutual inductance between the armature and the direct-axis main-field winding, henries
$M_s$ = average value of mutual inductance between phases, henries
$\phi$ = angle between the direct axis and the axis of phase $a$
$\omega$ = rated angular frequency = $2\pi f$ radians per second
$f$ = rated frequency, cycles per second
$t$ = time, seconds
$p$ = time derivative operator = $\frac{d}{dt}$
$\mathcal{P}$ = permeance
$x_l$ = armature leakage reactance
$x_d$ = direct synchronous reactance
$x_q$ = quadrature synchronous reactance
$x_d'$ = direct transient reactance
$x_d''$ = direct subtransient reactance
$x_q'$ = quadrature transient reactance
$x_q''$ = quadrature subtransient reactance
$x_2$ = negative-sequence reactance
$x_0$ = zero-sequence reactance

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# Per-Unit Quantities

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## Summary

This paper discusses the use of per-unit quantities and their relation to dimensional analysis. It has been written at the request of the committee on education, and designed primarily for those interested in education, to serve as a background for discussion of the need which has arisen in the electrical engineering literature to translate new techniques into language readily understandable by students.

The use of per-unit quantities in the current machinery literature, although invaluable to the practicing engineer who wishes to obtain as much similarity as possible in calculations of machines and transformers of various ratings, is confusing to the average student, largely because factors which have physical significance are divided out and dimensions which would aid him in recognizing the origin of the different terms in an equation disappear.

IN THE electrical machinery field there has been for the last several years an increasing gap between the theoretical training given in the average engineering school and that required by industry. The accounts of recent developments, particularly in synchronous-machine theory, short-circuit calculations, and power-system stability, are not easy for the senior student in electrical engineering or even the young graduate to follow. The result has been that there is at present a wealth of technical literature in this field which is read by a small minority. The same condition, probably to a lesser degree, exists in the other fields.

It is felt that articles which supply fundamental theory not ordinarily given in undergraduate courses and which correlate the important developments during the past 10 years would greatly increase the value of a vast amount of literature now available only to a few.

The above remarks represent an untested opinion. The publication of this paper is an experiment. The AIEE committee on education and the author welcome comments from the membership both in regard to the general aims and to this paper specifically.

## Definition and Advantages of Per-Unit Quantities

The concept of per-unit quantity is by no means restricted to the field of electrical engineering; although the *term* is not usually employed elsewhere. For example, an infantry officer would hardly say "increase cadence to 240 steps per minute" but is accustomed to give the command "double time!" "Double time" may be regarded as a per-unit speed of 2 to the base 120 steps per minute; the latter being normal or unit speed.* Any system in which quantity is expressed as the multiplying factor of some normal value, rather than in the usual units for the quantity being expressed, is called a *per-unit* system. The ordinary percentage system is a per-unit system. Here the base is 100 per cent, consequently a given percentage value is 100 times the equivalent per-unit value.

In accordance with the above, currents, voltages, resistances, etc., may be expressed in per-unit values. A per-unit current of 2 means that the current under consideration is twice some preassigned current which has been designated as the base or unit current. It is convenient in most engineering work to use the normal rated value of a given quantity as the base to which the per-unit value of that quantity is referred. If this is done a per-unit current of 3 is immediately recognizable as a dangerous overload. From a practical viewpoint this means more than to specify the current as, say, 50 amperes, since the latter implies nothing at all about the propriety of allowing such a condition to exist.

A further advantage of expressing quantities in per unit is that measurements or calculations made on one of several similar devices are then immediately applicable to the others of the group by simply changing the base value.

A still greater advantage accrues from the fact that troublesome factors which appear in the normal quantity disappear when it is expressed in per unit. For example, the self-inductance of a coil is given by

$$L = 4\pi N^2 10^{-9} \mathcal{P} \text{ henrys} \qquad (1)$$

where $N$ is the number of turns and $\mathcal{P}$ is the permeance, in centimeter-gram-second units, of the flux path. If some value of the inductance be assumed as normal, or unit value, and if the inductance throughout a given set of calculations can change only due to changing permeance then we have

$$L(\text{per unit}) = \frac{4\pi N^2 10^{-9} \mathcal{P}}{4\pi N^2 10^{-9} \mathcal{P}\ (\text{normal})} = \mathcal{P}\ (\text{per unit}) \qquad (2)$$

Thus it may be possible to calculate a per-unit self-induced electromotive force without ever inquiring into the question of the number of turns involved. Such principles can actually be put to use in electric-circuit and electric-machine calculations.

## Application to Simple Equations

Although it is obviously possible to express all quantities relating to a given problem in per unit, it is not at all

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* The writer has taken a certain liberty here with military terminology, actually "double time" means approximately "1.5 time."

obvious that the per-unit quantities will satisfy the same equations as the quantities from which they were derived. As a matter of fact they will not satisfy such equations unless the bases are chosen in a particular manner. This will be illustrated by simple examples.

EXAMPLE I

The voltage drop in a circuit containing resistance only is

$$v = ri \tag{3}$$

In this equation $r$ and $i$ may be considered independent variables and $v$ the dependent variable. Suppose it be desired to express this equation in per-unit form. It will be necessary to use some value of current, preferably the rated current $I_0$ as the base or unit current and some value of resistance $R_0$ as the base or unit resistance. Thus

$$I_{pu} = i/I_0 \tag{4}$$

and

$$R_{pu} = r/R_0 \tag{5}$$

If it is required that the per-unit current and resistance satisfy Ohm's law then the per-unit voltage associated with them is given by

$$V_{pu} = R_{pu}I_{pu} = \frac{ri}{R_0I_0} = \frac{v}{R_0I_0} \tag{6}$$

hence the per-unit voltage *must* be expressed as

$$V_{pu} = v/V_0 \tag{7}$$

where $V_0$ is the base voltage defined by

$$V_0 = R_0I_0 \tag{7a}$$

Let $v$, $r$, and $i$ be variables related as in equation 3 and let the unit or base value of $r = 10$ ohms, of $i = 15$ amperes, then the unit or base value of $v = 150$ volts. Suppose $r$ is changed to 15 ohms, then $R_{pu} = 1.5$, and if $i$ is changed to 30 amperes, then $I_{pu} = 2$. Now $V_{pu} = R_{pu}I_{pu} = 3$. Since the base of $v$ is 150 volts the new value of $v$ is 450 volts.

This example suggests that, although the bases may not all be specified independently, the rules for specifying them are relatively simple. Let us look at another example.

EXAMPLE II

The voltage drop in a circuit containing resistance and self-inductance is given by

$$v = ri + L\frac{di}{dt} \tag{8}$$

Let us express all quantities on the right-hand side in per unit and attempt to calculate the base voltage which must be used on the left-hand side of the equation.

$$V_{pu} = \frac{r}{R_0}\frac{i}{I_0} + \frac{L}{L_0}\frac{d\left(\frac{i}{I_0}\right)}{d\left(\frac{t}{T_0}\right)} = \left(\frac{1}{R_0I_0}\right)ri + \left(\frac{T_0}{L_0I_0}\right)\frac{di}{dt} \tag{9}$$

In order to make this equation agree with equation 8 we must divide out the coefficients on the right-hand side of the equation. This cannot be done unless

$$\frac{1}{R_0I_0} = \frac{T_0}{L_0I_0} \tag{10}$$

Making use of equation 10 we find that the base voltage must be chosen as

$$V_0 = R_0I_0 \tag{7a}$$

which agrees with example I.

It is easy to see why equation 10 must be satisfied. Both of the terms on the right-hand side of equation 8 have the dimensions of volts; therefore they must both be represented to the same scale. In writing down equation 9 we attempted to assign arbitrary values to too many base quantities. From equation 10 it is evident that if $L_0$ and $R_0$ are assigned then

$$T_0 = \frac{L_0}{R_0} \tag{11}$$

This is not surprising in view of the fact that inductance divided by resistance has the dimensions of time.

Thus we see that of the 5 base quantities ($V_0$, $I_0$, $R_0$, $L_0$, $T_0$) necessary to express equation 8 in per unit only 3 may be specified independently. The other 2 are then determined by equations 7*a* and 11. These equations must be satisfied in order that the scales for each of the fundamental units throughout the equation may be consistent. In other words the dimensional relations of units must be taken into account since the equations are dimensional equations.

The following numerical example serves as a further illustration of the system: Let $r = 20$ ohms, $L = 0.03$ henry, and $i = 5\sqrt{2}$ sine $377t$. Then in ordinary units the equation 8 is

$$v = 20 \times 5\sqrt{2}\sin 377t + 0.03 \times 5\sqrt{2}\frac{d}{dt}(\sin 377t) = 115\sqrt{2}\sin(377t + 30°)$$

Let unit time be chosen as the number of seconds per radian in the sine wave, then $T_0 = 1/377$. Let unit current be chosen as $I_0 = 5\sqrt{2}$ and unit voltage as $V_0 = 115\sqrt{2}$, then unit resistance and unit inductance are given by

$$R_0 = \frac{V_0}{I_0} = 23$$

$$L_0 = R_0T_0 = 0.061$$

In per-unit terms we have

$$R_{pu} = 0.87 \qquad L_{pu} = 0.49 \qquad I_{pu} = \sin T_{pu}$$

and since the per-unit quantities satisfy equation 8 we have

$$V_{pu} = 0.87\sin T_{pu} + 0.49\frac{d}{dT_{pu}}(\sin T_{pu}) = \sin(T_{pu} + 30°)$$

## Dimensions of Electrical Quantities

From the above it is evident that it is not possible to assign mutually consistent base values for the calculation of

**Table I**

| Quantity | Exponents in Dimensional Formula L | M | T | Q | MKS Unit |
|---|---|---|---|---|---|
| Length | 1 | 0 | 0 | 0 | Meter |
| Mass | 0 | 1 | 0 | 0 | Kilogram |
| Time | 0 | 0 | 1 | 0 | Second |
| Quantity of electricity | 0 | 0 | 0 | 1 | Coulomb |
| Velocity | 1 | 0 | −1 | 0 | Meter per second |
| Acceleration | 1 | 0 | −2 | 0 | Meter per second per second |
| Force | 1 | 1 | −2 | 0 | Joule per meter |
| Torque | 2 | 1 | −2 | 0 | Joule per radian |
| Power, kilovolt-amperes | 2 | 1 | −3 | 0 | Watt |
| Energy | 2 | 1 | −2 | 0 | Joule |
| Moment of inertia | 2 | 1 | 0 | 0 | Kilogram-square meter |
| Current | 0 | 0 | −1 | 1 | Ampere |
| Electromotive force | 2 | 1 | −2 | −1 | Volt |
| Resistance (reactance or impedance) | 2 | 1 | −1 | −2 | Ohm |
| Inductance | 2 | 1 | 0 | −2 | Henry |
| Capacitance | −2 | −1 | 2 | 2 | Farad |
| Magnetic flux | 2 | 1 | −1 | −1 | Weber |
| Magnetomotive force | 0 | 0 | −1 | 1 | Ampere turn* |
| Permeability | 1 | 1 | 0 | −2 | Henry per meter* |
| Permeance | 2 | 1 | 0 | −2 | Weber per ampere turn* |

*Rationalized units only given, see reference 10.

per-unit quantities without first investigating the dimensional nature of the equations at hand.

If per-unit quantities are to be used in equations involving mechanical quantities, such as torque, moment of inertia, etc., as well as electrical quantities, it is not sufficient to investigate the electrical dimensions of the quantities. All physical quantities involved must be broken down into their dimensions in terms of fundamental units such as length, mass, etc.; since only in this way can it be assured that electrical and mechanical entities are represented to the same scale.

The dimensions of electrical quantities in terms of the fundamental units length, mass, and time are not uniquely defined.[16] Historically the centimeter-gram-second (cgs) electromagnetic and the cgs electrostatic systems have been the most generally used. In the cgs electromagnetic system of units, the units are derived from mechanical forces observed to be exerted on the poles of a suspended magnet, on the assumption that the permeability of free space may be taken to be dimensionless. In the cgs electrostatic system, the units are derived from the mechanical forces observed to be exerted on suspended electric charges, on the assumption that the dielectric constant of free space may be taken to be dimensionless. In 1881 Maxwell showed that the product of the permeability ($\mu$) and the dielectric constant ($k$) of free space had the dimensions of slowness squared, i.e., (seconds per centimeter).[2] Depending upon the choice of dimensions for $\mu$ (or $k$), infinitely many consistent systems of dimensions can be set up for the various electric and magnetic quantities.

Electric current, for example, may be expressed dimensionally as

$$i = L^{1/2}M^{1/2}T^{-1}\mu^{-1/2} \tag{12}$$

or, since $\mu = k^{-1}L^{-2}T^2$, as

$$i = L^{3/2}M^{1/2}T^{-2}k^{1/2} \tag{13}$$

In the electromagnetic system, since $\mu$ is assumed to be dimensionless, equation 12 becomes

$$i = L^{1/2}M^{1/2}T^{-1} \tag{12a}$$

whereas in the electrostatic system, since $k$ is assumed to be dimensionless, equation 13 becomes.

$$i = L^{3/2}M^{1/2}T^{-2} \tag{13a}$$

It is apparent that (12$a$) and (13$a$) are inconsistent.

The present viewpoint is that a fourth fundamental dimension should be used. It appears that either electric charge or electric current would be the most convenient of the electrical quantities and it is likely that one of these will ultimately be adopted.[10] In this paper quantity of electricity will be taken as the fourth fundamental dimension. Table I gives the exponents in the dimensional formulas for various mechanical and electrical quantities. In accordance with the present international standard, the meter-kilogram-second (mks) system of units is given in the table.

## A Theorem in Dimensional Analysis

The following general principles derivable from the theory of dimensional analysis yield all necessary rules for the selection of base values for per-unit quantities.

Suppose a given quantity $x_1$ to be expressed by the equation

$$f(x_1, x_2, x_3, \ldots, x_n) = 0 \tag{14}$$

in which the quantities $x_2, x_3, \ldots, x_n$ are independent variables or parameters having physical dimensions; then $x_1$ will also have physical dimensions. For example equation 8 is of the form

$$f(v, r, i, L, t) = 0 \tag{14a}$$

Let it be desired to express all of the $x$'s in per unit and let it be required that the per-unit values satisfy equation 14. If the bases are represented by $B_1$, $B_2$, $B_3$, etc., equation becomes

$$f\left(\frac{x_1}{B_1}, \frac{x_2}{B_2}, \frac{x_3}{B_3}, \ldots, \frac{x_n}{B_n}\right) = 0 \tag{15}$$

Since each of the $x$'s represents a physical quantity having dimensions each may be written as a dimensionless factor times its dimensions.[3] Thus

$$\left.\begin{aligned} x_1 &= X_1L^{\alpha_{1l}}M^{\alpha_{1m}}T^{\alpha_{1t}}Q^{\alpha_{1q}} \\ x_2 &= X_2L^{\alpha_{2l}}M^{\alpha_{2m}}T^{\alpha_{2t}}Q^{\alpha_{2q}} \\ &\cdots\cdots\cdots\cdots\cdots\cdots \\ x_n &= X_nL^{\alpha_{nl}}M^{\alpha_{nm}}T^{\alpha_{nt}}Q^{\alpha_{nq}} \end{aligned}\right\} \tag{16}$$

in which the $X$'s are dimensionless quantities, the factors M, L, T, and Q are the fundamental physical units and the $\alpha$'s are the dimensions of the $x$'s in these units. If for example $x_4$ is an inductance of 0.03 henry it may be written as

$$x_4 = 0.03\ L^2MQ^{-2} \tag{16a}$$

In this case $X_4 = 0.03$, $\alpha_{4l} = 2$, $\alpha_{4m} = 1$, $\alpha_{4t} = 0$, and $\alpha_{4q} = -2$.

16. For all numbered references, see list at end of paper.

It is necessary that any fundamental physical quantity be represented to the same scale throughout any given formula,[6] hence the choice of unit or base quantities in an expression must not introduce inconsistent scales for length, mass, time, or electric charge. Thus

$$\left.\begin{aligned}
\frac{x_1}{B_1} &= X_1\left(\frac{\mathrm{L}}{\mathrm{L}_0}\right)^{\alpha_{1l}}\left(\frac{\mathrm{M}}{\mathrm{M}_0}\right)^{\alpha_{1m}}\left(\frac{\mathrm{T}}{\mathrm{I}_0}\right)^{\alpha_{1t}}\left(\frac{\mathrm{Q}}{\mathrm{Q}_0}\right)^{\alpha_{1q}}\\
\frac{x_2}{B_2} &= X_2\left(\frac{\mathrm{L}}{\mathrm{L}_0}\right)^{\alpha_{2l}}\left(\frac{\mathrm{M}}{\mathrm{M}_0}\right)^{\alpha_{2m}}\left(\frac{\mathrm{T}}{\mathrm{T}_0}\right)^{\alpha_{2t}}\left(\frac{\mathrm{Q}}{\mathrm{Q}_0}\right)^{\alpha_{2q}}\\
&\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\\
\frac{x_n}{B_n} &= X_n\left(\frac{\mathrm{L}}{\mathrm{L}_0}\right)^{\alpha_{nl}}\left(\frac{\mathrm{M}}{\mathrm{M}_0}\right)^{\alpha_{nm}}\left(\frac{\mathrm{T}}{\mathrm{T}_0}\right)^{\alpha_{nt}}\left(\frac{\mathrm{Q}}{\mathrm{Q}_0}\right)^{\alpha_{nq}}
\end{aligned}\right\} \quad (17)$$

In equations 17 the quantities $\mathrm{L}_0$, $\mathrm{M}_0$, $\mathrm{T}_0$, and $\mathrm{Q}_0$ are the base or unit values of the fundamental physical units which are associated with the base or unit values $B_1$, $B_2$, etc., of the derived quantities. The equations 17 are dimensionless because $x_1$ and $B_1$ have the same dimensions, L and $\mathrm{L}_0$ have the same dimensions, etc. If the first of equations 16 be divided by the first of equations 17, the second by the second, etc., the following equations result:

$$\left.\begin{aligned}
B_1 &= \mathrm{L}_0^{\alpha_{1l}}\mathrm{M}_0^{\alpha_{1m}}\mathrm{T}_0^{\alpha_{1t}}\mathrm{Q}_0^{\alpha_{1q}}\\
B_2 &= \mathrm{L}_0^{\alpha_{2l}}\mathrm{M}_0^{\alpha_{2m}}\mathrm{T}_0^{\alpha_{2t}}\mathrm{Q}_0^{\alpha_{2q}}\\
&\cdots\cdots\cdots\cdots\cdots\cdots\\
B_n &= \mathrm{L}_0^{\alpha_{nl}}\mathrm{M}_0^{\alpha_{nm}}\mathrm{T}_0^{\alpha_{nt}}\mathrm{Q}_0^{\alpha_{nq}}
\end{aligned}\right\} \quad (18)$$

Clearly the values of $\mathrm{L}_0$, $\mathrm{M}_0$, $\mathrm{T}_0$, and $\mathrm{Q}_0$ may be assigned in any manner whatever, but the bases $B_1$, $B_2$, etc., may be assigned only such as to satisfy equations 18. These equations therefore represent a set of restrictions on the $B$'s; they may be used to determine how many of the $B$'s may be independently assigned and to determine the relations from which the remaining ones may be calculated. The nature of the restrictions which these equations impose upon the selection of the $B$'s is more clearly seen if logarithms are taken:

$$\left.\begin{aligned}
\alpha_{1l}\log \mathrm{L}_0 + \alpha_{1m}\log \mathrm{M}_0 + \alpha_{1t}\log \mathrm{T}_0 + \alpha_{1q}\log \mathrm{Q}_0 &= \log B_1\\
\alpha_{2l}\log \mathrm{L}_0 + \alpha_{2m}\log \mathrm{M}_0 + \alpha_{2t}\log \mathrm{T}_0 + \alpha_{2q}\log \mathrm{Q}_0 &= \log B_2\\
&\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\\
\alpha_{nl}\log \mathrm{L}_0 + \alpha_{nm}\log \mathrm{M}_0 + \alpha_{nt}\log \mathrm{T}_0 + \alpha_{nq}\log \mathrm{Q}_0 &= \log B_n
\end{aligned}\right\} \quad (19)$$

These may be regarded as a set of $n$ algebraic equations in the 4 variables ($\log \mathrm{L}_0$), ($\log \mathrm{M}_0$), ($\log \mathrm{T}_0$), and ($\log \mathrm{Q}_0$). Since in general 4 such equations are all that are required for the determination of 4 variables, it follows that not more than 4 of the $B$'s can be assigned independently. The general rules for the assignment of the $B$'s, which follow from the theory of linear algebraic equations,[1] are:

1. It is never possible to assign more than 4 independent bases.

2. Any 4 bases may be assigned independently only if the determinant formed of the exponents in the 4 dimensional equations for these quantities is not zero.

3. Any 3 bases may be assigned independently only if there is at least one third-order determinant in the exponents, contained in the 3 dimensional equations for these quantities, which is not zero.

4. Any 2 bases may be assigned independently only if there is at least one second-order determinant in the exponents, contained in the 2 equations for these quantities, which is not zero.

The above 4 provisos are the conditions for *dimensional independence* of the arbitary base quantities for a per-unit system.

EXAMPLE

Referring again to example II, let us regard the assignment of base or unit values to $v$, $r$, $i$, $L$, and $t$ in the light of the foregoing. The equation relating these quantities, as pointed out in equation 14*a*, is of the form

$$f(v, r, i, L, t) = 0$$

hence we require values for the bases $V_0$, $R_0$, $I_0$, $L_0$, and $T_0$ in the equation

$$f\left(\frac{v}{V_0}, \frac{r}{R_0}, \frac{i}{I_0}, \frac{L}{L_0}, \frac{t}{T_0}\right) = 0 \quad (20)$$

Using the same numerical values as before the dimensional equations for the variables and parameters are:

$$\left.\begin{aligned}
v &= V\,\mathrm{L}^2\,\mathrm{MT}^{-2}\,\mathrm{Q}^{-1}\\
r &= 20\,\mathrm{L}^2\mathrm{MT}^{-1}\,\mathrm{Q}^{-2}\\
i &= (5\sqrt{2}\sin 377t)\,\mathrm{L}^0\mathrm{M}^0\mathrm{T}^{-1}\mathrm{Q}\\
L &= 0.03\,\mathrm{L}^2\mathrm{MT}^0\mathrm{Q}^{-2}\\
t &= T\,\mathrm{L}^0\,\mathrm{M}^0\,\mathrm{T}\,\mathrm{Q}^0
\end{aligned}\right\} \quad (21)$$

As developed in equations 16 to 19 the bases must satisfy the equations

$$\left.\begin{aligned}
2\log \mathrm{L}_0 + \log \mathrm{M}_0 - 2\log \mathrm{T}_0 - \log \mathrm{Q}_0 &= \log V_0\\
2\log \mathrm{L}_0 + \log \mathrm{M}_0 - \log \mathrm{T}_0 - 2\log \mathrm{Q}_0 &= \log R_0\\
- \log \mathrm{T}_0 + \log \mathrm{Q}_0 &= \log I_0\\
2\log \mathrm{L}_0 + \log \mathrm{M}_0 - 2\log \mathrm{Q}_0 &= \log L_0\\
\log \mathrm{T}_0 &= \log T_0
\end{aligned}\right\} \quad (22)$$

It is known at the outset that not more than 4 bases can be assigned independently. Let us attempt to assign 4 independent bases, for example, $V_0$, $R_0$, $L_0$, and $T_0$. The determinant of the dimensional exponents is

$$D = \begin{vmatrix} 2 & 1 & -2 & -1\\ 2 & 1 & -1 & -2\\ 2 & 1 & 0 & -2\\ 0 & 0 & 1 & 0 \end{vmatrix} \quad (23)$$

In this determinant, row 3 minus row 4 is equal to row 2; hence the determinant is zero. It will be found that all other fourth-order determinants contained in equations 22 are also zero, thus rule 2 above restricts the assignment to 3 independent base values. Even in the assignment of these there is a further restriction. For example, is it not possible to assign $V_0$, $R_0$, and $I_0$ independently. The dimensional exponents for $v$, $r$, and $i$ form the array

$$\begin{vmatrix} 2 & 1 & -2 & -1\\ 2 & 1 & -1 & -2\\ 0 & 0 & -1 & 1 \end{vmatrix}$$

Because the second row plus the third row of this array is equal to the first row, any third order determinant contained within it is zero. Selection of independent bases for these quantities would violate rule 3 above. A more detailed investigation reveals that it is permissible to assign 2 independent bases in one of the groups $V_0$, $R_0$, $I_0$ or $T_0$, $R_0$, $L_0$ and one independent base in the other group, but that it is not permissible to assign all 3 in one group. This

is in agreement with the previous observation that $V_0 = R_0 I_0$ and $L_0 = R_0 T_0$.

## Inductively Coupled Circuits

Consider a pure turn ratio having $N_1$ turns on the primary and $N_2$ turns on the secondary. Such a device has the property of stepping up the voltage in the ratio $N_2{:}N_1$ and stepping down the current in the ratio $N_1{:}N_2$, the kilovolt-amperes remaining unchanged. The device is assumed to have no other properties. Let the ratio $N_1{:}N_2 = a$. If 2 circuits are coupled by means of such a turn ratio it is evident that a current $\mathbf{I}_1$ in the primary circuit is equivalent to a current $a\mathbf{I}_1$ in the secondary circuit

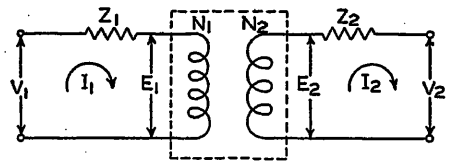



Figure 1

and that a voltage $\mathbf{V}_1$ in the primary circuit is equivalent to a voltage $\mathbf{V}_1/a$ in the secondary circuit. From this it follows that an impedance $\mathbf{Z}_1$ may be removed from the primary circuit providing an impedance $\mathbf{Z}_1/a^2$ is inserted in the secondary circuit. These principles are commonly used in referring transformer equivalent circuits to a given side of the transformer.

Suppose it be desired to express the quantities in 2 circuits coupled by a turn ratio in per unit. Referring to figure 1 the equations are

$$\left.\begin{aligned} \mathbf{V}_1 - \mathbf{Z}_1\mathbf{I}_1 &= \mathbf{E}_1 \\ \mathbf{E}_2 - \mathbf{Z}_2\mathbf{I}_2 &= \mathbf{V}_2 \\ a\mathbf{I}_1 &= \mathbf{I}_2 \\ \mathbf{E}_1 &= a\mathbf{E}_2 \end{aligned}\right\} \quad (24)$$

Combining equations 24 the following well-known single equation for the performance of the circuits is obtained:

$$\mathbf{V}_1 - (\mathbf{Z}_1 + a^2\mathbf{Z}_2)\,\mathbf{I}_1 = a\mathbf{V}_2 \quad (25)$$

Let us rewrite these equations in per unit. The quantities involved are voltages, currents, and impedances. As has been shown only 2 independent bases may be chosen. Suppose $\mathbf{V}_0$ and $\mathbf{I}_0$ be taken as the arbitrary bases, then $\mathbf{Z}_0 = \mathbf{V}_0/\mathbf{I}_0$. In per-unit terms we have

$$\mathbf{V}_{1pu} - (\mathbf{Z}_{1pu} + a^2\mathbf{Z}_{2pu})\,\mathbf{I}_{1pu} = a\mathbf{V}_{2pu} \quad (26)$$

which is identical in form with equation 25. Equation 26 is the result of setting up a consistent per-unit system in accordance with the methods outlined in the foregoing. Suppose however that instead of demanding a *consistent per-unit system* which yields per-unit quantities which satisfy the *same equations* as the ordinary quantities, we attempt to set up an *inconsistent per-unit system* which satisfies *simpler equations* than those satisfied by the ordinary quantities. Let the same base values as before be retained for quantities on the primary side (denote these by $\mathbf{V}_{10}$, $\mathbf{I}_{10}$, and $\mathbf{Z}_{10}$) and let new base values be used for the quantities on the secondary side in accordance with

$$\left.\begin{aligned} \mathbf{V}_{20} &= \frac{\mathbf{V}_{10}}{a} \\ \mathbf{I}_{20} &= a\mathbf{I}_{10} \\ \mathbf{Z}_{20} &= \frac{\mathbf{Z}_{10}}{a^2} \end{aligned}\right\} \quad (27)$$

Designating the new per-unit secondary quantities by primes we have

$$\left.\begin{aligned} \mathbf{V}_{1pu} - \mathbf{Z}_{1pu}\,\mathbf{I}_{1pu} &= \mathbf{E}_{1pu} \\ \mathbf{E}'_{2pu} - \mathbf{Z}'_{2pu}\,\mathbf{I}'_{2pu} &= \mathbf{V}'_{2pu} \\ \mathbf{I}_{1pu} &= \mathbf{I}'_{2pu} \\ \mathbf{E}_{1pu} &= \mathbf{E}'_{2pu} \end{aligned}\right\} \quad (28)$$

from which

$$\mathbf{V}_{1pu} - (\mathbf{Z}_{1pu} + \mathbf{Z}'_{2pu})\mathbf{I}_{1pu} = \mathbf{V}'_{2pu} \quad (29)$$

If the numerical values of the primary bases are taken as the rated values on the primary sides, then equations 27 give numerical values for the secondary bases which are also rated values. This selection of base quantities, although dimensionally inconsistent, effects a twofold simplification in the calculation of circuits involving turn ratios: the numerical values are held to convenient and readily interpretable sizes and the equations themselves become easier to write down. This principle can be used in a variety of practical problems in which turn ratios are involved: armature, field, and amortisseur relations in synchronous machines, transformers, etc.

## Calculation of Power Networks

One example of the above, commonly encountered in engineering practice, in which a considerable simplification is effected, is the calculation of the current and voltage relationships in power networks. Consider a simple

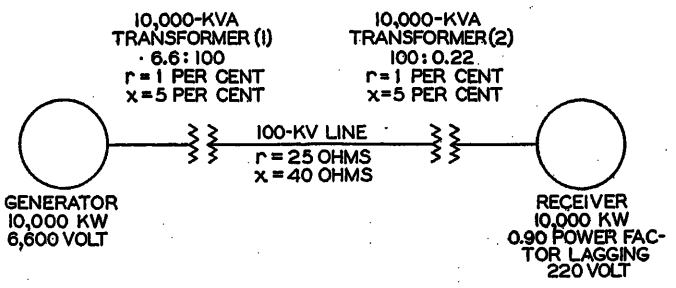



Figure 2

network in which a load or receiver is supplied from a distant generator by means of a transmission line having transformers at either end. Such a system is indicated in the single line diagram, figure 2.

Let it be required to calculate the generator terminal voltage necessary to maintain 220 volts at the receiver.

Divide the network into 3 parts separated by the turn ratios of the transformers. Choose a common kilovolt-ampere base $(\text{kva})_0 = 10{,}000$. Choose the rated voltage of each part as the voltage base of that part $V_{10} = 6{,}600$,

$V_{20} = 100{,}000$, $V_{30} = 220$. Then in per unit the data may be rewritten

Receiver: $Z_0 = 0.00484$, $R_{pu} = 0.90$, $X_{pu} = 0.435$

Transformer (2): $Z_0 = \begin{cases} 0.00484 \\ \text{or,} \quad R_{pu} = 0.01, X_{pu} = 0.05 \\ 1{,}000 \end{cases}$

Line: $Z_0 = 1{,}000$, $R_{pu} = 0.025$, $X_{pu} = 0.04$

Transformer (1): $Z_0 = \begin{cases} 1{,}000 \\ \text{or } 4.35\ R_{pu} = 0.01, X_{pu} = 0.05 \end{cases}$

Total per-unit impedance $= 0.945 + j0.575 = 1.11 \angle 33.5°$. Since the current is unity the voltage required is $1.11 \times 6{,}600 = 7{,}326$ volts.

## An Electromechanical Example

In synchronous-machine calculations it is customary to choose as base armature voltage the rated voltage of the machine and as base armature kilovolt-amperes the rated kilovolt-amperes of the machine. This results in a base armature current which is the rated current of the machine. Base time is usually taken as seconds per radian at normal frequency. In certain stability calculations it is necessary to write a differential equation for the acceleration of the rotor of a synchronous machine in terms of the difference between the electrical and mechanical torques and the moment of inertia of the armature. In mks units the equation is

$$J\frac{d^2\theta}{dt^2} = \Delta T \tag{30}$$

in which

$J$ = moment of inertia in kilogram square-meters, or in joule seconds-square per radian-square
= angular displacement from synchronism in mechanical radians
$t$ = time in seconds
$\Delta T$ = difference between electrical and mechanical torques in joules per radian

Since the associated electric circuit will in general be calculated in per unit, equation 30 should also be expressed in per unit.

Three independent bases [$(\text{kva})_0$, $V_0$, and $T_0$] have been specified; is it permissible to assign base values for moment of inertia or torque, or are these calculable from the 3 already assigned? In order to answer this question write down the determinant of the exponents taken from table I for kilovolt-amperes, electromotive force, time, and moment of inertia. The determinant is

$$D = \begin{vmatrix} 2 & 1 & -3 & 0 \\ 2 & 1 & -2 & -1 \\ 0 & 0 & 1 & 0 \\ 2 & 1 & 0 & 0 \end{vmatrix} \begin{matrix} \text{(kilovolt-amperes)} \\ \text{(electromotive force)} \\ \text{(time)} \\ \text{(moment of inertia)} \end{matrix} \tag{31}$$

If the third row be multiplied by 3 and added to the first row the fourth row is obtained; hence the determinant is zero. It is therefore not permissible to select a base moment of inertia $J_0$ independently. It must be calculated from the relation

$$J_0 = (\text{kva})_0 T_0^2 \tag{32}$$

In the case of torque we find that the dimensional exponents for torque may be obtained by adding the exponents for kilovolt-amperes and time, hence

$$T_0 = (\text{kva})_0 T_0 \tag{33}$$

In terms of these bases equation 30 becomes

$$J_{pu}\frac{d^2\theta}{dT_{pu}^2} = \Delta T_{pu} \tag{34}$$

in which $J_{pu} = J/J_0$, $T_{pu} = t/T_0$, $\Delta T_{pu} = \Delta T/\Delta T_0$, and $\theta =$ angular displacement in *electrical radians* (on account of the choice of seconds per electrical radian as base time).

Instead of using $J_{pu}$ in stability calculations it is customary to use a quantity $H$ defined as twice the kinetic energy in the rotor per rated kilovolt-ampere. Since kinetic energy has the dimensions watt seconds, the quantity $H$ has the dimensions of seconds. To make equation 34 true if $H$ is substituted for $J_{pu}$ we must multiply by $2\ T_0 = 2/2\pi f = 1/\pi f$. The usual form of the equation is

$$\frac{d^2\theta}{dT_{pu}^2} = \frac{\Delta T_{pu}}{\pi f H} \tag{35}$$

Although this is not a complete per-unit system it has the advantage that $H$ is a readily measurable quantity. It can be shown that $H$ is the time in seconds required to bring the machine to rest from normal speed when normal full load is continuously applied.

## Dimensional Homogeneity in Per-Unit Equations

It is commonly accepted that a physical equation must be dimensionally homogeneous.[6,14] Therefore an equation which, although true numerically, seems not to "check" dimensionally requires special consideration. An equation often encountered in the machinery literature is an excellent example:

$$E = T\,p\psi + I \tag{36}$$

in which

$E$ = per-unit electromotive force in the field
$T$ = per-unit time constant of the field circuit (armature open circuited)
$p$ = derivative with respect to per-unit time
$\psi$ = per-unit field flux linkages due to the armature current
$I$ = per-unit current in the field

This equation is derivable from the differential equation

$$e_f = r_f i_f + L_f\frac{di_f}{dt} + \frac{d}{dt}(Mi_a) \tag{37}$$

This may be rewritten as

$$\frac{e_f}{r_f} = i_f + \frac{L_f}{r_f}\frac{di_f}{dt} + \frac{L_f}{r_f}\frac{d}{dt}\left(\frac{M}{L_f}i_a\right) \tag{38}$$

The quantity $L_f/r_f$ is a time constant and may be written $T$, hence we may write

$$\frac{e_f}{r_f} = i_f + T\left[\frac{di_f}{dt} + \frac{d}{dt}\left(\frac{M}{L_f}i_a\right)\right] \tag{39}$$

Let base resistance be taken as the actual resistance of the field circuit.

$$R_0 = r_f \tag{40}$$

and let the bases $E_0$ and $T_0$ be selected in any convenient manner. In per unit equation 39 is

$$\frac{E_{pu}}{R_{pu}} = I_{pu} + T_{pu}\frac{dI_{pu}}{dT_{pu}} \tag{41}$$

in which $I_{pu}$ is the total equivalent field current. From equation 40 $R_{pu}$ is unity, hence *numerically*

$$E_{pu} = I_{pu} + T_{pu}\frac{dI_{pu}}{dT_{pu}} \tag{42}$$

Note also that per-unit flux linkages are given by

$$\psi_{pu} = \frac{N^2Pi}{N^2PI_0} = I_{pu} \tag{43}$$

in which $P$ is the permeance in rationalized mks units.

Thus we have the numerical equation

$$E_{pu} = T_{pu}\,p\psi_{pu} + I_{pu} \tag{44}$$

which is the same as equation 36.

Although simplification of calculation may be effected by use of equation 44, this advantage is sometimes more than offset by the increased difficulty in interpretation. It is true that equations expressed in per unit are dimensionless; however, it is of great importance to preserve a notation which indicates the dimensional origin of the various terms of the equations.

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# 1937 Index—Electrical Engineering and Transactions

This multientry annual reference index covers comprehensively the entire text content of the 12 issues of ELECTRICAL ENGINEERING published during 1937 and the identical content of the 1937 AIEE TRANSACTIONS, volume 56; the index covers also a supplement of 28 pages published in the TRANSACTIONS, which contains the following two papers not published in ELECTRICAL ENGINEERING:

1. FUNDAMENTAL CONCEPTS OF SYNCHRONOUS MACHINE REACTANCES, by B. R. Prentice (pages 1–21 of supplement).

2. PER-UNIT QUANTITIES, by Irven Travis (pages 22–8 of supplement).

A special effort has been made to provide effective correlation between references to technical papers and all published discussions of those papers. Discussions of many technical papers published during the latter part of 1936 were published in the early part of 1937, and hence appear in this current index. Likewise, many discussions of the later 1937 papers will be published early in 1938, and consequently will not be found among the references contained in this current index.

For convenience in use, this index is subdivided into the following general sections:

1. Technical subjects.
2. Authors, including the writers of discussions.
3. News items pertaining to Institute activities.
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